Trust–brokerage systems for the Internet

by

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Abstract

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This thesis addresses the problem of providing trusted individuals with confidential information about other individuals, in particular, granting access to databases of personal records using the World–Wide Web. It proposes an access rights management system for distributed databases which aims to create and implement organisation structures based on the wishes of the owners and of demands of the users of the databases. The dissertation describes how current software components could be used to implement this system; it re-examines the theory of collective choice to develop mechanisms for generating hierarchies of authorities; it analyses organisational processes for stability and develops a means of measuring the similarity of their hierarchies.
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Preface

This thesis attempts to use the principles of the design of political systems for information processing systems. Political systems are the means by which governments order the affairs of states and a political system in a liberal democracy uses elections as a feedback system which allows the subjects of the political system to direct it in the long-term.

The political systems that govern commercial businesses are not as well evolved — the only feedback they have formalised is from their shareholders. There should be inputs from customers, suppliers and government agencies. The information processing systems used by businesses reflect this lack of controlled feedback. Most information systems are designed to solve the problems of a particular management strategy for a business organisation.

The goal of this thesis is to liberate the management of information from enterprises and return it to the people who are its subjects and should be its owners. If ordinary people can control who has access to their personal information then, the hope is, it will not be as easily abused. Further than that, the behaviour of honest people should be the norm, but it is more often the case in modern society that honest and trustworthy people must prove themselves to be so, because most organisations have no means of distinguishing between the honest and the dishonest. Such information should be made available, so that genuinely honest people would find it easier to function in society than those who are not.

My hope is that this thesis will stimulate research into and development of information systems that rank people and institutions according to different metrics: how solvent they are, what areas of expertise they have, and, generally, how trustworthy
they are. And from this, be able to give suitably-qualified people more influence over different aspects of policy. It is, of course, unlikely that this would be the immediate result and it would seem more sensible to prove this technology with direct research towards managing resources where the ethical issues would not cause so great an obstruction. Computer and telephone network resources would be one such example of a good proving ground.

I must express my thanks to some of the people who have helped me over the years: in particular, from the Electrical Engineering department: Dr Clarke, my research supervisor, Mrs Margaret Saunders and Mrs Valerie Hayes, our secretaries, who have helped me through the administrative maze. Dr Robert Zimmer of Information Systems and Computer Science must be thanked because he first introduced me to the more formal areas of computer science. Mr Callum Downie of the Faculty of Technology and Mr Theodorous Georgiou of Electrical Engineering for keeping the outstanding computing services of Brunel University ticking over.

This research was supported by the Engineering and Physical Sciences Research Council, but only thanks to the efforts of Bob Thurlby and Bill O’Riordan of ICL and Russell-Wynn Jones of the Chorleywood medical practice.

I would like to dedicate this thesis to the memory of Dr. Alan MacDonald and Frau Marie Kohl née Schneider.
Part I

Trust Broking
Chapter 1

Overview

The original brief for this project was to develop a software system that would allow a community of individuals to access each other’s information with the owner’s consent and yet to do so in such a way that:

- That consent could be delegated but never forced
- and there would be no prejudice against an individual for choosing not to release information

The immediate goal was to realize a means whereby medical practitioners based in surgeries and hospitals could access the medical records they held on each other’s patients. Such facilities are already available in Germany [Blo01] and Iceland [And98], but neither system provides assurances that consent will be obtained, nor that records will remain confidential.

It became apparent that many of the problems of controlling the release of this personal information would need to be resolved by a joint decision of the owner of the database holding the information, the person who wants to use the information and the person, or persons, who are referred to by it. The decision would resolve whether the person wanting to use the information was entitled to access it and, if so, how much of it.

This is a fundamental business process and most people would recognise it as one they take part in all the time. Even more fundamental than the process is the
commodity that is traded when the decision to grant access is made. The sole criterion that both the database owner and the subjects of the records held within it must feel is satisfied is simply: “Can this new user be trusted not to misuse the information contained in our records?” and trust is the commodity that is exchanged by all three parties. Trust is a belief that someone else will keep their promises:

- The subjects of the records trust the owner of the database and the user of their records.
- Because:
  1. The owner of the database promises the subjects to release information on them to mutually agreed users.
  2. The owner of the database promises the subjects to release only the information they have agreed to release.
  3. The user of the records promises not to misuse the information contained in the records.

The goal then is to develop systems which will provide individuals with the degree of trust they require from each other: it is because of that, that the systems and mechanisms proposed by this research are described as, jointly, providing a trust–brokerage system.

Broadly, this research is in the area of computer–supported co–operative working and it is an active field, but has concerned itself with environments where there is enough implicit trust between all the parties involved that confidentiality safeguards can be largely omitted in system designs. Hubermann has developed a system known as Beehive [HK96] which has been employed as the basis for computer–aided engineering systems. There are also proposals for the joint management of investment portfolios [DSZ95] and there have been conferences discussing a number of digital library projects [Bat98] which provide on–line texts from a number of sources and access is only slightly restricted. All of these systems are to some extent predicated on the existence of virtual organisation — an organisation that has been created and
designed to fulfil a function within one real organisation or, more usefully, across a number of them. An interesting paper that describes how a virtual organisation can be created to fulfil a need is given in [Mil95].

Within the medical profession such systems are not as mechanised, but are developing a trust model within national organisations [And96a], [DWS99] and standards for security mechanisms specific to healthcare are being developed within Europe and elsewhere.

This Dissertation and Its Structure  This dissertation concentrates on providing co-operative working environments built upon databases of information. The databases must preserve confidentiality, so it divides naturally into two parts:

- Secure Distributed Processing
- Virtual Organisation for Resource Management

Secure Distributed Processing  This part re-examines the basic theory of data and database security and applies it to a distributed processing environment. A practical architecture for the secure management of access to any number of databases is developed and a prototype implementation is discussed.

In the context of medical information systems, this part of the documents describes mechanisms that must be implemented—such as those proposed by the European working group [DE96].

Virtual Organisation for Resource Management  Originally this section concerned itself with generating a virtual organisation for access control to databases, but it is now more general: it addresses the issue of how to manage access to any resource and the problem of how a virtual organisation for the management of authorisation hierarchies can be evolved from the needs of owners and users. This introduces three research issues:

1. Forming, analysing and quantifying hierarchies

\[\text{[And96a], “Standards”}\]
2. Resolving conflicts within hierarchies

3. Ensuring the stability of self-organising hierarchies

For medical information systems, this follows the argument of Anderson [And96b] that the medical profession operates under a collegiate structure: policies for allocating access rights are applied within autonomous organisations, but must be enforced within co-operating peer organisations.

**This Chapter** The remainder of this chapter provides a further introduction to the research by providing some examples of how it might be used.

### 1.1 Application: Universally Accessible Personal Information

In this section, the way in which the affairs of people are managed will be described.

The difficulty most people face is that mechanised information processing systems rely upon them to provide them with input — basically people have to fill in forms. To add further annoyance, people have to collect the information that the information processing systems generate about them to be able to fill in more forms — apply for a bank account, be given a bank account number and a sort code, then arrange a money transfer by quoting your bank account and bank sort code.

It would be much simpler, and less error-prone, if people had a repository of their personal information that was already in machine-readable format, but which could be projected into a human-readable form that people could reorganise. A simple drag and drop environment would be very attractive. For example, log on to a system, this generates an identity object which appears as an icon, go to a folder which represents your bank, make a new cheque, find the identity icon of the person you want to give the cheque to, drop his identity and one’s own identity icon into the cheque icon to sign and address the cheque and drop the cheque icon into an e-mail and send it. The
e-mail application will read the cheque’s identity icons, look up the e-mail addresses associated with them and address the e-mail correctly.

Such a system would greatly enhance the operation of information systems. There are already prototype banking systems that operate in a manner similar to that described above and it is hoped that more of them will be developed. The following discussion looks at the difficulties of mechanising the access and use of personal information. The discussion begins with how people manage their confidential information in the paper-based world we occupy now and then moves on to how they might organise their information in an electronic environment.

1.1.1 People

Paper Lives

Most people will have a collection of papers in their possession that, more or less, defines the person they have been and how they stand now:

Certificates a birth certificate, possibly a marriage certificate and, ultimately, a death certificate will complete the collection.

Qualifications there will be school-leaving certificates, examination results, degree certificates, driving licences.

Earnings Employers will have provided the Inland Revenue’s P60.

Status Notifications of tax codes, a passport, valid visas, employment permits.

Finances Bank account and credit card statements. Direct debits, standing orders.

Bills Receipts showing bills have been paid, statements from suppliers, which, for most people, will be the utility bills they have settled.

Memberships Libraries, clubs, professional organisations.

Properties and Contracts One may own a property, rent one or hold a mortgage, similarly for cars. There may be contracts with managing agents, rental companies and service company warranties.
**Histories** There will be one’s medical history; perhaps details of legal cases in which one may have been involved.

**Addresses and Contacts** Just about everyone has a list of addresses and phone numbers listing all the companies and organisations who supply all of the information held on them. There will also be contact addresses for oneself and for friends and business associates.

If one were to bring all this information together it would amount to a complex inter-related bundle and would suffer from all the typical problems of data collections:

**Replication** If one were asked to prove one’s identity: one could use one’s passport, driving licence, cheque card. To prove one’s address: bank statements, driving licence or utility bills.

**Specialist Knowledge** Tax codes can only be deciphered by someone familiar with tax regulations; leasehold agreements need contract lawyers. X–rays, radiographers.

**Inconsistent** Driving licences can hold details that are out–of–date. Membership cards can have mis-spellings.

**Unsubstantiable** One piece of information can be useless without another to substantiate it. For example, if one possesses a national insurance card, it is quite possible to pose as the person whose card it is; there is no substantiation of the holder’s identity.

**Location** A piece of paper is easily lost, or one does not have it when one needs it.

**Electronic Lives in a Honest World**

If we were to take all of the information used to lead one’s life and make it available electronically, then software applications could be developed, like the chequing account mentioned above, which would require no paper–based input. The information would be easier to manage and to access.
In an entirely honest world all of our personal information could be placed on a web-site and we, and others, could freely access it.

A Person’s Web-site  The World-Wide Web could be used to host a web-site which would act as an organised repository of all these documents in electronic form. They could then be organised to fulfil their different purposes. A diagram of how such a web-site might be organised is given in figure 1.1. It is owned and administered by an individual who has had a full professional working life: working in a number of countries. The web-site could contain the following pages.

Figure 1.1: Web-site used to provide personal information

1. Addresses

   The current contact addresses of the web-site owner would be held. These would reference his residential property address and his employer’s address.
2. Family and Friends

The owner might provide references to his wife’s and children’s web-pages; friends and former business colleagues. He might include his employment and academic referees here.

3. Advisors

The owner might provide references to his doctor, solicitor, accountant and others.

4. Permits and Licences

The owner might store references to his driving licences, employment and residency permits and proof of certain tax exemptions.

5. Projects Portfolios

The owner may have decided to record his work to help in finding suitable employment, so he would keep web-pages detailing his work, his employers and so forth.

6. Investment Portfolio

The web-site owner may have made some investments and might want to have a financial adviser manage them for him, so he might construct a web-page that contains references to the current value of his investments, where they are held and the account details.

7. Curriculum Vitae

This composite document would reference to other pages, or part of their contents:

- Addresses
- Projects Portfolios
- Permit and Licences
• Family and Friends

and would also reference educational qualifications, memberships of professional organisations.

8. Liquidity Statement

This shows the owner to be solvent and would be used to obtain credit or accounts. It would reference bank statements, accounts held elsewhere (credit cards and utility accounts) and property ownerships. It would of course refer to:

• Investment Portfolio

9. Tax Details

This would be used by the web-site owner’s accountant to pay his taxes. It would reference statements of his earnings, tax–deductible outgoings and would contain a reference to the address of his current tax office and possibly his past offices as well.

Providing Up–to–Date Information  A desirable enhancement would be for the web-site to provide current information: bank account statements could be updated with each transaction, as could the investment portfolio and any other records that change frequently.

• Either: provide a link to the provider of the information with the owner’s reference number to provide an index look–up in a directory service at the information providers web–site.

• Or: have a dynamic web–page that would create itself on demand and carry out the look–ups and the formatting of records itself.

• Or: have the information provider issue a new page by e–mail and have that page replace or be appended to the existing one.
The first of these two require the same operation: being able to make a remote query on a database. As an example, consider looking up the owner’s driving licence in the “Permits and Licences” web-page. The page could simply contain a reference to the issuing authority of the driving licence, with the index look-up:

http://www.open.gov.uk/dvla/drivers.htm/driver_number?EAVES60762WD9AK

A diagram for the interaction is given in figure 1.2.

Using the Information  With this scheme an individual’s personal information could be kept up-to-date and available over a universally accessible medium. If someone wanted to join a library they need not fill in any forms, but could just present the address of their web-page and have that recorded. The library could then see if the web-page owner provides enough information for its needs and could take whatever information it needed from the individual whenever it needed it.

The library would then notify the web-page owner of his new account at the library and send the address of the remote database that could be queried for his account details with them.

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2The URL used here is fictitious, but most insurance brokers are able to acquire this information and some make it available in web-based quotation systems.
Security Problems  Of course, no–one should have a web–site like this because there is no protection of one’s privacy. For example, someone visiting this site could learn the owner’s credit card details and commit fraud with them.

Electronic Lives in the Real World

Access Control Mechanisms  What is is needed to make the web–site secure are a number of access control mechanisms

- Placed at the entrance to each web–page
- Placed at every remote database that can be queried

The former restricts access to the page, the latter is a restriction put in place by the owners of the remote database as to who may access the data held on the owner. The owner would probably be entitled to see the record held on himself, but that need not be the case. If the owner is able to access his record, he may decide to allow other people to see it as well.

For example, only the owner of the web–page for “Tax Details” and his accountant would be allowed to access it, but he may also decide to allow his accountant access to the tax details held at his different tax offices, see figure I.3.

Granting Access Rights  There would also need to be a mechanism in place to grant access rights to the web–page owner’s record held in remote database. These issues have to be resolved:

- Does the web–page owner have the right to grant access to his record to someone else?
- Does the owner of the database where the record is held want to allow access to the person the web–page owner proposes?

The latter issue might appear contentious, but the data held at the remote database may have an intellectual copyright attached to it — there may be design documents in the “Project Portfolios” — or it may give rise to a conflict of interest —
it may contain a company’s information that should not be released to a stockbroker who might be involved in a rival bid for the company.

The web–page owner and the owner of the database must come to some kind of agreement and in so doing they would want to be as well–informed as possible about the individual to whom they are proposing to grant the access rights to. If that individual were known to the web–page owner then he should appear in his “Advisors” page or perhaps in his “Family and Friends” pages and if he is there, then his web–pages could be accessed and it should be possible to gain enough information about him to make a decision. There would be a system of implicit and explicit permissions. Company directors would implicitly grant rights to each other to view information that is common to them in the course of their business, but some rights may need to be granted explicitly: the right to sign cheques would be explicitly granted to the finance director, for example.

The mechanism for granting access rights could be anything: e–mail or a secure web–form. All three parties should be notified and record the rights granted and this
information should also be made available through a database.

1.1.2 Organisations

Responsibilities So far only the information needs of individuals have been discussed. The organisations that own the databases that hold individuals’ records would also want to use the data. Going back to the example of the library the web-page owner had joined, it will have access rights to some of the “Addresses” information so that it can send out statements to the web-page owner, but, if it has access to the address information for all of its borrowers, it can construct a mailing list and sell it to a direct-mail company and more junk-mail is almost certainly something that the library’s borrowers would not want.

On the other hand, the library may decide to do something useful with the address data, it may use it for planning where to build a new library. It is a matter of intent and a requirement that can be made is that whenever data is required from an individual, a statement of intent should be made with the request.

A statement of intent is no protection against abuse of the data held in the individual’s web-site unless one can show that the data has been properly used and the only way to do this is for the library to show that it has fulfilled its intent. This would involve proving to owners of the information that the data has been used correctly.

This is simple enough: if the library accesses an individual’s address record, it should leave a token with him saying that it will be used to send a statement, when the statement arrives, it will contain a reference to the token. The token and its reference can then be reconciled. In effect, every piece of information can be tracked to its source: one can think of this process as like recording the progress of a note of currency in the economy by tracking its serial number. There are already mechanisms for this form of transaction processing in most modern information processing systems: in particular, web servers have a system of transferring “cookies”, unique session identities that can be attached to the transactions an individual undertakes.
**Possibilities**  The possibilities for co–operative information sharing between responsible organisations and individuals are enormous. The health-care industry in particular could benefit by having near instantaneous access to medical records. Insurers would be able to evaluate risks better; law enforcers could isolate groups of people who may demonstrate a propensity to become offenders and take preventive measures; they could also determine which groups of people are most likely to have crimes committed against them. Of course such systems would need to protect civil liberties: if someone were determined as being a potential offender, it must be possible for him to appeal against that classification.
Part II

Database Security on the World–Wide Web
Chapter 2

Requirements and Analysis

The original brief for this project was to develop a software system that would allow medical practitioner’s databases to be accessed securely and safely. In this first part of the dissertation, a functional design is developed based on existing technology which could be used for a system that could provide personal information in the manner described in §1.1.

There are already systems in use that have similarities to that proposed: OncoNet [Blo01] provides oncological information to a high degree of data security because it is operated and used by one well–managed organisation.

When access is more open and management more collegiate, then such systems are more akin to digital libraries [Bat98, MeD98, SRI98]. These are well–funded and have reached a high degree of sophistication, but, it will be seen, they have a simple internal organisation, which effectively allows only one level of access.

There are other research projects for the health-care industry; these, too, are better developed — the LIOM project [LIO99], for example. Although that project aims to reflect the more complicated internal organisation of the health-care industry, it is not intended to be self–administering, which this system aims to be. The LIOM project, like others in this field, uses a meta–data model which has to be maintained [RHC96]. This is feasible on a small–scale (100 users or so), but the coordination effort needed would probably be excessive for larger systems (1000 users).

In the security model proposed by Anderson [And96a] there are recommendations
for technology, ITSEC standards for operating systems and databases. There are also recommendations for access control schemes, variants of Role–based access control, [San98], appear to be most adaptable to the collegiate federation of organisations proposed by Anderson. There is an implicit argument for a Public Key Infrastructure, PKI, which could support cross–certification, such as that analysed in [Mau96].

Secure Distributed Computing  The system design is also complicated by its attention to secure distributed computing [Sch94, Bir96], which is a relatively mature field. Secure computing requires that processes have proven implementations and execute on a safely constructed computer system with the least privilege needed to complete successfully: the principal requirement is that it should not be possible for other non–privileged processes to access any of the information produced or consumed by the secured processes.

In distributed secure computing, this problem is doubly difficult. One safely constructed computer system, system A, may hold confidential data, d, and another safely constructed computer system, system B, may hold a proven implementation of the process, p, to be used with the data. A may be able to pass d to B securely, but B cannot be trusted not to compromise it. B can however send its process implementation, p to A where it could execute and process the data, but A must be sure that p has no means available to it which would allow it to communicate d by a covert channel as well as be sure that p does not compromise the integrity of A. This interaction is fairly simple: more problems ensue if the data from different sources has to be merged.

Open Distributed Computing  The analysis and design process is within the framework of an Open Distributed Processing, ODP, system, [ISO97b], which is to address the information processing problem from these five perspectives:

- **Enterprise:** what has to be achieved
- **Information:** what information is needed to do it
- **Computational:** how can that information be obtained or deduced
• Engineering: what quality of service can be achieved in providing it

• Technological: what technology exists that could be used to achieve it

ODP merely recommends that the system design be addressed from all these perspectives and that each one could be modelled, if need be — see for example this discussion of working within the ODP framework [Can96].

The technological model is usually a given because it is the dominant technology at the time of design. The remaining four models can be traded off against one another. This chapter will be just a first pass over design issues and does nothing more than describe how such a system might work. Usually one begins with a sketch of the technology and enterprise models, then one sketches the information and computational models from the other two models to allow one to produce an engineering model, which is a set of interacting agents and more or less defines the operation of the system. The engineering model is then the basis for another iteration of design, where the enterprise, information and computational issues for each agent are addressed.

2.1 Technology Model: The World–Wide Web

This section describes the technology available at the time of writing. It will be seen, as the system is analysed, that the technology is fully capable of achieving what is required of it. The real design problem is to establish policies for authorising access and showing that they have been followed. Distinct aspects of information security should be clarified because they are addressed by different technologies.

• Secure access: the information is protected against indiscriminate access.

• Safe access: the information is protected against indiscriminate use by those who are allowed to access it.

Incidentally, the reason the World–Wide Web [W3C97] has been chosen as the communications medium ought to be stated.
• Wide access: the information can be accessed from as widely available a medium as is available.

Wide Access — Web Technology  As far as end-users are concerned the World-Wide Web has only:

• Web–browsers
• Web–servers

It is worth mentioning that the Internet protocols underlying the World-Wide Web can also offer secure electronic mail delivery [RSA99].

Probably the most useful piece of web technology for system designers is Java [SUN98]. This is an object code interpreted language that runs on a virtual machine; it can be constrained to only use specific operating system resources (files, sockets and so forth). This programming language allows system designers to load software from anywhere on the World-Wide Web and run it on a designated host in a safe environment. This is absolutely ideal for agent-based software.

Encryption and Authentication Products — Secure Access  The capabilities of this web technology are widely-known and some specifications can be found in [Cor98]. Most web-browsers can establish secure connections with suitably enabled web-servers. (The latest version of the secured socket protocol is called Transport Level Security and is discussed in [Eav99].)

This hinges upon public-key cryptography and secure repositories for public-key certificates. The standard governing this is X.509, [X5088], and the certificates are consequently known as X.509 certificates. They are available widely, at a charge, from certification authorities such as Thawte, [THA99]. There is some discussion of their limitations in [Ros95].

There are some well-evolved software security products producing public-key infrastructures [RSA98].
Operating Systems and Database Products — Safe Access  Operating systems are now relatively safe. ITSEC \cite{ITS} grades them and, currently, there are a number of products that have reached the acceptable security levels recommended by Anderson \cite{And96b}: E3 and above, \cite{UK96}.

Database systems are also graded by ITSEC and there are a number of suitable products for the system proposed \cite{Ill96} and it is possible to integrate these with web–servers \cite{Cor98}. Most databases support SQL, the Structured Query Language \cite{Nor96}, which provides a set of access control mechanisms which, it will be seen later, are adequate for the system proposed.

2.2 Enterprise Model: Contracts

The aim is to propose a suite of protocols that will allow access to databases to be strictly controlled and thereby allow more and qualitatively better information to be distributed and to simplify, standardise and partly mechanise the procedure whereby individuals are granted access. This section will describe the relationships between the parties as a set of contracts in the style of an enterprise modelling language as described in \cite{ISO97b} and, at slightly greater length, in \cite{Eav99a}.

A key argument in Anderson’s model for the security of clinical information systems is that individual information systems are assumed to be well–managed and align to the structure of the organisation they serve. The access control mechanisms of these information systems may use either a Bell–Lapadula \cite{BL73} or Clarke–Wilson \cite{CW87} mechanism for determining rights. They form part of a collegiate system which has some federal infrastructure which manages access control lists for the component systems. Anderson’s argues that the access control system for the access control lists can only be Clarke–Wilson in form.

This section attempts to develop rôles that could be used within the federal system, so that they might be used in a rôle–based access control system with constraints such as RBAC2 described in \cite{San98}.

In this section, these rôles will be specified using the principles of deontics \cite{MW93}, which aims to reduce difficult contractual relationships to sets of rules concerning
rights and duties.

**Adjudication and Loss** Contracts describe expected behaviour — usually, the formalisation of an existing behaviour. Each party to a contract believes that the expected behaviour will be forthcoming because it would be too costly to do otherwise. Either because it is practically too expensive not to behave as required, (it might change existing procedures), or, that penalties will be incurred by the party who breaches the contract. The latter requires that an adjudication service be available to determine if one party has not complied to the terms of the contract and that that party be punished and the other recompensed for the loss suffered. The operation of an adjudication service is quite sophisticated, but is discussed, in outline, in chapter 7; recompense for loss suffered is achieved by surety or insurance. The insurance industry already has some policies for disclosure of information, but it would be desirable if they were able to give cover at the time a contract is formed and it should be a precondition that cover be arranged before granting access. The insurance and surety process is capable of being mechanised [LMN97]; this paper also discusses how licences could also be issued for people offering services through web–servers.

### 2.2.1 Parties

There are four types of party to the contracts. These are specified with respect to the rights and duties they must possess and should fulfil. These are the entities that must follow the principles given in Anderson’s model [And96b] and would appear as rôles within the federal superstructure of the collegiate organisation.

- **Subjects**

  Subjects are the people (or organisations) on whom information is kept by the owners of databases.

- **Custodians**

  These individuals are appointed by the subjects; the appointment is usually *de facto*, a person’s doctor is obliged to act as their medical representative and is
therefore the custodian of their medical information. It should be possible to
make the appointment of a custodian explicit and a subject should know who
there custodian is. It may also be possible for a subject to be his own custodian.
The function of a custodian is to make access control decisions for the subjects.
It will almost certainly be necessary that custodians do this, because:

1. Subjects will not usually have the specialist knowledge needed to assess
access requests.

2. Custodians can act on behalf of groups of subjects which have similar
interests.

Subjects will usually delegate decision–making to one (or more) custodians. If
they choose to delegate to a group of custodians, then the subject can choose
from a number of decision processes — *e.g.* veto, unanimity, majority vote —
how the decision will be taken.

Custodians are responsible for the safety of information. They are not respon-
sible for the security of data storage and transfer of the information. That is
the job of the owner of the database, or databases, upon which the information
is stored and the facilities by which it is communicated. In short, custodians
specify the policies for information use, storage and transfer; owners execute
these policies. Very often the custodian and the owner will be the same person
acting in two rôles. Within a medical practice, a doctor will make decisions
regarding information safety when he decides what to include in a letter of re-
feral and will make decisions regarding data security when he chooses to send
the letter of referral by electronic mail.

Custodians should have some legal responsibility to the subjects. Most custo-
dians will be subject to legislation, such as, in the United Kingdom, the Data
Protection Act [DPAS4]. It may be useful to think of legislation, and other
policies a custodian should adhere to, as having a custodian, which could be
made an active part of the system.

• Owners
These people (or organisations) own the databases and the communications infrastructures that hold and distribute the information held on the subjects. They follow policies from custodians.

The owners will add their own information to that the subjects have provided. The owners will want to protect this information in the same way that subjects will want to protect theirs. In this respect they can thought of as a subject who is its own custodian for all the records in the database.

- Accessors

These are the people (or organisations) who access the databases held by the owners. Accessors will be assigned a security clearance class and each of these will have a membership panel of trusted peers who should be known to appropriately qualified custodians.

It may prove expedient for accessors to copy those parts of databases that interest them, add their own interpretations to the data and republish the data and, in so doing, they become custodians.

Closed Relationships A simple set of relationship rules might help clarify the entities’ rôles with respect to one another. The aim here is to ensure that the relationships are closed, so that the system can be self-governing.

There are four sets of rules.

1. Database management and composition

2. Subject–Record–Custodian

3. Multiple rôles

4. Accessor permissions

They are expressed as class relationships of the HAS–A and IS–A kind. HAS–A relationships can be by aggregation or by reference. Aggregation means that one entity is a composition of the others. The reference relationship means that one entity
knows about the existence of the others and there is some association between them, usually ownership or delegation or use.

*IS–A* can be of two kinds: by generalisation and by template. The latter is best called the *IS–KIND–OF* relationship and means that the two classes have the same meta–class, but have distinct identities and behave autonomously. The *IS–A* is usually implemented by inheritance and allows one class to be used in the same way as the other sharing a more abstract identity and cannot always act autonomously.

**Database management and composition**  This first pair of rules state that an owner manages a database, which is composed of a set of records. The relationships are one to many. An owner may manage more than one database.

(Database should be a more general concept because the rules describe control relationships. The more general concept is one of a *Resource*. This would include networking resources. An example of which might be a port number on a host computer. Only databases have been described here because they refer back to subjects directly.)

\[
\begin{align*}
&\text{Owner} \xrightarrow{\text{manages}} \text{Database} \\
&\text{Database} \xrightarrow{\text{is–composed–of}} \text{Setofrecords} \\
&\text{Record} \xrightarrow{\text{describes}} \text{Subject} \\
&\text{Subject} \xrightarrow{\text{has}} \text{Custodian}
\end{align*}
\]

**Subject–Record–Custodian**  The second pair state that each record maps to a subject and that each subject has a custodian. This is the most important rule: it associates data with information.

All the relationships can be one to many. In particular, a subject may have more than one custodian. There might be a custodian responsible for policy regarding data encryption of medical records and another responsible for the policy regarding the disclosure of confidential information.

One to many also implies that if you have obtain a record, it will have a subject and *vice versa*. 
Multiple rôles  The following IS–A relationships closes the system, so that all the entities introduced must have at least one custodian. There are three cases to cover:

- The database is a record which must describe a subject — this would be itself and the record would be the database’s meta-data. Each subject must have a custodian.

- An owner is a subject and must therefore have a custodian.

- A custodian is also a subject and so must have a custodian.

These rules encompass the relationships as they so often arise in practice. That an owner also acts as a custodian, but in different rôles — the example of a doctor sending a letter of referral by e-mail. It also allows a custodian to be his own custodian. This is useful for expressing supreme legal relationship: governments are only answerable to themselves.

\[
\begin{align*}
\text{Database} & \xrightarrow{\text{is}} \text{Record} & \text{Accesser} & \xrightarrow{\text{has}} \text{Permission} \\
\text{Owner} & \xrightarrow{\text{is}} \text{Subject} & \text{Permission} & \xrightarrow{\text{has}} \text{Record} \\
\text{Custodian} & \xrightarrow{\text{is}} \text{Subject} & \text{Set of custodians} & \xrightarrow{\text{creates}} \text{Set of permissions}
\end{align*}
\]

**accessor permissions**  The last three HAS–A relationship state how accessors are involved. They stand outside the system, because there are no practical means of enforcing any behaviour upon them. They access records via permissions. Permissions are created by custodians.

Each permission has a record so the custodians act as a linking entity between records (and their corresponding subject) and the set of permissions.

**Summary**  The important points are:

- That a database of records has custodians for each of the records contained in it and for the database as a whole.
• Subjects, owners and custodians themselves all have one or more custodians.

The latter point makes the system closed and self-governing.

This set of relationships is very similar to the architecture of per-formative agents proposed by [ISO97b] and also described in [Eav99a].

### 2.2.2 Grades of Anonymity

A well-known problem with personal information is that anonymity is no real protection if it is possible to obtain an identity and a profile from one database and use the profile to isolate some other confidential information from another database [DSW90]. Anonymity can prove to be an obstacle to legitimate use of data. A grading of degrees of anonymity might prove useful in specifying access contracts. This grading, see table 2.1, is illustrated with reference to the medical profession, but can be used elsewhere.

| Class          | Name to Identity Relationship          | Examples                  |
|----------------|----------------------------------------|---------------------------|
| Synonymous     | Person is named                        | Personal Physician        |
| Pseudonymous   | Person goes under an assumed name       | Secondary Physicians      |
| Anonymous      | Person is unnamed                      | Researchers and Administrators |
| Eponymous      | Group to which person belongs is named. | Researchers and Administrators |

Table 2.1: Name to Identity Relationships for Medical Information

Pseudonymous identities are already widely-used in medical research; it allows a particular patient to be referred to consistently and a thread of discussion can be developed around that identity.

Eponymous identities are subtly different from anonymous ones, because an individual is tagged as belonging to a particular group. Usually, genuinely anonymous
subject data is partitioned over and over until all the subjects have eponymous identities. *If* it is possible to write back to the original record that a particular subject has been designated as belonging to a particular group, *then* the subject has an eponymous identity. Under some methods of inference control, in particular *random sample queries* \[\text{Den80}\], it is not possible to attach any deductions, and therefore eponymous identities, to particular sets of records.

Some accessors may make local copies of datasets from databases and would add their own classifications, if these are re-published then the identities would be eponymous — because it is possible to use the original database to establish a profile and, by inference using that profile, obtain the classification made in the copied and augmented database.

### 2.2.3 Views of Records

When a record of a subject is released, it should not be the entire record, but rather a restricted view of the record that contains enough information to allow the accessor to do their own processing. This is a principle more or less enshrined in most information system security texts: “The principle of least information”\[\text{Den76}\].

Having a restricted view of a record does allow identities to be restricted to eponymous, but anonymity — or at least the anonymity granted by using random sample queries — requires an additional mechanism.

### 2.2.4 Duties of a Custodian to a Subject

Custodians are usually practicing professionals in a particular field. The relationship between a custodian and their subjects is usually governed by an accepted code of practice from a professional body, which is the collective identity of the custodians. These professional bodies usually grant licences to their members to practice their profession and there is usually an adjudication procedure to determine if a member has acted improperly. This is the only contract between custodian and subject that is needed. The duties of the custodian are to:

---

\[1\] See for example, \[\text{Den76}\].
1. Grant minimal views to accessors.

2. Inform subjects of:
   (a) Classes of accessors granted access to their records.
   (b) View of record given to those accessors
   (c) Evaluation of risk and insurance of surety gained on their behalf

2.2.5 Duties of the Owner to the Custodian

Owners are instructed by custodians as to whether or not the records for the custodian’s subjects can be released. The duties of the owner are to:

1. Release no record without prior approval from a Custodian
   This is actually required by the Data Protection Act [DPA84].

2. Provide Stated Degree of Anonymity
   If a custodian allows a subject’s record to be published then the degree of anonymity must be upheld.

3. Minimal View of the Record
   The custodian will state the view of the record that can be granted to a class of accessor and will expect no more than that to be released.

4. Minimal Set of Accessors
   A custodian will grant access to a particular security class of accessors.
   It is usually the case that a lattice model [Den76] of secure information flow is in force. This would allow accessors who have a “higher” security clearance to be given de facto access as well, without having to negotiate with the custodians. The lattice model is a generalisation of the Bell–LaPadula access control hierarchy [BL73], which could be described as “read–down, write–up” or an

\textsuperscript{2}Lattice models are described in section §6.3.2. For now they can be thought of as hierarchical organisation structures.
accessor at a particular security clearance can read everything graded below his own grade, but what he writes can only be read by those above his grade.

Whether *de facto* access is granted should be open to negotiation between custodians and accessors as well.

### 2.2.6 Duties of the Accessors to the Custodian

The main problem is that accessors may need the right to re-publish the data they have acquired from a database owner. An accessor could be an organisation and might need to re-publish the data internally or the accessor may decide to re-publish to a wider audience.

1. External Re-publication

   The accessors must ensure that other accessors be vetted and approved by the custodians in the same way that they were vetted and approved for access.

2. Internal Re-publication

   It may be possible for the accessor to show that his organisation’s own data security procedures are good enough to provide the custodian with enough assurance to forgo vetting procedures for every internal accessor.

### 2.2.7 Duties of the Custodian to the Accessors

If an accessor is *denied* access then they have a right to know how they can put themselves in a position whereby they may be granted access.

- Provide justification for denial of access

   If an accessor fails to meet particular security clearance requirements they should be told which so that they can change their clearance.
2.3 Enterprise Model: Adaptability Issues

There is enough tested and approved technology available to implement a system that could implement these relationships and provide the means for each entity to fulfil the duties imposed upon it, the challenge is to design it in such that a way that authorisation policies can formulated in a semi–automated way and that the system could be almost wholly self–governing. The use–case scenario for accessors would be something like this:

1. Reference to a database appears at a secure web–server
2. An accessor requests a particular set of records using secure e–mail from the relevant custodians
3. Custodians make their decisions and return them by secure e–mail
4. Based on the replies: a set of views for the records is generated and the owner of the database is instructed to publish it for the accessor’s eyes only
5. Accessor is notified of the views to use
6. Accessor uses secured connections to submit queries to the database on these generated views

There are a number of problems with this. Firstly, the custodians will make their decisions based on the current state of the records: a particular epoch of their existence. The accessor should either be restricted to that epoch or negotiate access for all subsequent epochs. Only a few databases directly support epochs — PostgreSQL [PSQ] does — without that different tables would need to be created for each epoch and separately maintained.

Secondly, the collation of the replies would need to employ some least lower denominator for the records, because some custodians may not grant access to particular fields within the record.

Thirdly, the process would generate a lot of request traffic, which custodians would be hard–pressed to keep track of and, therefore, to be consistent when applying their
own criteria. It would be useful to employ precedents, \textit{e.g.} a custodian has granted similar access rights to an accessor who has been classed at a lower level than the current requesting accessor, is it permissible to allow this accessor the same rights? This requires a lattice of information flow, which, it was specified above, would be the subject of negotiation between custodians and accessors. Using precedents requires that accessors and records be classified. The process of generating precedents can be accelerated if custodians are also classified, so that clearance gained from a custodian who is ranked higher than another means that there is no need to secure acceptance from the lower-ranked.

Fundamentally, custodians would either have to specify rules for access which could be applied by a mechanical agent on their behalf, or a mechanical agent would deduce rules from their actions and, after checking them with custodians, add them to a rule base to be used later. Similar systems to this have been deployed \cite{BW94, Cas97}.

2.4 \textbf{Rôle–based Access Control Systems: Information Model}

The information model proposed is that used for rôle–based access control systems. These are described in Sandhu \cite{San98}, in which he argues that rôle–based access control systems have such a sophisticated information model that they can be constructed to support all the other important forms of access control system.

Sandhu gives a simple information model, but this has been modernised, using Booch’s notation \cite{Boo94}, and clarified. (A more suitable notation would \textit{object role modelling}, \cite{Hal95}, which is more easily formalised for implementation, but Booch’s notation has been used for consistency.)

\textbf{Objects} The principal innovation of Sandhu’s rôle–based design can be seen in figure 2.1. Each object in the system has its own set of rôles associated with it. Each rôle acts as an interface to the object. Each rôle has a set of permissions associated
with it. Both relationships — object–rôle and rôle–permissions — have constraints objects associated with them.

Epochs and Constraints These permissions can be qualified by applying a set of constraints, the Epoch constraints.

Although Sandhu specifies that these constraints exist, he does not make it especially clear what they constitute. This denotation follows the practice in modern database design that access control rules and data descriptions can be revised so that the previous generation is still available as a different epoch. It will be seen that a self–organising access control system will need to remember its previous state.

Hierarchies The lattice structure of many access control systems is effected by allowing rôles to have a hierarchy. This is illustrated using the class tree in figure 2.1. There is an abstract role and this is sub–classed twice for role A and role B and role A is sub–classed once for role A1. Modern database systems such as PostgreSQL have support for sub–typed data classes.

Subjects Figure 2.2 shows how a subject obtains the set of rôles by which he may access the objects. A subject first obtains a session. A session is an engineering entity that qualifies what rôles may be used by means of a session constraint entity.

Constraints The session constraint is dependent upon the manner in which the session is established and is designed to reflect the different ways in which the same subject may access the system. Access from a physically secure local area network will be less constrained than from an insecure dial–up line. Other constraints may be imposed because of accepted usage practice: some records may only be available for specified dates and times.

Each session may have a different rôle set. This allows the same subject to act in the system in a different way.

Constraints A simple information model for constraints entities is given. These control the system who may access what within the system.
Each object in the system has a set of roles it is accessible through. The role is an interface to the object.

Each role has a set of permissions defined for the operations permitted on an object.

Roles are defined as subtypes of a generic abstract role type.

Only three roles are shown here. This shows how a hierarchy can be supported.

Figure 2.1: Role–based access control: object information model
Figure 2.2: Role–based access control: subject information model
Figure 2.3: Role–based access control: constraint information model
Summary Sandhu’s model for rôle–based access control systems is very useful to this design discussion. It will be seen that most of the design and analysis for this system will focus on generating the rôle hierarchy and a structure for constraints objects and the information that must be placed in the constraints objects.

2.5 Computational Model

Most of the computation performed by the system would be to provide its adaptability:

1. Generating views of records
2. Classifying accessors
3. Generating access rules

2.5.1 Generating Views of Records

Custodians would deny access to records or restrict access to certain fields. This suggests two strategies:

- Either provide a full record with *NULL* put into the field values where a custodian has denied access.
- Or generate a least common denominator view.

Nulling fields

- Either a new database table has to be created and the modified records inserted,
- Or a set of *triggers*\(^3\) to be generated to insert the *NULL* values where specified.

Neither of these is particularly desirable: the former requires a new table which would need to be separately maintained; the latter requires triggers to be written which would need to check a profile (specified by the custodian) for each record for every access of the view, which would greatly affect performance.

\(^3\)\text{SQL allows a function to be invoked when a record is operated upon, see ISO92.}
Least Common Denominator View  The collation procedure to produce the least common denominator view could employ one of two strategies:

- Maximum field coverage by minimising records included
- Maximum record coverage by minimising fields included

Both of which could be qualified by the accessor stating percentages of coverages and ranking fields to be included.

2.5.2 Classifying Accessors

Accessors would need to be grouped and then those groups ranked relative to one another to produce an authorisation lattice. Clearly, there are many policies for this: most involve some arbitration outside of the information system itself between the representatives of the different entities.

One procedure would to make use of professional standing within a respected professional institution. There are many groups extant that could be used as the basis for accessor control groups. The British Medical Association is the accrediting professional organisation for practicing doctors in the United Kingdom. The Law Society for solicitors. Belonging to a professional group implies that one performs a certain rôle. It may be necessary to enforce members of groups not to use their group identity if operating in a rôle not sanctioned by the group.

Grouping Accessors  This is a proposal for system of grouping accessors together which makes use of modern certification technology. The aim is that accessors and their groups would be self–regulating.

Each accessor would have an X.509 certificate proving their identity. They would then need to obtain a proposer and seconder from the group they wish to join. The proposer and seconder would corroborate the identity of the applicant and make some recommendation to the membership committee.

This protocol can be secured using a certificate chain and blind–voting protocols described in Sch96. (Certificate chaining is just one message encrypted using the
private key of one certificate and then by another. Blind voting allows a vote to be taken which allows each party to prove to themselves that their vote has been counted, without knowing who else has voted.)

Once an applicant has been granted membership of a group, they would then need to be issued with a new certificate which would be their group membership. This is an X.509 certificate with the group acting as the certification authority. In the event that membership is revoked, the certificate could be made void without inconveniencing any other members of the group. It also reduces the amount of encryption needed to just one pass.

(Incidentally, the method proposed above produces a “Web of Trust”. There are a number of different mechanisms for achieving this, again see [Sch96] and also [YKB94].)

**Ranking Groups**  There are two other functions that need to be developed for self–organising groups. They must be able divide themselves up and to merge. This, combined with an authorisation hierarchy, will allow them to better define who may access what information. Groups, in this context, are abeyant to set theory and what is needed is a defining membership function: much as one might say, $X$ is the set of all odd dice throws. This requires a distance measures which would allow someone to say that under, a particular distance measure, member $x$ is very similar to $y$. Statisticians and actuaries do this all the time, it just remains to develop it for professional groupings.

**Deference**  For groups and their members to be ranked: the rôle of the group (or the function of its members) has to be quantified. The principle of deference is a useful basis since professional groups apply it. Referring again to the British Medical Association, it has sub–groups: student members, juniors, general practitioners, consultants and specialists. At the same time, members of the BMA will have different affiliations to other organisations, the Royal College of Surgeons, British Pædiatric Association and so forth.

A family doctor with no special pædiatric expertise involved in a pædiatric case
would be expected to defer to another doctor who is a member of a paediatric association.

**Rôles and Ontologies** This can be quantified by a distance measure. Doctors would collect accreditations and whoever has the most of them over the range of issues involved would be ranked above the others. The issues effectively determine the rôles. This, again, is a collective choice procedure which will be analysed in more detail later. Suffice to say, that the members of the groups would rank themselves within their own groups and rank their groups with respect to others *with respect to their current rôle*. There is no objective ranking between groups, or, come to that amongst group members, because it depends on the issue at hand, which demands that individuals take certain rôles. This concept is explained in more detail in [Gl97].

“Issues” is too imprecise a term, so *ontology*[^4] will be used in place of it.

Some relationship diagrams might help clarify this. An individual possesses certain rôles. The ontology within which the individuals are operating will require that certain rôles be fulfilled. With regard to accessors and custodians, these are both types of individual. This relationship analysis is applicable to both accessors and custodians, because mappings between the two sets using a common ontology will help in allocating access views.

\[
\begin{align*}
\text{Accessor} & \overset{\text{is-kind-of}}{\rightarrow} \text{Individual} \quad \text{and} \quad \text{Individual} \overset{\text{has}}{\rightarrow} \text{Roles} \\
\text{Custodian} & \overset{\text{is-kind-of}}{\rightarrow} \text{Individual} \quad \text{and} \quad \text{Ontology} \overset{\text{requires}}{\rightarrow} \text{Roles}
\end{align*}
\]

Given the rôles and the ontology, an ordering of individuals for an ontology can be formed.

\[
(Roles, \text{Ontology}) \overset{\text{orders}}{\rightarrow} \text{Individual}
\]

[^4]: This is the term used in KIF see chapter §3.
2.5.3 Classifying Records and Fields

Initially, views of records, and the fields within them, will be classified by the custodian for each accessor given the ontology. The accessors will themselves be classified and it should be the case that certain classes of accessors will require certain types of record view. Consequently, classifications for record views will evolve for different ontologies. This is another important requirement of the system so that it can be self-organising: if views are ordered relative to group memberships then it will be possible to recommend that groups be sub-divided to match information protection requirements. Conversely, it can be used to simplify access rules by merging similar groups.

These relationship diagrams might help to make clear how records can be ordered. A record will have a number of views. Each ontology would require certain views.

\[
\text{Record} \xrightarrow{\text{has}} \text{Set of views} \quad \text{and} \quad \text{Ontology} \xrightarrow{\text{requires}} \text{Set of views}
\]

Individuals have been ranked relative to one another for a particular ontology, so if an individual is given access to a view, then granting that permission effectively orders the views of the records in that ontology.

\[
(\text{Individual, Ontology}) \xrightarrow{\text{orders}} \text{Views}
\]

**Discussion**  There are three classification processes at work; the last is a corollary of the first. This assumes that all the individuals are working within the same ontology.

1. Individuals classify one another
2. Individuals classify views
3. Custodians classify accessors

If the system is bootstrapped by a number of carefully deliberated classification decisions, then more specific access rules can be generated. When it is not possible
to apply a rule, it will be resolved by another classification decision by a custodian and a new rule can be added.

2.5.4 Generating Access Rules

This process relies upon the generation of an information flow model [Den76, Den82]. Without going into detail, an information flow model requires:

- A security classification scheme that classifies:
  1. All views, and
  2. All the accessors

Then, for a given set of views, an accessor must have a security classification that is greater than or equal to the least upper bound of all the views demanded. So, one can conclude, that computationally it is relatively simple to determine access rights, if accessors and views are graded.

In figure 2.4, two sets of views are presented: Body Mass Indices, BMI, and treatment costs. There is a choice of sub–views for each. §2.5.1, paragraph “Least Common Denominator View”, stated that there are two parameters that a custodian varies in generating a view for an accessor: the fields in the view and the range of records. The fields here are the BMI entries in an historical medical record and the treatment costs. The ranges varied are the age and ethnic groups.

A simple medical practice is shown in figure 2.5. The practice has two organisational functions: medical and administrative. Referring to the views available, the medical staff, doctors and nurses, would be given write access to Body Mass Index data, but not to treatment costs; the administrative staff would be given write access to treatment costs, but not the BMI data. The owner of the treatment cost data is the administrative arm of the practice, the owner of the BMI data is the medical arm.

The health authority which reimburses the medical practice for treating people in its catchment area would need access to treatment costs records for all medical practices in its area.
Figure 2.4: Some example of record views

Body Mass Indices

- 0-14
- 14-65 Males
- 14-65 Females
- 65+

Treatment Costs

- Asian
- Caucasian
- Afro-Carribean
- 0-16
- 16-65
- 65+

Treatment Costs: Views
In administering the practice — aligning it to the needs of the health authority — it would be necessary to value the cost of taking a BMI reading and this would be discussed at a meeting of the Practice Management Committee. In the classification of the information held by the practice, the least–upper–bound of the medical and administrative arms of the practice is the practice management committee.

Figure 2.5: Medical practice and health authority
A medical consultancy is shown in figure 2.6. It has a similar structure to a medical practice, see figure 2.5, but would also undertake the training of students, who would be answerable to the consultant. A medical consultancy would undertake research and would be answerable to a research organisation for any funding it receives.

The difficulty is to join the two organisations’ structures. This would need to be performed in the appropriate ontology.
1. Consultancy

The most typical scenario is, of course, that patients would be referred to consultants. The consultant would obtain his own information on the patient. The patient’s practitioner would expect to be informed of the consultant’s findings. The consultant might want to use the information he has obtained from the patient for his research; the consultant should obtain the patient’s consent from his custodian the patient’s medical practitioner.

2. Research

If the medical practice decided to make available the BMI information it holds, the medical practice and the health authority would place stipulations on its release.

2.6 Information Model — Views and Constraints

As stated, the technology to realize this system is already available, so it is not necessary to detail all of the information the databases and web–servers would need to operate. The information that is of concern is that needed to provide the newer features:

1. Granting access to views

2. Provide assurances that each party is keeping its contract with the other.

3. Facilitate classification of accessors and views.

2.6.1 Granting Access to Views

There are two cases to consider:

- Either an access rule exists and can be applied
- Or there is no applicable access rule
(Bear in mind, that an access rule may actually deny access.)

It is only necessary to consider the latter case, the procedure is simply a custodian receives a request from an individual who wants to access some specified records.

Clearly, to do this the accessors will need to know who the custodians are and how they can be contacted.

The custodians will need to know:

1. Accessor’s identity and proof of group memberships
2. Ontology under which the accessor is operating
3. View of the record they require
4. Precedents set by other custodians
5. Precedents set by access rules

The accessor will then be informed of the custodian’s decision. The decision could then be formalised as a precedent upon which an access rule could be based.

2.6.2 Proofs of Contract Compliance

Most of the information that needs to be retained by the system will simply show that the duties of each party are being fulfilled. All of this information would be available from the log files of the databases and web–servers used.

1. Custodian Actions

Views of which records granted by a custodian to which accessors or groups of accessors. Whether the view is re–publishable by the accessor and whether any access rules are in force which would allow unvetted access.

If a custodian rejects an accessor’s request for access, then it must retain a justification for that denial.

2. Owner Actions

Log all transactions by each accessor stating views and records accessed.
3. Accessor Actions

Retain notifications of access rights granted.

This is the information that would need to be reconciled to show a subject that either his custodian or a database owner has acted improperly.

2.6.3 Adaptability Support

Enough information has to be retained to classify accessors, and to group them, and to classify the record views they are granted.

**Classifying Accessors** Each accessor has to retain the membership certificates they have been granted by the groups they are members of. The group membership committees should also retain their justifications of why each member was given membership.

**Classifying Record Views** This information can be derived: as custodians grant views to accessors, their group memberships and the ontology under which they are working will be known. Consequently, the views can be classified.

2.7 Engineering Model

The engineering of an information system usually concerns itself with how services can perform best. This is usually a choice between resilience and speed. This information system has very different primary requirements: security and safety, and, as noted above, this is a secure distributed processing problem. There are two functions that must be engineered safely and securely: the protocol and formatting of messages and the processing of them.

1. Security

   • Integrity
• Confidentiality
• Authentication

2. Safety

• Authorisation
• Information Flow
• Inference Control

There is no problem with message security, well-proven protocols, like Transport Level Security [Eav99e] and its predecessors, the Secure Socket Layers [FKK95] are supported by web-servers and web-browsers. It is the safety of the processing that needs to be considered. The most important point is that a process is effectively an accessor and any process that operates on secured data should have the appropriate security clearance. A security clearance would be required both for the implementation of the process and the host machine it runs on. This has long been recognised in secure processing, see [Ash99] for more explanation on the difficulties this gives rise to.

Security clearance for implementations is needed because they may possess covert channels of communication, see, for example, [TGC90] and security clearance for the host machine is required because the process owner, or a corrupt systems administrator, could trace the process as it runs and capture any information it holds.

Secure process implementations and secure execution environments are collectively known as a Secure Computing Base; the need for which has been well-known for some time [Den82]; the difficulties of developing a secure computing base for mobile agent-based systems are discussed in [ST93].

2.7.1 Functional Specifications

The database access system proposed has the following functions to fulfil:

• Memberships accreditation
• Database broking
• Access negotiation
• Query formulation
• Query delivery
• Results delivery
• Results presentation

Memberships Accreditation  The accessors would organise group memberships amongst themselves at a web–server which supports secure transactions. This would require that the professional organisations that accessors would belong to have a Certification Authority, CA, available. (Thawte [THA99], for example, offers a cross-certification service.)

Database broking  At a web–server, access to which may also be secured, accessors would see which databases are available to them to negotiate access to. This is essentially a trading service, [ISO977]. This would seem the sensible point to put them in contact with the database owners and begin the process of access negotiation.

Access Negotiation  There are three processes that could be followed:

• Access by rule
• Access by custodian consent
• Both of the above

If there is a rule that can be followed, then it is simply a matter of checking the accessor’s credentials (group memberships) with the requirements of the rule for the given database and the stated ontology of the accessor.

The other two require that either all the custodians be contacted or those custodians who have not delegated to a rule.
Some agent has to be put in place that can:

- Apply access rules
- Obtain access decisions from custodians

**Query formulation**  Most accessors would not want to formulate queries using standard *SQL*. They would probably use some kind of forms interface, as is common with most commercial web–based databases [ill96], but this might be specific to their ontology and may be recommended by their professional organisation.

**Query delivery**  The query, once formulated as *SQL*, would be encrypted and submitted to the database back-end. The query should be archived as evidence in the event of misuse.

**Results delivery**  The results of the query may need post–processing to minimise the opportunities for inference\(^5\). The results would also need to be archived as evidence.

**Results presentation**  Again, it is unlikely that accessors would be able to use the results in the format returned by the database and some post–processing may be required to present the results in a usable format for them.

### 2.7.2 Agents

The agents for the system can now be specified following the functional specifications:

1. Accessor Memberships Agent
2. Database Trader
3. Access Negotiator

\(^5\)See [Den82] for inference control mechanisms.
4. Query Formulator
5. Query Delivery Agent
6. Results Delivery Agent
7. Results Presentation Agent

2.8 Enterprise Models: System Agents

As stated there are three parties to each access contract:

- Owner
- Accessor
- Custodians (Owner is a custodian of the database as a whole)

The functions performed by each agent have been listed and briefly described. It is now necessary to specify who has responsibility for providing each agent’s secure computing base and who uses it and to whom the secure computing base must provide assurances. Table 2.2 clarifies this. Supplier indicates which of the parties should provide the secure computing base, Users is a list of the parties who would use the agent, Assurances to is the list of those it must provide assurances to. (Bear in mind, again, that the owner of the database is also the custodian of it as a whole.) The concept of a supra–organisation has to be introduced — Supra–accessors etc. — they vet their own members or act, collectively, on their behalf.

What is unusual about these “ownership, use and trust” relationships is that they are tri–partite. Most relationships between entities in systems are bi–partite. All bi–partite system interactions can be reduced to be (produce, consume), but tri–partite relationships have to introduce a second interaction which is to observe the produce–consume interaction: (produce, consume) and ((produce, consume), observe). Observation is achieved by having the producer and consume both sign the information they produce and consume and using that as a product the observer consumes. The observer would reconcile the information produced and consumed.
Table 2.2: Ownership, trust and use relationships for system agents

| System Agent                        | Secure Computing Base Suppliers | Users     | Assurances to                      |
|-------------------------------------|---------------------------------|-----------|-----------------------------------|
| Accessor Memberships Agent          | Supra-accessors                 | Accessors | Owners, Custodians                |
| Database Trader                     | Supra-owners                    | Accessors | Owners, Custodians                |
| Access Negotiator                   | Supra-custodians                | Accessors | Custodians                        |
| Query Formulator                    | Supra-accessors                 | Accessors | Accessors                         |
| Query Delivery Agent                | Owner                           | Accessors | Custodians                        |
| Results Delivery Agent              | Owner                           | Accessors | Custodians                        |
| Results Presentation Agent          | Supra-custodians                | Accessors | Custodians                        |

As Spreitzer [ST93] has pointed out, one secure computing base will do for all parties, if they are all satisfied that the computing base is secure enough for all of them.

2.9 Engineering Model

It is now possible to specify the system. Booch [Boo94] object interaction diagrams are used here. (The class relationship diagrams are not given.) The interaction diagrams are easy to understand.

1. Objects are described by Name: — the name may be omitted. The attributes of the object are listed under the name and class. Very often one of the attributes an object possesses is a back-reference to the object that contains it.

2. The short arrows are method invocations by one object onto another. The arrows terminated by a small circle are the return values of the method.

3. The lines connecting objects denote that the object sending a message has the object reference to the recipient a priori: it is part of the object’s state when the interaction starts. Object references can be qualified by an F if the object is a field of the one referring to it.
4. New object references are obtained as the interaction proceeds by returning an object reference as the result of a method invocation.

5. Objects can create other objects. The creation call is the name of the class with the construction parameters. An arrow to the object indicates which has been produced.

In the text, classes are denoted by this style Class, objects by this A.

2.9.1 Accessor Memberships Agent

Every accessor is initially an object of class Member. Each one of which has been issued an X.509 certificate, encapsulated in an object of class Credential.

When an Member object applies to join a group, Group, it follows the object interactions shown in figure 2.7. Object $A$ has a credential $B$ and applies to join group $G$ having credential $H$. The group has a membership committee which vets the application and, if successful, asks a certification authority to create a new credential specifying $C$ that states $A$ is a member of $G$. This credential is then passed back to $A$, who accretes it for its own use.

(Note in the interaction diagram, the Membership Committee object has a reference to the prospective Member. This is just shorthand. Ordinarily, the new credential would be sent back to $A$ by $G$.)

2.9.2 Database Trader

This system agent is best provided by some collective agency for the owners of the databases — Supra-owners.

Custodians will want to prevent database owners from publishing their databases indiscriminately, because it will mean they will have to vet too many access requests and possibly incur greater risks of disclosure. The database trader has to provide assurances to them.

Database owners will want to specify which type of accessors be allowed to know what databases they possess.
Figure 2.7: Accessor Memberships Agent
(This is not specified in the interaction diagrams: the database trader should also provide a justification for any denial of access to an accessor.)

It should be apparent that publishing the database at a trader is a similar access control problem to that of determining whether access to the records to a particular accessor is allowed.

The interaction shown in figure 2.8 shows how a member would obtain a list of databases. Each database has a set of views and each set of views contains a statement of its relevant ontology.

Figure 2.8: Trader Agent

Once the member has obtained a reference to a database, it can interrogate it to see what ontologies it can be used for and the current set of groups who have designated as existing in that ontology. This is illustrated in 2.9.
Figure 2.9: Database, Views, Ontology and Groups
2.9.3 Access Negotiator

The Access Negotiator agent is best provided by a collective agency acting on behalf of the custodians — Supra-custodians. It services the requests of the accessors and provides assurances to the custodians.

Figure 2.10 shows the arrangement of the objects, before access negotiation begins in earnest. A submits a request to the Access Negotiator G stating his credentials, the database Z and set of views Y A wishes to access. Because A has been able in figure 2.9 to interrogate the database directly, it can supply a subset of its credentials B which it knows will satisfy the criteria.

The Access Negotiator would be empowered to determine if A has supplied a set of credentials B which do entitle A to access the requested views Y in Z by referring to a SetOfPrecedents for the SetOfViews Y. This is not detailed in an interaction diagram. In this activity, the access negotiator simply acts as an access control list enforcer.

The real work of access negotiation is shown in figure 2.11. The Access Negotiator passes the access request to the SetOfCustodians. Each of the custodians would obtain the ontology and the groups working within that ontology for the views requested by the Member object making the request and the ontologies and groups of the Member by referring to the SetOfCredentials supplied by the Member object.

If the SetOfCustodians collectively agree that the Member object should be allowed access they would create a new Precedent object allowing members of group G to access views Y.

Incidentally, it may be necessary to create a new group with corresponding credentials to allow a particular accessor a set of views.

2.9.4 Query Processing

A set of four agents form a call and reply chain. The incomplete object interaction diagram appears in figure 2.12. The Member object instructs a Factory object to create the objects using the SetOfCredentials B to access the database Z, the views may need to be provided if the accessor has a choice of views available to him. The remainder
1. accessRequest(Z,B,Y)

Figure 2.10: Access Negotiator Agent
Figure 2.11: Custodians establishing new precedents
of the object interaction is not diagrammed, but it would consist of formulating a query, which would then send it on to $Q_2$, which would encrypt it correctly for the database, and would probably share an encryption key with $R_2$. $R_2$ would send the results on to $R_1$ which would then return them to the accessor.

Queries submitted and results delivered would need to signed and returned to the respective originators as part of the observation procedure. Again, this is not detailed in the interaction diagram.

**Query Formulator**

The view granted to the accessor will provide meta-data describing its contents. Although this information could be construed as being sensitive, there seems little point in protecting this, so the query formulator can be wholly owned by the accessor.

**Query Delivery Agent**

This agent is responsible for delivering the query securely to the database that can answer it. This agent is responsible for collecting the query from the query formulator. Constructing a message containing the query. Having that query signed as originating from the accessor and sending it. On receipt, the server at the database would check the signature and so be able to check that the accessor submitting the query has the right privileges to do so.

The database owner knows best how to do this, but the query has to be logged, should evidence of a breach of trust between owners and custodians be needed.

**Results Delivery Agent**

The results will contain classified information and they need to be logged to prove breach of trust if needed. As pointed out above, there may be a need to perform post-processing, so the results delivery agent should be owned by the custodians.
2.9.5 Results Presentation Agent

The results are classified, so the presentation agent has to be owned by the custodians. The accessor would collect the results from the agent using a secure channel.

2.10 Summary

The design issues that have arisen from this analysis are that lattices of information flow are needed.

- Each accessor would require a set of security clearances assigned to them
- Each view of the records available in the databases must be assigned a security clearance
- Each of the system agents must have a security clearance
- Each secure computing base must have a security clearance.

It should be possible to generate these lattices by interpreting the following information:

- Hierarchy of group memberships produced by accessors’ supra-organisations
- Adjudications by custodians of views granted to accessors
- Hierarchy of secure computing bases.

Methods of generating lattices will be addressed later.
Figure 2.12: Query Formulation and delivery; results delivery and presentation
Chapter 3

Access to a Database

Chapter 2 took the functionality — and the security features — of databases very much for granted. This chapter sets that right, with a positive result: SQL databases do have the functionality to support an adaptable information service. The previous chapter proposed a system architecture, this chapter is a technical analysis of the capabilities of the most important component of that system.

3.1 Issues

All that is required is that a database can be shared by two sets of users: “native” local users and World–Wide Web-based remote users. This produces its own set of issues:

- Capabilities
- Ownership and Autonomy
- Portability and Adaptability
- Security and Safety

The first of these addresses how different databases grant or deny access — what information and computations can be performed by them. The second addresses: how much can a database owner allow a foreign administrator to operate upon the
database. Thirdly, how flexible is database access technology, can it adapt to a client’s environment or must the client adapt to it. Finally, can databases be secured and how safe are they.

3.1.1 Capabilities of Databases

What follows is a brief summary of the differences in design between a number of databases that support SQL. The differences considered are how may the database be secured. Currently, SQL is at version 2.0 or that standardised in 1992. Unfortunately, there are three types of SQL conformance: full, intermediate and entry.

Meta-data SQL-conformant databases have different internal architectures, since it depends on the type of SQL conformance as to whether catalogues must be provided. Catalogues and schema are implemented as tables, so it is possible to emulate them. Only in full-SQL is it required that the full set of procedures to manipulate catalogues be available. Catalogues contain schema. If catalogues are supported then at least the Information Schema must be contained in each catalogue. The information schema contains meta-data about tables, views and procedures. It will contain names and descriptions of fields and the behaviour of procedures. All persistent objects named by a schema are associated with the authorisation identifier of the schema. When an SQL-session is started a cluster of catalogues is assigned to the session.

Relations Relations are tables or views and all SQL databases support both.

Accessing Two aspects to this: security and loading. Most SQL databases support the access control primitives. These are “Revoke” and “Grant” for a named user or group and are only applicable to relations. Rights are not associated with procedures. As for loading, most databases can limit the number of clients that can simultaneously access it, but not all of them allow clients to be differentiated between internal and external users.

\footnote{Oracle, Informix, Postgres and Illustria.}
Rules Some databases support an additional “rules” or “triggers” feature which is relatively recent and should be required in the next issue of the *SQL* standard. A rule allows one to specify actions to carry out in addition to *or instead of* the invoker’s action to select, update, delete or insert a record. One of those actions is to do nothing. The rule concept was originally introduced to allow indices to be updated or for exported keys to be updated. A “where” clause is permitted which allows one to perform any tests on or with a user’s identity. So this mechanism could be used to check whether a record can be released to a given user or not. Unfortunately, the behaviour of rules is difficult to specify and, consequently, implementations vary. The main point of debate is whether a rule is to be applied to a table or a record — with records inheriting rules from tables.

To secure *SQL* databases potentially every accessor would need to be given an information schema of the set of views and procedures to use. And there would need to be a corresponding set of grant and revoke commands issued on those views.

The only rights that can be granted or revoked are select, insert, update or delete. There is no means of preventing the execution of a procedure, but there is no need to, since one can only operate upon relations and access to them is constrained.

In addition, full *SQL* con-formant systems support the propagation of grant rights by allowing a user to grant the “WITH GRANT OPTION” to another. This particular feature is very useful for delegation and re-publication and is discussed in more detail later §3.1.4.

3.1.2 Ownership and Autonomy

Most organisations regret that their own database administrators have complete access rights to their information and so are unlikely to extend those rights to an external administrator. Further to that most databases are so complex, it is unlikely that any administrator would allow an external administrator to create views for each group of external accessors, but both of these requirements are a necessity for the system proposed.
3.1.3 Portability and Adaptability

Portability addresses how easily a system can be used in a different technological environment. Adaptability: how easily that system can be modified for a different end-user.

**Portability**  A residual problem when remotely accessing a database has been the lack of any standard for the database driver. This problem has been eliminated by the adoption of the Open Database Connectivity, ODBC, standard, see [Nor96] for references. It provides an addressing scheme that can locate databases on remote hosts and specify how access should be gained (user-name and password). It does not propose a standard protocol. ODBC drivers are still specific to the databases they drive — a client side needs to be installed for each type of database. There is directory service, one simply has to know the correct form of the address.

It is now possible to use a platform independent database querying engine, namely the *Java* Database Connectivity package. It relies upon each database having a Uniform Resource Locator, URL, and the JDBC manager attempts to load a driver class having a specified relationship to the URL. The driver class can be loaded over the network, this means that client machines can be configured for accessing a particular database with no down-time. Also, because URLs are used to locate databases, the directory service is a world-wide browser and one can use catalogues of URLs to locate the resources needed.

**Adaptability**  Because a URL is used to specify the driver class and the driver class can be loaded over the network, it is possible to load a different driver class for the same database: one that might have different access rights available or access to different catalogues.
3.1.4 Security and Safety

Security

This topic covers practical aspects of database access. Can the queries and results sent to and received from a database be confidential to the client? The simple answer is yes, but most databases do not support secured channels directly, it is necessary to have an encrypting and decrypting agent placed in the communications channel between client and server database. Using the JDBC package, it is possible to write a custom driver which encrypts queries and sends to them its decrypting counterpart which would then forward the query to the database and then encrypt the results. More sophisticated protocols can be implemented by using remote procedure calls between the encrypting and decrypting agents, such as the scheme described in [Eav99]. These could negotiate keys, add sequence numbers and perform time-stamping transparently to the client and server.

Safety

Views One of the assumptions made in chapter 2 was that accessors would use negotiated views of records and that these could be made safe by granting rights to a set of accessors and revoking rights from all others.

There are two authorities which justify this: Minsky [Min76] and Denning [Den89]. Also one needs to consider how access rights might be propagated.

Branding, Tickets and Capabilities Minsky [Min76] describes a concept called branding. Essentially, every data type is branded and each user has a set of brands that can be accessed. This is easily realized for a database in the following way:

\[
\begin{align*}
\text{DataType} & \quad \text{View} \quad \text{and} \quad \text{Brand} \quad \text{Username}
\end{align*}
\]

Although this might seem facile, SQL is one of the few data access languages that supports branding. It is not possible to brand objects in most other programming
languages because there is no access control mechanism which could require a brand. It is possible to implement branding in object-oriented programming languages that support a call-back mechanism, but this is cumbersome. Only Java has institutionalised it with the SecurityManager, GuardedObject and the Permission classes of their security architecture \cite{SUN98a,GS98}. An object-oriented system presents an additional problem for branding, because it might be desirable to brand a base class and allow access to it, but not to branded derived classes. Java avoids this problem by only allowing implementation classes to be extensions of GuardedObject — not interfaces or abstract base classes.

Finally, it should be said that object-oriented database access languages, such as those proposed by the Object Database Management Group \cite{Cat93}, have not really addressed security issues in their language proposals. It is well-known that safe and secure programming needs to be implemented in the programming language\footnote{Again, see Denning’s discussion of flow control in \cite{Den82}.}. Denning in \cite{Den89} advocated a database system known as System-R, developed by IBM, which supported branding and had other attractive features. The query language developed for System-R was the prototype for SQL.

It should be added that branding is now considered to be a variant of ticket-(or capability-)based authorisation. An accessor must be in possession of a valid “ticket” to access an object \cite{BW94}.

**Subjects, Objects and Rights** On the occasions that authorisation systems are discussed it will be necessary to use some special terminology. This is a précis of a description found in \cite{JLS76}. Users of an information system are usually designated as *subjects*\footnote{This kind of subject is different from the subject that was described in the requirements chapter \ref{chap:requirements}. Subject in an authorisation context would be an accessor in the context of the system requirements.} and the data entities they access as *objects*. Which subjects may access which objects is specified by a lattice model: this acts as an organisation hierarchy, lattice models have useful properties which are discussed in \S 6.3.2.

Every subject and object has a specified access classification. It is this that determines whether access is granted. There are just two access rights — read and write.
— and one special right: invoke and two meta–rights, take and grant. These latter two are discussed in detail in the next section, but it should be pointed out that the grant right is something of a misnomer, it does include the ability to deny a right as well. There is one relationship which is ownership.

The create and destroy rights can be thought of as the right to invoke the create operation on a factory object or the destroy operation on an object itself.

The creator of an object is its initial owner. Ownership can be transferred and shared. Subjects are not owned by any other subject or object. All objects are owned.

Subjects can create and destroy objects and objects can create and destroy objects if they are the owner of the object or the owner grants permission to invoke the destroy operation. Subjects can only be created and destroyed by some special means.

A subject can also take on the rôle of an object, but an object cannot take on the rôle of a subject. Subjects may try to access other objects, objects other objects and, because subjects are also objects, subjects may try to access other subjects and objects subjects.

Because every subject or object may access every other subject or object, then, as far as data access is concerned, they can all be thought of as objects. This makes the rule for granting access easier to express:

Access is only granted if the accessing object has a high enough security clearance for the object it wishes to access for the specified right.

There are two other rights which are more subtle in their operation. These are discussed next.

**Taking and Granting Rights** Denning in [Den82] gives a fairly complete discussion of the difficulties of taking and granting rights to data objects. In particular, the “Take–Grant” model of Jones, Lipton and Snyder [JLS76]. This model is constructed as follows: between a subject \( S \) possessing certain access rights and a data object \( O \) which requires particular access rights, there must exist a path of actions to take or grant rights from and to other agents before \( S \) can access \( O \).
**Take** A take action is performed by $S$, or an entity acting on the behest of $S'$, and takes access rights from others.

**Grant** A grant action is performed by another agent $R$ who grants access rights to $S$ or an agent, $S'$, acting for it.

Clearly, if $S$ is to access $O$, then $S$ must find a $tg$–connected (t for “take”, g for “grant”) path to $O$. Jones, Lipton and Snyder show that this path can be found in linear time. They introduce the concepts of bridges and islands. Islands are maximal $tg$–connected subgraphs of subjects only, where everyone may take whatever rights the others (on the island) have. A bridge is a $tg$–connected path which gains access to an island — a chain of take actions is an example of a bridge. An initial span is a bridge to an island from a user. Figure 3.1 shows a principal $p$, using an initial span to reach an island where $p'$ has a $tg$–path across a bridge to another island where a terminal span from $s'$ to $s$ gains access to an object $x$.

This is exactly what people do every day when they make use of computer systems. They log-on — the initial span — they are placed in the island of their group and may access particular objects because of that.

As for databases, SQL only supports a “GRANT” action — there is a corresponding “REVOKE” action — and it is quite difficult to conceive of a system that actually employs a “TAKE” action. Bishop [Bis81] argues that take actions are only performed by privileged users — the superuser in a Unix system, Administrator under Windows and the DBA, database administrator, under most SQL systems — because they are able to grant rights to whomsoever they wish. It could be argued that if a user in one role, such as system administrator, grants to himself in another role, an ordinary user, a right that he would not normally have, then this constitutes a take action. It would seem then, that a take action is a grant action that does not require inducing the owner of the right to grant it.

In which case, there are many examples of take actions. If one inspects the CERT Coordination Centre’s archives, see [CER98] for example, it is all too clear that there are many ingenious ways to take rights. A common method is to force an overrun on a statically allocated command buffer, which, if correctly formatted, will
Figure 3.1: A take–grant path across islands and bridges
overrun into another more privileged command buffer which can then make an illegal
grant command. These are implementation errors which one can only hope would
not appear in well–designed software — CERT do issue guidelines for application
programmers.

SQL users can only grant access rights, this requires the owner’s permission which
must be negotiated. If that negotiation is subject to peer review, such as the group
membership committees, then one must hope that such membership committees will
not grant membership rights lightly.

This, still, may not be a sufficient safeguard, because it may be the case that
members of a group have access rights they do not use, but, were they to make use
of them, they would have access to data they should not have.

It is therefore necessary to require that as security clearance lattices are con-
structed, it must be proven that there is no access path from lower classes to infor-
mation accessible to only higher classes and as Jones et al. make clear, this is possible
in linear time.

Republishing Databases  There are two aspects to republication that need to
be considered. Firstly, if a user has legitimate access to the database through a safe
system, what prevents him from republishing it through an unsafe system. Secondly,
it would be desirable if a group can decide to grant a limited right of republication
to a sub–group, under the ægis of one of its members, and possibly to allow access
to other accessors who may not have been vetted by the group, but who are vouched
for by the member to whom the republication rights have been granted.

The former can be dismissed quickly. It is practically impossible to prevent re-
publication of material gathered electronically, but it can be costly to do. Some
web–browsers now have the ability to deny the user the ability to print or save a
web–page [SUN99] (and not store the page in a local cache), but it is possible to
capture the page by other means.

It is the cost of republishing without permission that makes republication with
permission so attractive that system designers should it make easy to do. SQL fortu-
nately makes provision for this facility, but does not require that it be implemented:
it is the “GRANT” “WITH GRANT OPTION”: it grants to a user the right to grant the named right. This is exactly what is needed to give to one trusted accessor the ability to name his own group of accessors without having to duplicate the database. Unfortunately, it will probably be the case that the people he wants to grant access to will not be members of any groups known to the database owner. However, if it is possible for the trusted accessor to give certificates to the members of his group of accessors, then it should be possible to give them a security clearance.
Chapter 4

A Prototype System

This chapter describes a prototype database access system which is a proof of concept development for many of the ideas and analysis discussed so far.

In the chapter discussing requirements, chapter 2, emphasis was placed upon making the relationships between the different parties closed, see §2.2.1, so that the management of access rights could be self-governing.

The prototype developed implements some key processes described in §2.9.

- Access negotiator agent in figure 2.10.
- Custodians establishing new precedents in figure 2.11

The latter of these is the self-governing process and the former triggers its operation.

Some other processes were implemented for convenience: the database trader agent figure 2.8 and there is a simple means of submitting queries and receiving formatted replies figure 2.12.

The implementation is far from complete. The procedures implemented might allow one to claim the system is safe, but it is by no means secure. There is no encryption and no certificate technology has been deployed; so, data transfer is all in cleartext and authentication is rudimentary.
4.1 Technological Components

The prototype system contains just two components:

- A Web–server \textit{Jigsaw} \cite{Jig}
  
  The web–server is unusual because it is wholly implemented in \textit{Java}. This makes the use of software agents much simpler — they can loaded into the web–server and work within its secure environment. The web–server acts as the secure computing environment for all users — accessors, owners and custodians. Referring to \S\ref{sec:agents} the agents that were implemented in the prototype were implemented as \textit{Java} classes which were loaded and run by the web–server.

- A Database \textit{PostgreSQL} \cite{PSQ}
  
  This database system does provide some advanced features not usually found in similar products. It did not prove necessary to use them. The real attraction of using this product is that the source code for the database and for the \textit{Java} Database Connectivity driver \cite{Eav97} is freely available.

  The prototype system’s security features are very limited. The requirements for the system and whether they were implemented are listed in table\ref{tab:security} and \ref{tab:agent-status}.

4.2 System Agents

Regarding the implementation status of the agents \S\ref{sec:agents}:

1. Accessor Memberships Agent

   Not implemented. There are suitable systems available, for example, a moderated e–mail list would suffice for some applications. The prototype system used the configuration feature of the \textit{Jigsaw} web–server to add new members.

2. Database Trader

   Implemented. It is possible for database owners to post the URLs of their databases to the \textit{Jigsaw} web–server.
| Requirement                | Status | Notes                                                                                                                                                                                                 |
|----------------------------|--------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Secure web–server access   | No     | There is currently no web–server written in Java that can implement secured channels. Even if there were, it would be difficult to obtain a licence for the cryptographic technology. |
| Secure database access     | No     | Again the web–server cannot support secured channels and, because the JDBC driver is also written in Java, neither can the driver.                                                                       |
| Safe database access       | Yes    | Only makes use of user-name and password pair and the basic authorisation mechanism available within the hypertext transfer protocol.                                                                   |

Table 4.1: Prototype system: implementation vs. requirements (I)
| Requirement                | Status | Notes                                                                 |
|----------------------------|--------|----------------------------------------------------------------------|
| Certificate Technology     | No     | Certification Authority servers are costly and are effectively just a modern replacement for user-names and passwords. |
| Re-publication             | No     | PostgreSQL does not support the “GRANT” “WITH GRANT OPTION”.        |
| Adaptive Capabilities      | Yes    | This is the whole point of the prototype and a simple rule–adding system was implemented. |

Table 4.2: Prototype system: implementation vs. requirements (II)
3. Access Negotiator

This is the key feature and both of its parts, figures 2.10 and 2.11, have been implemented, and there no adaptive access control.

4. Query Formulator

Not implemented. There are suitable systems available. There was a JDBC-based database query agent freely available, but this has been superseded by a commercial product. In the prototype, one can only submit queries on the name fields and one receives the whole record, from the assigned view, in return.

5. Query Delivery Agent

Implemented. A query delivery agent is part of the database driver that is supplied by the database owner to the accessor.

6. Results Delivery Agent

Implemented in the same way as the results delivery agent.

7. Results Presentation Agent

Implemented. The accessor can choose which results format is used. The classes to present the data are posted to the web-server.

Most of the information needed to prove that the contracts between the parties have been adhered to §2.6.2 is available from the web-server’s logs. These would need to be reconciled with the database logs of the queries submitted and results returned.

4.3 Adaptive Components

The systems needed to provide adaptability support, §2.3, are not part of the prototype. They are more experimental and need a surer mathematical basis before they can be implemented.
4.4 Software

This section describes which parts of the system were implemented by which component of the software. The software is described in more detail in appendix B. The software used by the web-server to implement the functions of the system has a different engineering configuration.

4.4.1 Implementation Engineering

1. Database driver

   This provides the following system agents:
   
   • Query Delivery Agent
   • Results Delivery Agent

2. Queriers

   This provides:
   
   • Query Formulator

3. Formatters

   This provides:
   
   • Results Presentation Agent

The following agents have not been implemented in a way in which they can be recognised as agents.

• Access Negotiator — the access request component is implemented as a web-form; if access is granted, it is carried out using the configuration tools of the web-server.

• Database Trader — appear as web-pages within the web-server describing the databases available.
4.4.2 Design Engineering

1. Accessor Memberships Agent

   This was implemented by using the configuration features of Jigsaw and therefore custodians interacted with a set of web-pages. As new users (or accessors) were added to the system, they were made part of the UserRepository. Each user is allocated to a “Realm” which approximates to their ontology. (Unfortunately, a user can have only one realm in this implementation of Jigsaw.) The UserRepository actually makes use of a database as well. The idea underlying this is that each custodian, or supra-group for custodians, would provide a database of their members. Access to this database would be subject to a contract between the web–server provider and the supra–group administrators.

2. Database Trader

   This was implemented using an HTML form within the web–server known as the ResourceAdder. A database owner fills in the form on the web–server describing the database he plans to make available. He must provide URLs for a suitable JDBC database driver and for compatible query formulator agent — QueryByNames.

   The JDBC database driver provides the two delivery agents (query and results). The query formulator provided is a simple one that only allows a single query by a patient name to be submitted.

3. Access Negotiator

   This has been implemented as a web-page form which generates an e–mail which is processed by an e–mail filtering program operated by the custodian. If the custodian grants access, an e–mail is sent to the owner who then creates the view granted, a user identity and posts a new database resource to the web–server. The UserRepository is then modified by the owner using the configuration editor of the web–server. Periodically, e–mail messages were sent to users to tell them which database resources were available to them.
There is also some simple rule application. When the e-mail from the web-server is sent to the custodian, the custodian is informed in that message who else from which realms has been granted what views. The custodian can reply to the e-mail specifying which of these is applicable can be applied to the incoming access request.

4. Query Formulator

A simple version of a query formulator was implemented and appears as the resource **QueryByNames** in the web-server.

5. Query Delivery Agent

This is provided by the database owner when it posts the URL of the database into the database trader.

6. Results Delivery Agent

Same as the Query Delivery Agent.

7. Results Presentation Agent

This is posted with the database driver at the database trader. It need not be provided by the database owner, it is a set of text-processors which are compatible with the output of the database.

### 4.5 Testing and Discussion

#### 4.5.1 Tests

A fairly large database (1400 records) was made available. Two sets of tests: functional and performance.

**Functional** One set of tests showed that it was possible for accessors to send e-mail messages to custodians who could then instruct database owners to add views and that the users were notified of the views now available to them.
Another set of tests showed that the queries presented at the web-server were satisfied in exactly the same way as they would have been had there been no web-server interceding.

**Performance**  The test conditions are summarised below:

1. **Machines**

| Sub-system          | Machine                  | Load       |
|---------------------|--------------------------|------------|
| Client Web-Browser  | Sun SparcStation 50MHz   | less than 10% |
| Web-server          | Sun Ultra 5.10           | 30%        |
| Database            | Sun SparcStation 50MHz   | less than 10% |

Table 4.3: Test: Machines

2. **Query Parameters**

   (a) Select on indexed key
   
   (b) Display 38 field record

3. **Database Parameters**

   (a) 1356 records in table
   
   (b) Query satisfied in 4.5 seconds with text formatting by the database acting alone.

The results were:

| Quality     | Time (seconds) |
|-------------|----------------|
| Startup: Worst | 45             |
| Startup: Best | 25             |
| Worst       | 30             |
| Best        | 10             |

Table 4.4: Database Query Access Times
Some analysis  The web-server system is a lot slower than the database alone: up to ten times slower on start-up and a constant 3 times slower when running.

1. Implementation: The performance has the characteristic of Java systems, which is that first time operation is particularly slow, since the Java virtual machine must load all the classes needed. Thereafter, access can be faster, but Java memory management is non-deterministic because classes are unloaded if space becomes cramped.

2. Communication Overheads: the browser is connected to the web-server which is connected to the database twice, once for the meta-data and once for the query. PostgreSQL operates by receiving a query on one process — the postmaster — and forking another process for the connection and processing the query. When using the database’s own front-end, the forking has been performed already and the same process is used for both meta-data and data enquiries.

3. Extra Processing: the web-server implementation formats the query results into an HTML table which the PostgreSQL query frontend does not. The implementation of this formatting code is quite a general parser, so it is fairly inefficient.

Some discussion  There is unlikely to be much improvement in performance from running the processes on the same machine, since most operating systems treat internal pipes in the same way as remote sockets.

Despite there being three processes involved there is not much parallelism to exploit: the only opportunity might be with sparse queries in a very large database, one could be retrieved and formatted while the next is sought at the database.

There is one very real reason why performance suffers:

- Looking up catalogues on each query submission

HTTP is a stateless protocol — the server holds no state — the client must present all credentials on every access. The client only presents his identifier when accessing the server, so a call has to be made to the database to collect the catalogue and the
view and then another call to submit the query and the results. When one considers this, it becomes clear why the best performance of the system is at least twice as slow that of the PostgreSQL frontend.

The obvious improvement is to cache the catalogues against each accessor. This is quite feasible in Java, it would be possible to hold catalogues against a [cookie]\(^1\) associated with the client at the web–server. Unfortunately, caching is troublesome to implement. It might be the case that a view is revised, in which the catalogues held in the client’s cache at the server would be out–of–date. This might lead to a security breach.

Lately, Java has added a better database access facilities under the Enterprise Beans framework. This manages cookies and reuses a pool of database connections. Future implementations of web–based database access products should use this technology.

### 4.5.2 Discussion

The proposed system’s use of agent technology has been proven in concept and it only remains to consider how it might be improved and extended to provide all of the functionality given in §2.7.

**Improved Implementation** The performance can be improved with a cache for catalogues and improved implementations of the formatting functions. However, as always with software systems, it is best not to concentrate any coding effort on improving performance until the design is complete, but the need for improved performance must be recognised in the design.

### 4.6 Realizing the Proposed System

The prototype system is quite similar to the proposed system in its use of agent technology: the database driver contains the query and results delivery agents, which

\(^1\)Cookies are just randomly generated signatures which both a client and a server hold, effectively a session identifier.
do the bulk of the work. The query formulator and results presentation agents are pieces of software that the accessor runs. The former uses the catalogues generated for the accessor, the latter uses the results when delivered. The prototype system does not implement re-publication, but it would be relatively easy for it to do so.

To secure the system: encryption and certificate technologies have to be used and each agent implementation has to be signed with a manifest so that accessors, owners and custodians can be sure that the agent implementations are authorised. Encryption is available, certificates can be bought and there are application development libraries that allow the two to be used together. Application signatures under certificates are already available. The only difficulty is to implement and integrate it all.

Integrating the application signatures for the agent implementations of the query formulator and results presentation agents would take the form of presenting them on the web-pages where they are selected. The server at the database can check the signature of the query delivery agent and the web-server can check the signature of the results delivery agent.

All of the agents — query and results delivery, query formulator and results presentation — would need to be assured that they have been invoked on a mutually acceptable secure computing base, (SCB). This SCB would need to sign the messages going between client, web-server and database as well.

There is currently no well-evolved technology to do this. The only method that is appropriate is secured remote procedure calls. There is a proposal to extend the remote procedure call system of Java to support this [Eav99d]. When there is a solid technology on which to base these interactions then the system will be fully realizable.

The prototype does not perform any adaptive work — it does not attempt to classify views granted, secure computing bases or accessors.
Part III

Political Control Mechanisms
Chapter 5

Political Control of Access Privileges

The first part of this dissertation has described sophisticated mechanisms for securing data and making information safe, all of which would require that policies be specified stating what information may be accessed by whom, when and where data may be accessed would also need to be made plain. It is the notion of policies and the formulation of them that prompts one to consider using political procedures to control them.

As will be seen, this thinking is not entirely new but it does not appear to have been openly acknowledged that policy-making for system management is a political process. Add to that, that politics is not as amenable to quantitative analysis as economics. There are many excellent mathematical analyses of the operation of auctions, see [MRS90], for example, but, in comparison, there are relatively few that describe how an organisation structures itself.

The remainder of this chapter describes how authorisation systems can be thought of as political systems and introduces the quantifiable concept of norms. It then briefly describes some more suitable languages for communicating rules and concludes with a discussion of the enterprise: its goals and norms.
5.1 Authorisation Policies for Databases

Access control policies will be discussed in this section. The same terminology used in §3.1.4 in the paragraphs Subjects, Objects and Rights and Taking and Granting Rights will be used. The rules described there will be changed here to demonstrate how different access control policies are implemented.

5.1.1 Mandatory and Discretionary Access Control Policies

The formulation of authorisation policies can be carried out in, broadly, two ways: mandatory or discretionary access control.

Before describing the differences between them, it is best to describe what they have in common. Both systems are under control of an administrator. The administrator is the only entity that can create subjects. In access control system design, the systems are idealised. It is not possible to copy an object and use it in place of the original. This is form of object protection is cryptographically feasible see [GS98].

Mandatory access control If the lattice of information flows between subjects and objects cannot be changed by the subjects while the system is operational, then access control is mandatory. This is the case with military systems which use variants of the Bell–LaPadula model [BL73].

The rights management rules for mandatory access control systems are as follows:

1. Ownership may not be transferred or shared by any subjects or objects. Only the administrator can change ownership. When ownership is changed, the object can be thought of as being destroyed and created anew. One would then apply §3.

2. When a subject creates an object, the object’s access rights are fixed in that state and can only be changed by the administrator.

3. When a subject reads an object and modifies it, a new object is created and rule §2 is applied.

\[1\text{This is a summary of a longer, illustrated argument in } Eav99a]
4. The take and grant rights are denied to all except the administrator.

Usually, the delete right is denied to all except the administrator.

**Discretionary access control** The alternative is to allow enough information to flow within a system so that subjects and objects can interact with one another. They will then evolve a lattice of information flows by specifying security clearances for the objects they create between themselves — Discretionary Access Control. This is the case in most operating systems and SQL databases. A system administrator creates an initial set of subjects and objects and the initial lattice flows by allocating the subjects and objects to groups. As each subject or object creates another object, it can specify which groups may access it. Only the system administrator can create subjects and give them group memberships.

1. Rules §§1, §3 from mandatory access control are applicable.

2. When a subject creates an object, the object’s access rights may only be changed by the owner.

3. All owners possess the grant right, but the grant right may only be possessed by owners. It may not itself be granted. The take right is denied to all except the administrator.

Usually the delete right is available to owners and may be granted to others.

**Unix System V release 4** This system of rights is the same as that found in Unix operating system since System V release 4, (SVR4). System V release 3 and prior versions allowed owners to transfer ownership which proved to be a major security flaw. It has made inter-working between subjects more difficult.

**Berkeley Standard Distribution 5.2 Unix** The BSD of Unix overcame the security problems of transferring ownership in a much more flexible way. It does so by applying set semantics to access control. Each subject has a group of his own, of
which he is the sole member and there are additional groups of which he is also a member. When a user changes group ownership of a file, it can only be to a group of which he is a member of; in this way subjects can act in a limited way as an administrator.

BSD also allows designated areas to belong to a particular group. The *setgid* bit of a directory can be set and this ensures that every file in that directory belongs to the group of the directory, which was set by the subject when he created the directory.

Only the administrator can create subjects and groups, but the subjects now have a means of administering group membership of objects indirectly. What subjects designate as belonging to a group defines the membership of the group. For example, if there are three users $a, b, c$ and four groups $W, X, Y$ and $Z$, such that $W = \{a, b\}$, $X = \{a, c\}$, $Y = \{b, c\}$ and $Z = \{a, b, c\}$. If $a$ grants $r$ to $Z$ of $o$ then he allows everyone to read it, but if $a$ grants $r$ to $W$ of $o$ then only $a$ and $b$ may read $o$.

(The problem with conventional operating systems is that $b$ may now copy $o$ and make it available to $c$, which may not have been what $a$ intended. This is not allowed in an idealised system.)

**SQL** Finally in this section, the discretionary access control system of SQL must be analysed: it is essentially the same as *Unix SVR4*, but allows a grant right. The grant right can be constrained to grant only read or write from objects. In effect, this gives to table owners in databases a *setgid* bit on any of the views they create from the table.

**5.1.2 Authoritarian and Self–governing Access Control**

**Authoritarian** Both mandatory and discretionary access control policies are effectively authoritarian because of the privileged position of the administrator. Under the more liberal schemes used in BSD and SQL, it is possible for the subjects to determine the information flow, but the administrator controls group membership and subject creation.
Self-governing For a system to be self-governing the privileged rôle of the administrator must be removed by distributing it amongst the subjects. They will vote collectively to specify group membership and whether new subjects can be admitted.

Subjects could then choose to migrate to groups which are able to accept them and would be able to provide them with better information. The act of migrating to a different group with a different collective administration is very similar to electing a political leader. It is, in fact, a generalisation of the election process. This is a simplification of political control that is used in the analysis of a well-known economic policy issue: the Tiebout model [Tie56]. It can be thought of as an adaptive optimisation problem [KMP95] where voters cluster around norms of their expectations.

5.1.3 Adaptive Discretionary Access Control Policies

There are some system proposals which attempt to discern norms of behaviour and use them to constrain the information flows between the subjects and objects of a system. Minsky proposes a system of laws under which software systems would work [Min89, Min95]. A paper by Rabitti et al. [RBKW91] describes additional authorisation generation mechanisms to support the lattice model for an object-oriented database. The innovation of the system is that it generates its authorisation policy as it operates by generalising current behaviour to form norms. Authorisation is viewed as having three dimensions:

**Expression** Authorisations specified by users, which are known as *explicit* and those that are derived by the system, known as *implicit*.

**Direction** An authorisation can be *positive*, stating what may be done, or *negative* stating what may not be done.

**Strength** An authorisation may be *strong*, in which case it may not be overridden, or *weak*, in which case it can. Strong authorisations can be thought of as axiomatic.

This model has been extended [BW94] and a recent contribution by Castano [Cas97] introduces metrics that can be used to generate norms, including:
- Operation compatibility
- Subject similarity co-efficient
- Authorisation compatibility
- Semantic correspondence
- Clustering of subjects

All of which seem to be methods of ascertaining if different subjects (or objects) belong to the same type. If the subjects and objects are typed already, then some concrete questions can be resolved by using abstract rules. If a subject $z$ is able to grant rights to an object $o$, if $z \text{grant}_r \to x \ o$ and $\text{type}(x) = \text{type}(y)$ then $z \text{grant}_r \to y \ o$ is implied.

### 5.1.4 Preferential Logics and Operators

If two organisations are to share information, then a new organisation is formed which contains the authorisation hierarchy of both. This requires that the two information flow lattices be combined and this, in turn, requires a well-defined logic to do so. There has been some research into preferential logics [ARS98] and some useful operators have been defined. This work is based on graph-theoretical analysis of the flow lattices which is something taken up later in this dissertation.

### 5.2 Suitable Languages

If preferential logics are to operate on authorisation hierarchies of organisations using databases, the combined hierarchy will need to be communicated to all interested parties. There are already some suitable languages for this purpose.

**KQML** The Knowledge Query Manipulation Language is an agent-communication language and is described in [Fin93]. It is part language and part protocol.
KIF The Knowledge Interchange Format is an ontology definition language defined in [GF92].

Both of these languages are explained in more detail in appendix [G]. For the time being, KIF would be used to define the boundaries within which agents may operate, (see §2.5.2, paragraph Ranking Groups.) KQML would be used to communicate KIF descriptions of group membership lists and rules to the different databases.

The attraction of KQML is that it is a more enterprise-oriented language and has been proposed for governing the interactions of agents. KIF is a formal language which would define the information model for a set of collaborating organisations.

5.3 Enterprises, Goals and Norms

In chapter 2 the Open Distributed Processing modelling perspectives were introduced. The least understood of these is the enterprise model. It is considered to be a statement of the goals that an enterprise wishes to achieve — it would include “The Mission Statement” — and the management structure that coordinates the enterprise to achieve its mission. An enterprise is a network of performative, constative and normative agents.

Performative A performative agent can claim that it has carried out some action: Executive function.

Constative A constative agent can judge if the action has been carried out: Judicial function.

Normative A normative agent determines which performative agent should do what task and which constative agent should verify it: Legislative function.

Most information processing systems have performative and constative agents which are machine-processes, but the normative agents are usually human.
**Example: A Library**  System designers allow policies to be specified for the number of books that may be borrowed simultaneously for particular classes of borrowers. They also allow policies for fines to be specified. The policies actually in place at a particular library will vary.

Implicit in the design of the system are norms of behaviour expected from borrowers. The local policies can be tuned to the behaviour of the borrowers at a particular library when the library system is installed.

The enterprise model for the library system has been specified in part by both the designers of the library systems (the policies that may be effected) and its administrators (how those policies are put into effect). The library system will have many performative and constative agents: when a borrower takes a book out a performative agent initiates a process which will invoke a constative agent to determine if the borrower would exceed his quota. The only normative agents are the library administrators who determine the local policies. It may be possible to have adapting normative agents which are programs — they might, for example, set the level of fines relative to a cost index, for example.

But if there are new norms of behaviour: can the enterprise model’s system of normative agents cater for them? A simple case might be a new class of borrower, the system designers may have made it possible to add new classes of user. A normative agent, in the form of one of the library administrators, will then add a new class of user and allocate people to it.

But some norms of behaviour may be not be so easy to cater for. For example, if borrowers feel that fines are too high and borrowing periods are too short, they might organise some collective action: they choose to take their full quota of books out and return them on the same day. This appears to have no effect on the library system other than an increase in turnover, but it is very annoying for the library staff.

Under these circumstances, would it be possible to cater for this new behaviour by the borrowers? Would it be possible, for example, to charge for re–shelving if books are returned too soon? Would it be possible to isolate the borrowers who are taking part in the collective action and enforce the re–shelving cost on them alone? Would it be possible to invoke a new process altogether, for example, preventing users from
entering the library if they appear to be taking part in the collective action. If that were the case, how could a borrower appeal against the decision to bar him.

Most library systems, like most information systems, do not have the degree of flexibility needed to integrate new policies based on new norms of behaviour without significant re-engineering. There are even fewer information systems that are able to generate and instigate new polices without human intervention.

5.4 Summary

Political processes cater for changes in norms of behaviour: the judiciary reports increased numbers of adjudications, the executive reports increased workloads, the legislative modifies the law to accommodate the changes in behaviour observed by the judiciary and legislature.

By contrast, information systems are usually incapable of changing to accommodate new norms of behaviour. One of the reasons for this is that it was, until recently, very difficult to re-engineer an information system. As can be demonstrated with the prototype system described earlier, chapter [4], processes can be specified by the interactions of agents and these agents can be replaced, upgraded and relocated without any loss of service.

The remainder of this dissertation addresses norms of behaviour and how to isolate them.
Chapter 6

Preference Aggregation

The database access system proposed should provide some adaptive discretionary access control partly supported by automated deduction based on a rule-base of precedents §5.1. There will be some relevant information available within the system on which to base these decisions §2.6.1, but it is unquantified. This chapter concentrates on finding general quantification methods — preference aggregation and collective choice procedures.

6.1 Generating Security Hierarchies

Generating security hierarchies is an exercise in classification. This section describes the information that needs to be classified. This is a generalisation of the descriptions and examples given in §2.5.4.

Information The information available is derived from the relationships in §2.2.1 and §2.5.2.

- Databases hold records
- Views are made up of sets of fields
- Views are made up of sets of record ranges
• Custodians make views

• Accessors hold views

• Accessors have group memberships

Group membership is effected by issuing certificates as described in the engineering model §2.9, in particular in figure 2.7.

Rules There are information–ordering rules which are derived from the ranking of individuals and their membership of groups, see §2.5.2 paragraph Rôles and Ontologies.

1. A set of fields may be accessed by an ontology.

2. There is some set of group memberships which maps an accessor to an ontology.

3. Within each group, members rank one another by seniority.

and because of this, information can be ordered.

Two consistency rules can be added.

• The most senior member of an ontology is allowed access to a maximal set of records for the view.

• The most senior member of an ontology is allowed access to a maximal set of fields in the view.

Hierarchies Seniority hierarchies are needed for the following:

• Within groups

• Within an ontology, i.e. across groups.
**Voting Processes** Votes will need to be taken within an ontology to determine:

- Which fields, and
- Which records

it would be desirable to access. Accessors vote by making requests of custodians.

Votes will need to be taken from custodians to determine:

- Which fields, and
- Which records, by
- Which accessors

can be accessed. Custodians vote by granting (or denying) requests. Custodians may also create views to meet accessors’ requirements.

**Note Bene** Groups are usually of a broad professional concern, *e.g.* British Medical Association, Royal College of Surgeons; ontologies will usually be project–related, *e.g.* “study of cellular immune responses against KSHV in HIV infected patients during anti-retroviral treatment”.

Only groups rank, ontologies inherit the rankings from groups, but groups have to be ranked relative to one another or seniority levels within groups have to be equated with those in other groups. This may give rise to anomalies, it will be seen later that these anomalies should appear in the preference hierarchies and, hopefully, will be detected before the combined preference hierarchy is put in place.

### 6.2 Preferences, Values and Norms

In section 5.1.2, it was argued that a self–organising access control system would allow subjects wishing to access objects a choice of groups to join. These groups would emerge around norms of behaviour. In section 2.5.2, it was argued that an ordering for individuals could be used to form new groupings which would better align with the ordering of views of data in different ontologies.
What is needed is a means of converting the preference hierarchies derived from classifying individuals and data views into norms of behaviour which would then be used to reclassify groups. To do this, a metric is needed.

That there is a means to do this is partly justified by Swanson et al. \textsuperscript{SBM97}. Swanson, a theoretical accountant, analyses the function of money in economies and notes that it is used as an indicative measure of abstract quantities such as: “worth”, “liquidity” and “earnings potential” in real instances. Anyone who analyses systems within an object-oriented programming paradigm knows the distinction between a class and an object: an object is an instance of a class. In the real world, classes are an artificial construct and there are only objects, so given an object, how does one know to which class it belongs in a particular context. So, for example, a particular dog would belong to the class \texttt{Canine} and possibly the class \texttt{Pet}. A metric is needed to measure how many of the qualities of \texttt{Pet} exist in this dog.

A class is an expected norm of behaviour and classification involves ranking behaviours relative to one another. If one could say that a class has a set of behaviours with \textit{expected} rankings, then it would be possible to state, with some statistical certainty, if an object could belong to a class if its actual rankings for its behaviours are close to the expected rankings of the class.

\subsection{Norms from Preferences}

Norms are expressed by means of preferences. Table \ref{tab:vote} is a simple voting procedure that illustrates a difficulty in collective choice theory \textsuperscript{Eav99a}, which is known as \textit{Susceptibility to Irrelevant Alternatives}.

| Voter | Policy and Ranking |
|-------|--------------------|
|       | w | x | y | z |
| i     | 4(3) | 3(-) | 2(2) | 1(1) |
| j     | 4(3) | 3(-) | 2(2) | 1(1) |
| k     | 1(1) | 2(-) | 4(3) | 3(2) |
|       | 9(7) | 8(-) | 8(7) | 5(4) |

Table 6.1: The Borda “Preferendum”
There are three voters: $i, j, k$ and they are asked to rank:

- Four policies: $w, x, y, z$ — rankings in plain text
- Three policies: $w, y, z$ — rankings given in brackets

Using the *Borda Preferendum* voting system to aggregate their preferences, the results are:

- Four policies: $w > x, x = y, y > z$
- Three policies: $w = y, y > z$

When there were four policies, it was quite clear that $w$ was preferred to $y$, but with only three policies $w$ and $y$ are equally favoured. An anomaly like this undermines confidence in political choice.

### 6.2.2 Values from Preferences

Voters $i$ and $j$ rank $w > x > y > z$ and voter $k y > z > x > w$. They all agree that $y > z$, but not on $w > x$. If one were to group $y$ with $z$ to form $y'$ and $w$ with $x$ to form $w'$, then they disagree on the merits on $w' > y'$. This seems to indicate that the two groups of voters $\{i, j\}$ and $\{k\}$ have different values at a higher level of abstraction.

To give this example a little more intuitive credibility, the three voters, $i$, $j$ and $k$, have been asked to rank four individuals $w, x, y$ and $z$ on their ability to fulfil a task. This poll of their opinions has actually revealed that one voter has a different idea (or value) of what is the most important ability needed to fulfil this task: for example, $i$ and $j$ may have concurred that “trustworthiness” is the most important ability. $k$ feels that “trustworthiness” is important, *but* that some other quality such as “ability to take the initiative” is *more* important.
6.2.3 Values are Relative

Put simply, \{i, j\} have assessed \{w, x, y, z\} with a different set of values from \{k\}. Discerning the underlying values of voters provides two courses of action, which could be used to eliminate the effect of an irrelevant issue, the courses are:

- Either: refine the issues
- Or: refine the voters

Refining Issues Refining the issues would require conditional questions to be posed. For example: “Rank w, x, y, z in order of their trustworthiness” and “Rank w, x, y, x in order of their ability to take the initiative”.

Refining Voters Refining the voters is simply discarding or downgrading the rankings of voters who do not meet one norm. Although this might seem undemocratic, most proportional representation voting systems do this.

6.2.4 Trading Goals

In the management of information systems, it is not appropriate that more abstract goals be traded against one another. For example, some users may require an information system to be “safe” and some require it to be “fast”. Safe and fast are abstract. The users will request quite specific features: the general goal of safe may appear as a wish-list of a dozen or more safety features; the general goal of fast as another dozen or so. If these were presented on a combined wish-list, and a vote taken, then if the voters were equally split between those who want a fast system and those who want a safe system, then the resulting system would have some fast features, some safe, but fulfil the requirements of neither.

The more fruitful approach is to find those who want the system to be safe and those who wish it to be fast and separate them so that they use different, relatively autonomous information systems.
6.3 Organisational Structure

6.3.1 Managing Database Access

To relate this work to the management of database access hierarchies, Castano et al. proposed a number of metrics to determine similarities of usage between subject and operations. They are described in section §5.1.3. These metrics could be used to inform a custodian of a record if the accessor requesting access was behaving normally for someone with the accessor’s interests.

All that is known of a potential accessor is his group memberships and the view of the records he wishes to see. There are also precedents set by others which could be used.

There would also need to be a set of measures that would rank the trustworthiness of different secure computing environments.

6.3.2 Lattices as Organisational Structures

The metrics referred to above and described in section §5.1.3 are just some of those that might prove to be useful in helping a custodian decide if access should be granted to a set of records. There will no doubt be other metrics that might prove to be useful. What has to be addressed is how one should go about quantifying the choices that custodians have made vis à vis those who have been allowed access to records.

The metrics will be distance measures which effectively measure two orthogonal qualities:

- Trustworthiness
- Relevance

These are used to form lattices: the vertical dimension indicates the degree of trustworthiness, the horizontal dimension indicates the degree of relevance to an ontology. Referring again to the medical profession: seniority should be a reliable
| Comparator   | Comparee(s)                                | Qualities            | Notes                                                                                                                                 |
|--------------|--------------------------------------------|----------------------|--------------------------------------------------------------------------------------------------------------------------------------|
| Custodian    | Accessor                                   | Group memberships    | Subject similarity: specifies how similar the custodian is to the accessor                                                        |
| Accessor     | Accessor’s Peers in Group(s)               | Group memberships    | Subject similarity: specifies how similar the accessor is to other members of his own group(s)                                      |
| Accessor     | Accessor’s Peers in Group(s)               | Views                | Authorisation compatibility: specifies how similar the accessor’s requested view is to that used by others in the same group(s)     |
| Accessor     | Other accessors with Access                 | Group memberships    | Authorisation compatibility: specifies how similar the accessor is to those who have access                                          |

Table 6.2: Comparative metrics for Security Clearance Class Membership
trustworthiness measure and the field of medical work would be a suitable relevance measure: so a General Practitioner conducting private research into cardiology would be ranked lower than a consultant cardiologist with respect to cardiology, but the cardiologist would be ranked lower than the GP with respect to general practice issues.

These lattices are the basis for the structure of an organisation (or community): they form an organisation chart of the relationships that exist between groups. Organisation charts take the form of multi-way trees and lattices can be forced to take the same structure. This is done by introducing lowest and highest common points to all of the branches and creating joining groups where cycles or multiple choices exist. An example, is given in figure 6.1

![Figure 6.1: A lattice produced from a set of preferences](image)

The custodians will be called *voters* when discussing preference aggregation, since
their choices are effectively votes. Each custodian/voter will have their own lattice of preferences for the different types of accessors. The problem is to aggregate their personal lattices with those of their peers to form an aggregate lattice.
6.4 About Preference Aggregation

6.4.1 History and Importance

A leading contributor to the field of decision theory (to which preference aggregation belongs) feels that computer-aided decision-making would take the following form.

Computers will play an increasingly important role in applications during the next century. Along with routine tasks of data compression and high speed analysis, computers will have ever more sophisticated programs to ferret out interactively the most salient features of decision problems and structure problems accordingly. A few well-directed questions about values, acceptable risks and probabilities will yield a proposed solution or menu of solutions. Programs will discern the most likely directions for improvements and determine their promise by means of challenge questions. Sensitivity analyses that account for vagueness in preferences and probability judgements, and tend to discount marginal improvements, will be standard.

There are a number of problems with preference aggregation: it is a collective choice procedure and whenever there are more than two choices from which voters can choose there is no method of choosing that cannot be subverted by sophisticated voting strategies. This does not invalidate collective choice procedures that decide between more than two options, it means that one must be cautious when interpreting the results.

6.4.2 Structure and Notes

Before moving onto the analysis of preference aggregation, it is best to clarify some terms. This notation is the same as that used in [Eav99a]. The mechanics of the analysis will use graph theory, unfamiliar terms can be found in the appendix. There are a number of examples of the operations, these are also given in the appendix.

1 [Fis91] This paper is also an excellent summary of key results and the directions that research in decision theory is taking.
2 Based on the theorems of Arrow, [Arr63] and summarised in [Eav99a].
Preferences and Indifferences

Indifferences  A weak ordering allows voters to express their indifference between two choices. A strong ordering does not allow indifferences. A weak ordering is a tri-state logic. Indifference is represented by $=, \quad x = y$. Preference is, incidentally, represented by $> \text{ or } <$.

Transitivity  It is usually assumed that preference relations are transitive, \( i.e. \ x > y \text{ and } y > z \) then \( x > z \).

Lattices

Acyclic  A lattice of preferences must be an acyclic structure. It is usually assumed that individuals will not have a cycle in their own lattice of preferences, but when aggregated it is possible a cycle will arise. The voting paradox, see table 6.3 and figure 5.2, is a simple, and irreducible, example of this.

| Voter | Ranking          |
|-------|------------------|
| A     | $x > y > z$      |
| B     | $z > x > y$      |
| C     | $y > z > x$      |

Table 6.3: The voting paradox

Referring to the figure showing a lattice produced from a set of preferences, figure 6.1, it can be seen that cycles can be removed by grouping classes together. In the case of the voting paradox, this is not possible, since all classes are equally highly-rated.

Unanimities  These are very useful. A unanimity is a preference upon which everyone concurs. A unanimity can be said to express a \textit{Pareto-optimal} choice and there are degrees of \textit{paretian} choice.

\footnote{See \cite{Eav99a} for the original definition in the context of economic welfare.}
Figure 6.2: The voting paradox
6.4.3 Methods and Representations

The remainder of this chapter looks at methods and representations that could be used to form, manipulate and quantify the ordering of lattices of preferences. Essentially, individuals preference ordering superimposed upon one another give rise to a connected graph, which has to be reduced to a spanning tree which will be the collective preference hierarchy. This is a well–analysed task of graph theory [Chr75], but there are a choice of spanning trees for a graph, the preference hierarchy has to be the most preferred.

To simplify preference hierarchies to spanning trees, a number of graph and set manipulation techniques have to be used and some distance measures developed.

1. Cycles

These are the principal indicator of an anomaly in choice. They have to be detected and, in some way, eliminated.

2. Unanimities

It will be seen that unanimities can be used to partition lattices and can therefore be used to simplify them, which will allow anomalies to be avoided.

3. Chains and Anti–chains

Another useful structural indicator is the length of each chain in a lattice and the number of anti–chains in the lattice. Chains and anti–chains are described in appendix E, but they can be thought of the branches of a lattice. Each chain has at its head an anti–chain. There will always be at least as many anti-chains as chains. A small number of chains of similar length will give rise to fewer anomalies than a large number of chains of dissimilar lengths.

4. Distance measures

A useful distance measure will be introduced which will allow lattices to be compared to one another. This, combined with a knowledge of the chain/anti–chain composition of the lattice will allow less anomalous but sufficiently similar lattices to be chosen.
5. Deciding Sets

There are alliances between voters on issues. A method of determining the underlying values of voters will be introduced which will allow issues to be grouped together within lattices.

### 6.5 Cycles and Topological Entropy

The most obvious sign of an anomaly of choice is a cycle in a preference lattice. An aggregate preference lattice should be free of cycles or the effect of cycles should be controlled.

1. Complete Cycles

   A *complete cycle* can be interpreted as the voters assessing policies with values which are entirely different. The voting paradox, figure 6.2 is an example of a complete cycle.

2. Incomplete Cycles

   A *cycle* that is not complete is a statement that a group of people differ on the merits of some subset of policies. This may be due to the policies being too similar or too different. An example of this is the Borda Preferendum anomaly in 6.1. In the former case, the “conflict” represented by the cycle may be manageable by eliminating one of the policies. In the latter case, it would be best to partition the voters and allow them to resolve their differences using some arbitration process.

The following two methods are recommended for detecting and quantifying the effect of cycles.

#### 6.5.1 Using an Adjacency Matrix

Meyer and Brown [MB98] have developed a measure which they call the *topological entropy* of voting preferences. It enumerates cycles and their length.

*Topological entropy is more formally defined in [AKM65].
Using the *adjacency matrix* representation for each individual’s preferences — the graphs of which and the matrices themselves are given in appendix E — these can be added together and normalised by dividing by \( \#I = n = 3 \) to give:

\[
F = \frac{1}{n} \sum_{i=1}^{n} F_i = \frac{1}{n} (F_A + F_B + F_C) = \begin{pmatrix}
\frac{1}{3} & \frac{2}{3} & \frac{2}{3} \\
\frac{2}{3} & 1 & \frac{1}{3} \\
\frac{1}{3} & \frac{2}{3} & 1
\end{pmatrix}
\]

Following Meyer and Brown [MB98], the topological entropy of a choice matrix \( F \) can be expressed thus:

\[
\Lambda_F = \max(\text{Eigenvalue of } F)
\]

\[
S(F) = \log \Lambda_F
\]

The value of \( \Lambda_F \) gives the length of the longest cycle were one to generate \( F^n \). If logarithms are taken to the base \( n \) then an entropy of 1 indicates a policy cycle of length \( n \) and an entropy of 0 a policy cycle of length 1, *i.e.* only each policy with itself. For this example, \( S = 0.690759 \). (This is different from Meyer and Brown’s formulation as they had applied simple majority rule to the matrix \( F \), effected by rounding up to 1 or down to 0.) By *not* applying the social choice function, one can analyse how the choices of the individuals would be interpreted by a social choice function.

Unfortunately, this is not as useful a measure as one might hope. The graph representation, and thus the matrix form, does not handle statements of indifference particularly well. For example, \( a > c, b > c \) and \( a > c, b > c, a = b \) have different representations:

\[
F_1 = \begin{pmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
1 & 1 & 1
\end{pmatrix}, \quad F_2 = \begin{pmatrix}
1 & 0 & 1 \\
1 & 1 & 0 \\
1 & 1 & 1
\end{pmatrix}
\]

and correspondingly different entropies: \( S(F_1) = 0, S(F_2) = 0.63093 \) because the largest eigenvalue for each is 1 and 2 respectively.
6.5.2 Using a Transition Matrix

Probably better is to follow the approach used in games theory \[BO82\] and use transition matrices. In the language of probability theory, either voter $A$, $B$ or $C$ will get their way — assuming they are statistically independent, which means that they would vote sincerely. One transition matrix can be formed by addition, if one assumes they are equally probable to influence the election. The formation of the transition matrices is not difficult but is long-winded, so it is described in the appendix \[E\]. Normalisation here simply ensures that the sum of the probabilities in each row continues to be 1. The final result is very easy to interpret: the probability of the system reaching a state where $a$, $b$ or $c$ is more dominant than the other is exactly equal $\frac{1}{3}$ so $a = b = c$. More formally, using the formulation of the matrices described in the appendix \[E\],

$$F = \frac{1}{n} \sum_{i=1}^{n} F_i = \frac{1}{n} (F_A + F_B + F_C) = \left(\begin{array}{ccc} \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \\ \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \\ \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \end{array}\right)$$

Although it is now self-evident in this example that no one policy is preferred over the others, the method is to find the eigenvalue that has the value 1 and the most probable final state of the system will be described by the corresponding eigenvector, which specifies the probability of each policy being in force in the infinitely long-term. An entropy measure can then be generated from this steady state probability vector in the usual way.

The transition matrix representation is more intuitive for indifferences, for $a = b > c$, the matrix would be $\left(\begin{array}{ccc} \frac{1}{2} & \frac{1}{2} & 0 \\ \frac{1}{2} & \frac{1}{2} & 0 \\ 0 & 0 & 1 \end{array}\right)$, \(i.e.\) indifference means equiprobable. Unfortunately, this representation is still not satisfactory, since mutual indifference has the same representation as a mutual contra-position, \(i.e.\) if $a > b > c$ and $c > b > a$ for two voters and $a = b = c$ for another two voters both would yield the same steady state

---

5This approach has been used by at least one other author to show that ergodic Markov processes are in fact voting processes \[Mat77\], so that would substantiate its use here.

6Some authors prefer column sums to be 1 and so use the transpose of the matrix.
eigenvector and entropy, but, with the former, the two voters are in conflict over the relative merits of \( a \) and \( c \) and, in the latter, they are in agreement.

Nonetheless, this formulation of topological entropy is still quite useful for examining the effect of irrelevant alternatives, see table 6.1, which has a transition matrix representation as follows

\[
F_A, F_B = \begin{pmatrix}
1 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
\end{pmatrix}, \quad F_C = \begin{pmatrix}
0 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 \\
0 & 0 & 1 & 0 \\
0 & 0 & 1 & 0 \\
\end{pmatrix}
\]

in the first, four option case and when the second–ranked option is removed, the matrices are

\[
F_A, F_B = \begin{pmatrix}
1 & 0 & 0 \\
1 & 0 & 0 \\
0 & 1 & 0 \\
\end{pmatrix}, \quad F_C = \begin{pmatrix}
0 & 0 & 1 \\
0 & 1 & 0 \\
0 & 1 & 0 \\
\end{pmatrix}
\]

| Borda Order | Four Options | Three Options |
|-------------|--------------|---------------|
| \( w > x = y > z \) | \( w = y > z \) |
| Markov Order | \( w > x > y > z \) | \( w > y > z \) |
| Probabilities | \( \frac{12}{23} \cdot \frac{6}{23} \cdot \frac{3}{23} \cdot \frac{2}{23} \) | \( \frac{6}{11} \cdot \frac{3}{11} \cdot \frac{2}{11} \) |
| Entropy | 0.843 | 0.905619 |

Table 6.4: Topological Entropy for the Borda “Preferendum” with and without an irrelevant alternative

Referring to table 6.4, it is clear that the order produced by the transition matrices preserves the supremacy of option \( w \) over \( y \). Neither method ranks \( x \) as being the same as \( y \) — which is another anomaly of the Borda Preferendum — but it preserves the ordering of \( y \) over \( z \).

(A Mathematica package is available that calculates the topological entropy using transition matrices [Eav99c].)

Incidentally, this entropy measure as described only yields the entropy of the largest cycle: it may be the case that there are a number of lesser cycles, and that
would mean that the entropy of the system is greater, since there is more confusion over its content.

6.6 Unanimities

The preceding section looked at measures that detected and quantified the length of a cycle in an aggregation of a set of lattices, where the aggregation was achieved by simple addition to produce a likelihood of a particular policy being chosen amongst all others. A number of difficulties arose from that discussion. These are addressed now and, it will be seen, that the exploitation of any unanimous choices can be used to isolate cycles so that they can resolved.

1. Policies or Policy Preference

It will prove to be more useful to determine which policy preference is most often, or unilaterally, stated. For example, in the discussion of table 6.4, it was clear that all parties preferred $y$ over $z$. If this were represented in a graph, it would be clear that one edge is traversed more than any of the others. This can be used as a measure of how well-ordered a preference hierarchy.

If an edge (policy preference) is always traversed in one direction, then, it is a pareto-optimal preference: one policy, $x$, is always preferred over another, $y$, but other policies may be preferred to $x$.

2. Similarities or Contrasts

Under a strong ordering, two statements by voters $A$ and $B$ of $x > y$ and $y > x$ respectively could indicate:

- Either: a juxtaposition: $A$ and $B$ have entirely different values and that $x$ and $y$ are also different from one another and exemplify the differences between voters $A$ and $B$.
- Or: a similarity: $A$ and $B$ have similar values and that $x$ and $y$ both embody that same value, so that $A$ and $B$ are unable to sincerely and consistently choose between $x$ and $y$. 
This problem does not exist with a weak-ordering, but in an aggregation it can be obscured: an equal number preferring \( x > y \) and \( y > x \) would suggest \( x = y \) in the aggregate.

Pareto-optimality is a desirable quality for a edge in an aggregate preference lattice\(^7\) and it is denoted here as unanimity. In their paper, Batteau et al. [BBM81] defined two forms of Paretian choice: weak and strong. The former was defined as the case when all voters agree on \( x > y \) for one, or more, \( y \) and the latter was defined as the case where all agree on \( x > y \) for all possible \( y \). It will be seen that both forms can be discerned using methods described here (a strong pareto choice is, in fact, a source).

What is needed is an additional fitness measure that highlights if a set of preference lattices contain Pareto-optimal statements of preference.

If one can find some unanimities, so much the better, but, if there are no unanimities, one simply has to remove enough voters or enough policies to produce one (or more). Both of which are quite meaningful ways of partitioning the two sets, since a unanimity is a value.

**Definition 6.6.1 (Preference and Indifference Graphs).** This simple innovation makes use of two graphs to represent the lattice. One graph will represent the strong orderings between the vertices and will be the transitive closure of the directed graph. The other will be an undirected graph expressing the indifferences, which will, usually, contain mostly isolated vertices.

The directed graph will be the preference graph \( P\text{-}graph \) and the undirected graph will be the indifference graph \( I\text{-}graph \).

### 6.6.1 P-graph aggregates

The preference lattices will be aggregated in some optimal way for a particular voting rule. Aggregate weights will be assigned to each directed edge — the aggregates

---

\(^7\)Sen [Sen77] proposed that pareto-optimality should be ranked higher than simple majority preference and [FN73] has quantified this.
of the di-graphs is a 2–di-graph, i.e. a multi–graph with at most two directed edges between each pair of vertices, going in opposite directions.

**Definition 6.6.2 (For and Against–Weights).** If the P–graphs are aggregated then for any pair of policies $u, v$ two weights will be assigned to each directed edge between the pair of policies. The greater will be known as the *for–weight* and the lesser will be known as the *against–weight*. The vertex having the greater for–weight with respect to another vertex will be said to *dominate in aggregate* the other vertex.

### 6.6.2 Unanimities, Sources and Sinks

**Definition 6.6.3 (Unanimity).** When an edge within an aggregate of the P–graphs has a zero against–weight and a non–zero for–weight then it will be called a *unanimity*.

A complete cycle does not prohibit or invalidate a unanimity, since the latter is a statement of preference between just two (or more) policies. The other policies, which cause the cycle, can be dismissed as irrelevant alternatives, if need be.

**Definition 6.6.4 (Simple unanimity).** A unanimity $\vec{uv}$ is called *simple* if it is the only unanimity which involves either $u$ or $v$.

Note that a unanimity can be a compound simple unanimity, e.g. $\vec{uvw}$, if $\vec{uv}$ and $\vec{vw}$ are both simple unanimities.

**Definition 6.6.5 (Complex unanimity).** A complex unanimity $\vec{uv}$ is one where either $u$ or $v$ is not unanimously linked to another unanimity of the other. For example: $\vec{uv}, \vec{uw}$ are both unanimous, but not $\vec{vw}$.

A unanimity may prove to be a *sink* or a *source*.

It may arise that each vertex of an incomplete cycle is part of a unanimity. It might be helpful to interpret this as follows: all the voters may agree that $w$ is the best policy, but each voter ranks the other policies $x, y$ and $z$ differently. These definitions for cycles will be used:

**Definition 6.6.6 (A Dominated Cycle).** If each vertex in an incomplete cycle is dominated by the same vertex, then this configuration is a *dominated cycle*. 
The voters are agreed on what is best, but cannot agree on what is worst. For example, all prefer \( w \) to a cycle of \( x, y \) and \( z \).

**Definition 6.6.7 (A Dominating Cycle).** If each vertex in an incomplete cycle dominates the same vertex, then that cycle is known as a *dominating cycle*.

The voters are agreed on what is worse, but cannot agree on what is best. For example, all prefer \( x, y \) or \( z \) to \( w \).

It should be apparent that a complex unanimity is a form of cycle, since two (or more) policies have a policy which unanimously dominates the cycle or is dominated by it. Complex unanimities can be treated as if they were one of the cycles.

**Definition 6.6.8 (Condensed Aggregate I–Graph).** If all individuals have the same sub-set of vertices connected in their respective I–graphs then that sub-set can be reduced to one “super–vertex” and this change can be carried over to the *individual* P–graphs.

In effect, the individuals are unanimous in their indifference between particular policy pairs.

**Definition 6.6.9 (Condensed Aggregate P–Graph).** A *condensed graph* of the aggregate P–graph can be formed by reducing a sub–set of vertices to a single super–vertex if the sub–set of vertices forms one of the following configurations:

1. A simple unanimity including compound simple unanimities
2. A dominated cycle
3. A dominating cycle

A cycle may also be a complex unanimity.

The point of doing this is that it simplifies the aggregate graph. Simple unanimity can be replaced by the dominating vertex without loss of information, but the cycles may not. In effect, the resolution of the cycle has been deferred. This appears to be the process followed in [Den82] when producing a lattice from a set of relationships, see figure 6.1.
6.6.3 Unanimous Properties

Common Indifferences  This simple algorithm can be used to determine if any of the vertices in the I–graphs contain the same indifferences.

Rule 6.6.1 (Common Indifferences). The algorithm is as follows:

1. Form the adjacency matrix for the I–graph of each individual.

2. Form the intersection of the adjacency matrices, \( \bigcap_i A(i) \). If any element of the resulting matrix is non–zero, then the edge represents a common indifference.

For and Against–Weights

Rule 6.6.2 (For and Against–Weights). For a set of preference lattices: let \( i \) range over the voters, let \( u \) and \( v \) range over the policy vertices.

1. Form the P and I–graphs, \( P(i) \) and \( I(i) \) for each individual.

2. Find any common indifferences and carry them from the aggregate I–graph to the P–graphs.

3. Form the reach matrices for the P–graphs for each individual: \( Q(i) \).

4. Form the sum of the reach matrices, \( \Sigma_i Q(i) \).

The resulting aggregate matrix \( Q \) will have a central diagonal of zeroes and the entries can be evaluated for their properties.

All the other elements of the matrix \( q_{uv} \) will have a complementary edge \( q_{vu} \), the following conditions apply:

1. \( q_{uv} \geq 1 \) and \( q_{vu} = 0 \)
   
   Then there is a unanimity of \( u > v \)

2. \( q_{uv} > q_{vu} \)

   Then preference \( u > v \) has a for–weight of \( q_{uv} \) and an against–weight of \( q_{vu} \).
3. $\sum v q_{vu} = 0$ i.e. a row is zero
Then $u$ is a source.

4. $\sum u q_{vu} = 0$ i.e. a column is zero
Then $v$ is a sink.

One can also find just the unanimities by performing a logical conjunction of all the matrices and locating the entries that remain true.

### 6.6.4 Degree Of Unanimity

Given that it is possible to find unanimities within aggregate graphs, it would be useful to have an entropy metric based upon it. Entropy is a probabilistic measure and it is required that the total number of events needs to be calculated and also the number of events observed.

Unfortunately, there is no simple calculation for the total number of different preference orders given a set of policies, because using weak ordering complicates the formation of the permutations. The algorithm for the calculation of the total number of preference orders is relatively simple however, but there are no tables that can be consulted, so:

**Rule 6.6.3 (Preference Orders).** The total number of different weak preference orders for $n$ policies can be calculated as follows:

1. Generate all the partitions of $n$.
2. Calculate the number of permutations for each partition, call this $N(\text{partitions})$.
3. For each partition find the number of ways in which the policies could be allocated to the elements of the partition, $N(\text{policies})$.
4. Multiply $N(\text{partitions})$ by $N(\text{policies})$ for each partition and sum them together.

$$\sum_{\text{partitions}} N(\text{policies}) \cdot N(\text{partitions}) \quad (6.1)$$

\[8\] [Ski90], p. 56
A *Mathematica* package is available [Eav99c] that performs the calculation. Table 6.5 lists the total number of different preference orders for up to 6 policies and clearly shows how large the search space becomes.

| Policies | Orders |
|----------|--------|
| 1        | 1      |
| 2        | 3      |
| 3        | 13     |
| 4        | 75     |
| 5        | 541    |
| 6        | 4683   |

Table 6.5: Number of Different Preference Orderings for $n$ policies

As for the number of events observed (or distinct P–graphs produced by the voters) the data needed for the entropy calculation is the count of voters for each distinct P–graph. A suitable entropy metric will be presented in the next chapter. For now, if an entropy metric is available, then there are two entropy values for a preference hierarchy that can be calculated. These will give an indication of the degree of cohesion amongst the voters:

1. P–graphs before condensing
2. P–graphs after condensing

The entropy of the former will indicate how varied the opinion of the voters is with respect to the totality of choices available to them. The latter is best used in generating a *conditional entropy* amongst the voters. Just to illustrate why one would need both figures: consider two sets of votes, $A$ and $B$, the same issues but different equal numbers of voters. Both yield only two distinct P–graphs with the same proportion of voters supporting each: in vote $A$, the two P–graphs share no unanimities, while in vote $B$ there are a number of unanimities which can be exploited which allow both P–graphs to be combined to one. In vote $A$ there is still complete disagreement, but in vote $B$, apart from perhaps some “agreements to differ” in
the form of incomplete cycles, there is enough general agreement to form a single preference lattice.

6.7 Chains

The form and number of chains and anti-chains is a useful indicator of the structure of aggregate lattice. These concepts are described more precisely and references are given in appendix [E]. Briefly, one can say that a chain is an arm of the lattice and an anti-chain can be formed from all those elements in each chain that are not directly connected.

Under some circumstances, it may prove preferable that there be a few long chains and one short anti-chain. The anti-chain will contain all the maximal elements of a preference hierarchy and each chain will contain one element from the anti-chain.

For example, a company with a manager and a clerk in each of four departments has four chains and four anti-chains. The length of each chain is two. If each manager is responsible to a director and the directors meet together on a board, then there are four chains and no anti-chains. The anti-chains are removed by the board of directors where all conflicts are resolved. The length of each chain is now three.

To eliminate all the anti-chains it is necessary to extend all the chains by one. If a chain is long, it is more likely to produce a cycle under preference aggregation.

6.7.1 Size of Largest Anti–Chain

An important theorem regarding the Decomposition of Partial Orders can be used as a fitness measure. (A partially ordered set is a set of orderings and is the most appropriate mathematical structure to use for the analysis of preference hierarchies.) It is relatively easy to compute the maximum anti-chain of a partially-ordered set (and therefore a preference lattice). The largest anti-chain is the maximum independent set of the order. The theorem is given in appendix [F].
6.8 Distance Functions

The problem of preference aggregation has been addressed by researchers in other fields with different goals. In particular, statisticians have researched *pairwise comparisons*, there are two papers which have a direct relevance to preference aggregation as described here: Thompson and Remage [TR64] which deals with generating rankings from sets of pairwise comparisons each of which form a strong ordering; and, Singh and Thompson [ST68] which generates rankings from weak orderings. Singh and Thompson’s paper is the basis of what follows: all theorems, corollaries and lemmas are due to them. Unfortunately, Singh and Thompson analyse preferences with the goal of producing alternative rankings, effectively “league tables”, of all the policies rather than an aggregate lattice, but their analysis is also valid for the latter.

6.8.1 Bigraphs

Singh and Thompson define a *bigraph*, \( \langle X, C \cup D \rangle \), which has a set of vertices \( X \), \( C \) contains all the statements of indifference and \( D \) all the statements of preference — the I– and P–graphs respectively as described above §6.6.1. They make a distinction between *circuits*, which are directed cycles, and *loops*, which are cycles that may contain undirected edges. They also define *semi–completeness* — a generalisation of completeness — a lattice can be said to be semi–complete if for every distinct \( x_i, x_j \) in \( X \), \( i \neq j \), there exists a path between \( x_i \) and \( x_j \) or vice–versa. With these they are able to state the following theorem:

**Partial Rank Order**

**Theorem 6.8.1 (Partial Rank Order).** A partial rank order \( P \) is an ordering of the elements of \( X = \{x_1, \ldots, x_m\} \), so for \( P = \{p_1, p_2, \ldots, p_m\} \), then each \( p_i \in P \equiv x_j \in X \). \( P \) is a effectively a permutation of \( X \). A relation \( R \) is a partial rank order when \( (p_j, p_i) \notin R \) whenever \( j > i \). A partial rank order is reflexive, anti–symmetric and transitive.

- A relation \( R \) on \( X \) determines at least one partial rank order iff it is loop–free
• A relation $R$ on $X$ determines a unique partial rank order iff it is loop–free and semi–complete.

This simply states that for any graph, if there are no loops, then a ranking of the elements can be imposed. It does not specify how the elements of $X$ are compared to one another.

**Pairwise Comparisons**  Three relations are introduced which permit pairwise comparisons; they are: $E$, equivalence; $T$, strong order; $W$, weak order.

**Definition 6.8.1 (Indirect Relations).** Let $T$ be a strong order relation (asymmetric, anti–reflexive and transitive), $E$ be an equivalence relation (symmetric, reflexive and transitive) and $W$ be a weak order relation (reflexive and transitive). For any pair $(x, y)$ of elements of $X$:

1. $(x, y) \in E$ iff $x = y$ or they are in the same loop of $C \cup D$.
2. $(x, y) \in W$ iff $x = y$ or there is a path from $x$ to $y$ in $C \cup D$.
3. $(x, y) \in T$ iff there is a directed path from $x$ to $y$ in $C \cup D$.

Using these definitions it is possible to develop the following theorems for $(X, C \cup D)$.

1. There is at least one partial rank order

**Theorem 6.8.2.** In which case, the following conditions are equivalent:

- $C \cup D$ is circuit–free.
- $T$ is a preference relation.
- $T$ is loop–free.
- $T$ determines at least one partial rank order on $X$.

So a preference relation $T$ defines a partial rank order if it is loop–free.
Corollary 6.8.1. $T$ determines at least one partial rank order, $P = \{p_1, p_2, \ldots, p_m\}$, on $X$ for $(p_i, p_{i+1}) \in W$ for $i = 1, 2, \ldots, m - 1$ iff $C \cup D$ is semi-complete and circuit free.

Lemma 6.8.1. $W$ is a partial rank order iff $C = \emptyset$ and $D$ is circuit-free.

2. Exactly one partial rank order

Theorem 6.8.3. The following conditions are equivalent:

- $C = \emptyset$, $D$ is circuit-free and semi-complete.
- $W$ is a simple order (transitive, anti-symmetric and reflexive).
- $T$ is loop-free and complete.
- $T$ determines a unique partial rank order on $X$.

Corollary 6.8.2. $T$ determines a unique partial rank order, $P = \{p_1, p_2, \ldots, p_m\}$, on $X$ for $(p_i, p_{i+1}) \in D$ for $i = 1, 2, \ldots, m - 1$ iff $C = \emptyset$ and $(p_i, p_j) \in D$ for $i > j$.

6.8.2 Changing the Orientation of Edges

Bigraphs are not always circuit-free and it will be necessary to change the orientation of edges to make them so. There are three ways an edge can be re-oriented:

1. Reverse the direction of a directed edge.
2. Assign a direction to an undirected edge.
3. Make a directed edge undirected.

If an aggregate graph is generated, it can be forced to be circuit-free by applying a combination of re-orientations. How many of these, and which of the three they are, can form the basis of a distance metric.
Singh and Thompson prove a theorem which states that it is immaterial if one deletes edges or re-orient them. This might at first seem contentious, but if one bears in mind that a partial rank order is a transitive relation, then deleting an edge would remove a circuit and the transitivity of the relation would retain some preferences. For any graph there is a class of maximal circuit–free sub–bigraphs each one of which forms a partial rank order.

**Theorem 6.8.4.** If $C_1 \cup D_1$ is a maximal circuit–free sub–bigraph of a complete bigraph $C \cup D$, then $T(C_1 \cup D_1)$ determines a unique partial rank order iff $C_1 = \emptyset$.

The maximal circuit–free sub–bigraphs can be enumerated by generating all of the Hamiltonian paths.

**Theorem 6.8.5.** If $C \cup D$ is a complete bi–graph, then there is a one–to–one correspondence between the maximal circuit–free sub–bigraphs $D_1$ of $C \cup D$ and Hamiltonian paths in $C \cup D$.

### 6.8.3 Maximum Likelihood Preference Relations

**Probability Function** Fortunately, Singh and Thompson developed their graph–theoretical analysis into a probabilistic model. Unfortunately, some more notation has to be introduced.

**Notation 6.8.1.** $X$ the set of policies, $X = \{x_1, x_2, \ldots, x_m\}$. Typical elements $x_i$ and $x_j$. Each distinct pair of elements is compared in, statistically, independent trials to yield:

$(x_i, x_j)$ An ordered pair of $X$ which can be either $x_i \rightarrow x_j$ or $x_j \rightarrow x_i$ or $x_i = x_j$.

Each comparison may be carried out $n_{ij} > 0$ times.

$I$ is the set of all subscript pairs $(i, j)$ that have been compared and $1 \leq i < j \leq m$.

The total number of comparisons is $n$ and $n \leq \binom{m}{2}$.

$\pi_{ij}$ is a population parameter and is the probability that the voters prefer $x_i$ to $x_j$, viz. $P(x_i \rightarrow x_j)$. 

$\gamma_{ij}$ is a population parameter and is the probability that the chooser is indifferent between $x_i$ and $x_j$, \textit{viz.} $P(x_i = x_j)$.

$s_{ij} \text{ and } t_{ij}$ are the number of times that $\pi_{ij}$ and $\gamma_{ij}$ occur respectively.

These can then be used as parameters to a multinomial distribution. (The multinomial distribution is the binomial but has more than two outcomes.) This distribution is used to determine the probability that the number of statements of preference of one policy over another $\pi_{ij}$ is exactly equal to the number of times of times a preference is stated. It measures the strength of a preference: how often it is stated against how often the chooser is indifferent between them. This equates to the graph-theoretic notion that traversing an arc between nodes in the same direction is a better measure of order than counting the number of times a node is chosen, see §6.6.

\[
\begin{align*}
    s_{ij} + s_{ji} + t_{ij} &= n_{ij} \\
    \pi_{ij} + \pi_{ji} + \gamma_{ij} &= 1 \\
    \gamma_{ij} &= \gamma_{ji} \\
    P(\pi_{ij} = \frac{s_{ij}}{n_{ij}}, \pi_{ji} = \frac{s_{ji}}{n_{ij}}, \gamma_{ij} = \frac{t_{ij}}{n_{ij}}) &= \prod_j \frac{n_{ij}!}{s_{ij}! s_{ji}! t_{ij}!} \pi_{ij}^{s_{ij}} \pi_{ji}^{s_{ji}} \gamma_{ij}^{t_{ij}}
\end{align*}
\]

Because $\pi_{ij}, \pi_{ji}$ and $\gamma_{ij}$ sum to one, it is possible to eliminate $\pi_{ji}$ and use just $\pi_{ij}$ and $\gamma_{ij}$ as the parameters. In which case, because there are $n$ parameters in $J$, the set of all pairings, there are $2n$ parameters in all.

What is needed now is a measure of the most likely preference ordering: this can be represented as a point $\hat{\pi}$ being the ordered pair $(\hat{\pi}_{ij}, \hat{\gamma}_{ij})$. A sequence of these will form a preference relation $T(\pi)$ in a more constrained portion $\omega$ of the search space $\Omega$.

**Notation 6.8.2.** $\Omega$ is the parameter space, a subset of $2n$ dimensional space.

$\pi$ is a typical point in $\Omega$.

$\hat{\pi}$ is the maximum likelihood estimate of $\pi$. It will have coordinates drawn from:

$\hat{\pi}_{ij} = \frac{s_{ij}}{n_{ij}}$ and $\hat{\gamma}_{ij} = \frac{t_{ij}}{n_{ij}}$. 
\( \omega \) and \( T(\pi) \) is a preference relation over some portion \( \omega \) of \( \Omega \).

\( \hat{\pi} \) is the maximum likelihood estimate of \( \pi \) which is restricted to \( \omega \), \( i.e. \) to where \( T(\pi) \) is in force.

It is now possible to form a maximum likelihood measure. (Maximum-likelihood is analogous to the traditional entropy measure \( p \log(\frac{1}{p}) \), but does not necessarily have the same properties. Statisticians use it as a variance measure.) It is used as estimator, it can be formulated thus:

\[
L(\pi) = \sum_{n_{ij}} \left( \hat{\pi}_{ij} \log \pi_{ij} + \hat{\gamma}_{ij} \log \gamma_{ij} \right)
\] (6.3)

which, when maximised in \( \omega \), will yield \( T(\hat{\pi}) \), which is the maximum likelihood ordering of the elements of \( X \).

**Graphs and Voting Rules** Referring again to the graph \([X, C \cup D]\), \( C \) is the I–graph of indifferences and \( D \) is the P–graph of preferences. \( T(\pi) \) can be defined thus:

**Definition 6.8.2.** \((x_i, x_j) \in T(\pi) \) iff \( \text{Path}(x_i, x_j) \) in \( C(\pi) \cup D(\pi) \), where:

\( D(\pi) \) \((x_i, x_j) \in D(\pi) \) iff \( \pi_{ij} > \max(\pi_{ji}, \gamma_{ij}) \).

\( C(\pi) \) \((x_i, x_j) \in C(\pi) \) iff \( \gamma_{ij} > \max(\pi_{ij}, \pi_{ji}) \).

This definition also defines a particular sub–graph of \([X, C \cup D]\) which will be called \([X, C(\pi) \cup D(\pi)]\).

In effect, this defines a pair of voting rules for this distance function, which is simple majority, but requires that the “for”–vote be greater then the “don’t care”–vote as well. It has similarities to the normalised simplexes used by Saari \([\text{Saa94}]\), an illustration is given in figure 6.3.

Singh and Thompson’s result does hinge upon the definitions of \( T(\pi) \) and \([X, C(\pi) \cup D(\pi)]\), but it *should* be the case that they can be adapted to different voting rules.\footnote{Theorem 10 of [ST68] is the key to this argument since it relies on the properties of the voting rules.}
For $n$ where each is $n_{ij}$

$$\pi_{ij} > \max(\pi_{ij}, \gamma_{ij})$$

$$\gamma_{ij} > \max(\pi_{ij}, \pi_{ji})$$

$$\pi_{ij} > \max(\pi_{ji}, \gamma_{ij})$$

Figure 6.3: Simplex for Voting
Under these voting rules, if one requires a *unique* strong ordering of a *complete* set of comparisons, *i.e.* there exists a $T(\pi)$ that is contained in $D(\pi)$, which is what most theoretical political scientists want, then it can be safely *calculated* that any such order:

- Either: just does not exist, *i.e.* there are no strong orderings at all.
- Or: a strong ordering exists, but is not more likely than any weak orderings.
- Or: there is a strong ordering and it is maximally likely, in which case it will be unique.

**Minimising Uncertainty**  An interesting insight by Thompson and Remage [TR64] is as follows: the uncertainty of a single comparison of $x_i$ to $x_j$ is:

$$U_{ij} = -(\pi_{ij} \log \pi_{ij} + \pi_{ji} \log \pi_{ji} + \gamma_{ij} \log \gamma_{ij})$$  \hfill (6.4)

For all $n_{ij}$ comparisons of $x_i$ to $x_j$ the uncertainty is: $n_{ij}U_{ij}$ and for all comparisons:

$$U(\pi) = \sum_j n_{ij}U_{ij}$$

From which it is clear that $L(\pi) = -U_{ij}$ but in a specified subset of $\omega$ only, so maximising the likelihood of $L(\pi)$ is equivalent to minimising the uncertainty of $U(\pi)$. Thompson and Remage [TR64] make it quite clear by stating that $U(\pi)$ represents the total number of sample preferences which are violated by the ranking $T(\pi)$.

**An Example**  Table 6.6 contains some illustrative data for four options $X = \{x_1, x_2, x_3, x_4\}$. From this an aggregate bigraph has been generated, see figure 6.4, which is not circuit–free.

All of the possible maximal circuit–free sub–bigraphs have been enumerated in figure 6.5 and each of these has its own preference order, $\pi_1, \pi_2, \pi_3, \pi_4, \pi_5, \pi_6$. 
Table 6.6: Paired comparisons, $m = 4$, $n_{ij} = 6$ for all $i$ and $j$

| $(ij) \in J$ | $s_{ij}$ | $t_{ij}$ | $s_{ji}$ | $(\hat{\pi}_{ij}, \hat{\gamma}_{ij})$ |
|--------------|---------|---------|---------|-------------------------------------|
| (12)         | 2       | 1       | 3       | $(\frac{1}{3}, \frac{1}{6})$       |
| (13)         | 4       | 1       | 1       | $(\frac{3}{8}, \frac{1}{6})$       |
| (14)         | 0       | 4       | 2       | $(0, \frac{2}{3})$                  |
| (23)         | 1       | 3       | 2       | $(\frac{1}{6}, \frac{1}{3})$       |
| (24)         | 1       | 2       | 3       | $(\frac{6}{13}, \frac{13}{3})$     |
| (34)         | 4       | 0       | 2       | $(\frac{4}{3}, 0)$                  |

Figure 6.4: Aggregate bigraph from table 6.6
Figure 6.5: Maximal sub–bigraphs of bigraph in figure 6.4
For each of these the uncertainty has been calculated and is shown in table 6.7. From which it is clear that the most certain order is $\pi_4 : (x_1 = x_4) > (x_2 = x_3)$, but this is a weak ordering; there are two strong orderings which are equally certain: $\pi_2 : x_1 > x_3 > x_4 > x_2$ and $\pi_3 : x_2 > x_1 > x_3 > x_4$, which differ markedly in their ranking of $x_2$.

| $\pi$  | $(\pi_{12}, \gamma_{12})$ | $(\pi_{13}, \gamma_{13})$ | $(\pi_{14}, \gamma_{14})$ | $(\pi_{13}, \gamma_{23})$ | $(\pi_{24}, \gamma_{24})$ | $(\pi_{34}, \gamma_{34})$ | $U(\pi)$ |
|--------|----------------|----------------|----------------|----------------|----------------|----------------|----------|
| $\pi_1$ | $(\frac{12}{12}, \frac{1}{6})$ | $(\frac{5}{3}, \frac{1}{6})$ | $(0, \frac{5}{3})$ | $(\frac{4}{6}, \frac{5}{6})$ | $(\frac{1}{2}, \frac{5}{6})$ | $(\frac{7}{12}, 0)$ | $2.279224$ |
| $\pi_2$ | $(\frac{12}{12}, \frac{1}{6})$ | $(\frac{2}{3}, \frac{1}{6})$ | $(0, \frac{2}{3})$ | $(\frac{1}{2}, \frac{12}{12})$ | $(\frac{1}{6}, \frac{1}{6})$ | $(\frac{7}{12}, 0)$ | $2.286507$ |
| $\pi_3$ | $(\frac{12}{12}, \frac{1}{6})$ | $(\frac{2}{3}, \frac{1}{6})$ | $(0, \frac{2}{3})$ | $(\frac{1}{2}, \frac{12}{12})$ | $(\frac{1}{6}, \frac{1}{6})$ | $(\frac{7}{12}, 0)$ | $2.286507$ |
| $\pi_4$ | $(\frac{12}{12}, \frac{1}{6})$ | $(\frac{12}{12}, \frac{1}{6})$ | $(0, \frac{2}{3})$ | $(\frac{1}{2}, \frac{12}{12})$ | $(\frac{1}{6}, \frac{1}{6})$ | $(\frac{7}{12}, 0)$ | $2.343828$ |
| $\pi_5$ | $(\frac{12}{12}, \frac{1}{6})$ | $(\frac{12}{12}, \frac{1}{6})$ | $(0, \frac{2}{3})$ | $(\frac{1}{2}, \frac{12}{12})$ | $(\frac{1}{6}, \frac{1}{6})$ | $(\frac{7}{12}, 0)$ | $2.348928$ |
| $\pi_6$ | $(\frac{12}{12}, \frac{1}{6})$ | $(\frac{12}{12}, \frac{1}{6})$ | $(0, \frac{2}{3})$ | $(\frac{1}{2}, \frac{12}{12})$ | $(\frac{1}{6}, \frac{1}{6})$ | $(\frac{7}{12}, 0)$ | $2.303824$ |

Table 6.7: Sub–bigraphs uncertainty rankings

Finally, it can be said that Thompson and Remage’s work provides a good analytic method of determining which of a set of orderings is most preferred and it gives us the ability to choose between popular weak orderings which are less decisive, in that they cannot differentiate between as wide a range of choices, and less popular strong orderings which are more decisive.

A popular weak ordering is less prone to anomalies of choice than a strong one, but is not as useful in decision–making. Computationally, this calculation is not particularly difficult. The search space sizes are given in table 6.5. For this search space of four policies, table 6.5 requires a maximum of 75 running totals to be kept for the voter population.

### 6.9 Deciding Sets

Deciding sets are those groups of voters whose support is needed to win a vote. This concept is clarified (and re–named) in a paper by Batteau et al., [BBM81], as the preventing set. Most people would know them as coalitions, but they can be decisive without actually imposing their preferences for policies. In this sense, a deciding set
acts as a dictator or, more typically, as a vetoer.

Voters usually express their values by grouping sets of issues together and setting them against other sets of issues. Under some circumstances, a “Kingmaker” group can emerge, which has an unfair influence according to Arrow’s theorems. If one were to analyse an issue space then it would be necessary to search it for all the voter alignments that might give rise to “Kingmaker” groups emerging. The space is large, given by (6.1). This problem would be a simpler variant of the bin–packing problem, which is known to be NP–complete. There are some efficient genetic algorithms for the bin–packing problem and these could be adapted to search for voter alignments.

6.9.1 Spectral Analysis of Ranked Data

A paper by Diaconis introduced some interesting analysis of ranked data which is a Borda preferendum, see table 6.1: \( f(\pi) = \left( \begin{array}{ccccc} 1 & 2 & 3 & 4 & 5 \\ x_1 & x_2 & x_3 & x_4 & x_5 \end{array} \right) = n \), i.e. \( \pi \) is a ranked order 1 to 5 of 5 policies such that \( x_1 > x_2 > x_3 > x_4 > x_5 \) and \( n \) voters have chosen this ordering. Diaconis then introduces a suite of first–order functions which return counts, let \( j \) be the index of the policy \( x_j \), then:

\[
\delta_{\pi(j)} = \begin{cases} 
1 & \text{if } \pi(j) = i \\
0 & \text{otherwise}
\end{cases}
\]

Or, simply, the count of all those who place policy \( x_j \) in position \( i \).

And a suite of unordered second–order functions which return counts thus:

\[
\delta_{\{i,i'\},\{\pi(j),\pi(j')\}} = \begin{cases} 
1 & \text{if } \pi(j) = i \text{ and } \pi(j') = i' \\
0 & \text{otherwise}
\end{cases}
\]

Or the count of all those who:

- Either: place candidate \( x_j \) in position \( i \) and candidate \( x_{j'} \) in position \( i' \)
• Or: place candidate $x_j$ in position $i'$ and candidate $x_j'$ in position $i$

It is also possible to have a set of ordered second–order functions written thus: $\delta(i,i'),(\pi(j),\pi(j'))$ which returns the count of all those who place in the order $x_j$ at $i$ and $x_j'$ at $i'$.

And it is possible to have higher orders still, unordered and ordered.

In his paper, Diaconis used these functions to analyse the data of an election that used a proportional representation voting system and demonstrated that the election contained two main types of voters $A$ and $B$ who voted on two issue blocks $x' = (x_1, x_3)$ and $y' = (x_4, x_5)$, in the following way: $A, x' > y'$ and $B, y' > x'$.

This analysis would yield fitness metrics for selection. It would be used to partition the voters and the issues, so that each partition would demonstrate fewer cycles and more unanimities.

The computational complexity of spectral analysis is very high. It requires repartitioning the search space for each possible combination. If it is compared to calculation of distance between preference orderings given in §6.8 which required no more than keeping 75 running totals for a four choice system, spectral analysis would require $4! \cdot 75$ totals to be kept.

### 6.10 In Conclusion

A comprehensive set of analytic techniques have been presented which should allow aggregate hierarchies of preferences to be generated from individual statements of preferences with an option to choose either a strong– or weak–ordering and to quantify how acceptable they would be to the individuals. Other techniques have been described which would allow voters and issues to be partitioned so that the level of acceptance within those sub–groupings could be higher.

What this brings to the discussion of collective choice procedures is a reinterpretation of the limitations of Arrow’s *Impossibility Theorem* [Eav99a] using information theory: it is impossible to design a representative collective choice procedure that can select one from more than two issues if the preference orderings have too high an
entropy. If the preference orderings are sufficiently well–ordered, the collective choice cannot be subverted by a perverse and sophisticated clique.

The principal entropy measure is due to Thompson et al. and is given by (6.4). This allows a choice between strong and weak–orderings to be made. It should be possible to develop this to use Diaconis’ spectral analysis of collective choices to generate preference orderings for different sub–groups of the voters.

In short, the Thompson metric allows issues to be merged, the Diaconis method allows voters to be merged. Unfortunately, the computational burden for this latter measure would be very high, see §6.9, so only the Thompson and Remage method will be used in the remainder of the analysis in this dissertation.
Chapter 7

Stability of Self–Organisation

From the discussion in chapters 2 and 3 it was made clear that software technology is mature enough to support a self-organising database access system, but it was also apparent that such a system would need precisely specified policies in order to operate. Chapters 5 and 6 showed that these policies would necessarily be aggregations of preference hierarchies.

Chapter 6 introduced some distance measures which could be used to compare different preference hierarchies. This chapter uses distance measures to produce a self-stabilising system of interacting agents, which act autonomously but are controlled by their own peers. Essentially, this chapter addresses whether a self-organising system based on group memberships can be active enough to allow policies to emerge, but stable enough so that the agents do not follow inconsistent policies in a short time period.

7.1 Formation of Cultures

The system of creating access hierarchies based on group memberships is very similar to a series of simulations carried out by Axelrod [AAEC96], which were an attempt to elucidate the processes underlying the adoption of standards in industry [Axe95].

Axelrod’s analytical method is unusual in that he constructs systems which have
agents that have very simple behaviour. He then allows the agents to interact in a series of simulations and then analyses the behaviour of the system as a whole. The hope is that by specifying the behaviour of the agents, what Axelrod describes as small-scale behaviour, it is possible to control the large-scale behaviour of the system.

Axelrod gives a number of common-place examples of the formation of cultures. Consider nightclubs: people visiting nightclubs often want to meet other people going there and they try to emulate one another’s style of dress and manners. A set of features that might be considered important at nightclubs would be: hair length and cut, style of dress, dancing style and so on and so forth. So a person who dances in a particular way might see someone who dances in the same way and would choose to become more alike to them in the hope they might meet. To do this, that person might change their haircut. Now another person with the same haircut may choose to change his dancing style. If this behaviour continues, then either all the people visiting this nightclub will look the same and dance in the same way, or cliques will emerge. One group of people will dress and dance in one particular way and another group will do so in another particular way, which can be more or less incompatible. If these two cliques are completely incompatible, they can never become alike to one another, because they have nothing in common to begin with. It may also be the case, that there are a number of competing cliques who are slightly incompatible; they interact with one another only rarely and there is no long-term effect. It may also be the case that the cliques interact with one another so often that there is no discernible similarity between the people visiting the nightclub from night to night.

Surprisingly, many systems where standards have evolved are very similar in operation. Consider the variation of standards for electricity supply: for consumers in the United States, 120 volts at 60 hertz is the standard; in Europe, 240 volts at 50 hertz. In the US, industry uses 380 volts three phase, in Europe 440 volts. This kind of dissimilarity goes right across the electricity supply industry. Similar arguments can be made for the evolution of the metric and imperial measurement systems, or the morphology of human (and programming) languages. There do appear unique similarities that cut across all systems: for example, even though people in the United
Kingdom drive on the left and people in the Europe drive on the right, the system of traffic law is very similar: pedestrian crossings, giving way at junctions and so on.

To add some formalism, using the evolution of culture in a nightclub as an example, the way people visiting a nightclub choose to become similar to one another is the small–scale behaviour, the appearance of the nightclub and its constellation of cliques is the large–scale behaviour. Each individual’s small–scale behaviour is based on a particular probability distribution which is time–invariant and will be different from everyone else’s. The large–scale behaviour probability distribution is the superposition of all of the small–scale behaviours and may aggregate to something quite predictable: in the same way that the sum of a set of independent random variables can be assumed to behave as a normal distribution.

Consider the quality control of paint colours. The manufacturing of paint is a sophisticated process, the amount of dye added can vary because of changes in the granularity of the dye powder interacting with variation of tolerances in the injection heads, which can also interact with the frequency and thoroughness of the head–cleaning procedures. One should also consider variations in the temperature of the oil resin, the efficacy of the mixing motors, variations in phase in power supply. All these factors can be approximated as independent random variables, because the causality of one set is counteracted by the causality of another.

A statistician if asked to make an estimate of the intensity of a colour of a tin of paint would not attempt to analyse the whole of the paint manufacturing process but would simply assume the final probability distribution is a normal one.

Axelrod’s cultural evolution model aims to perform the same simplification: to determine a simple probability distribution for the large–scale behaviour of the system, but he allows himself the facility to control one causal probability distribution for the components of the larger system.

### 7.1.1 Small–Scale Behaviour

The simulation model employed by Axelrod was deceptively simple and is an example of the use of cellular automata simulation \[^{\text{vN66}}\]. Each agent was given a
fixed set of features $A = \{a_1, a_2, \ldots, a_n\}$, each feature had an enumerated set of values, known as the traits, for that feature. The traits were initially randomly generated and assigned to the features.

**Definition 7.1.1 (Distance Functions).** Axelrod developed a simple similarity function $S(\cdot, \cdot)$ which was used to evaluate how alike two agents were. If $X$ and $Y$ are their respective sets of features, with each feature being $x_i$ or $y_i$ respectively, then if the features had the same trait, $x_i = y_i$, a 1 is scored, otherwise 0.

This describes the behaviour of the trait comparator.

$$s(x_i, y_i) = \begin{cases} 0 & x_i \neq y_i \\ 1 & x_i = y_i \text{ if features have same trait} \end{cases}$$  \hspace{1cm} (7.1)

This describes the behaviour of the feature set comparator.

$$S(X, Y) = \sum_{i=1}^{i=n} s(x_i, y_i)$$  \hspace{1cm} (7.2)

This is Axelrod’s similarity function. Clearly, two agents, $X$, $Y$, are identical if $S(X, Y) = n$. Therefore a distance function would be

$$d(X, Y) \define n - S(X, Y)$$  \hspace{1cm} (7.3)

This can then be used as the basis for an interaction criterion. For example, if $d(X, Y)$ is equal to at least 1 the agents can interact, if $d(X, Y)$ is greater than one they are more likely to interact. If it is zero, they will be unable to interact.

**Definition 7.1.2 (Interaction Criterion).** Axelrod used a simple dice–throw to simulate human decision–making, the uniform distribution: $U(0, 1)$. The distance between two agents must then be scaled to fall within $[0, 1]$, so a factor of $k$ is introduced. An offset of $\epsilon$ can be set in the range $[0, 1]$ to make interactions less likely.

$$k \cdot d(X, Y) + \epsilon < U(0, 1)$$  \hspace{1cm} (7.4)

The interaction would be that $X$ would choose from $Y$ a feature that was different from its own and accrete it, i.e. set a feature to have the same trait as $Y$. 
It should be clear from the specification of the change procedure that each agent is biased towards agents that are similar to itself. For agents to interact, it is required that $k \cdot d(X,Y) + \epsilon > 0$. The choice of $k$ and $\epsilon$ determine under what small-scale conditions interactions cease. If $\epsilon$ were zero and $k = \frac{1}{n}$, then no interaction can take place if the agents are completely dissimilar. But setting $\epsilon$ to $\frac{1}{n}$ and $k = \frac{1}{n} \cdot (1 + \frac{1}{n})$ would mean there would be no interaction even if the agents had one identical trait.

7.1.2 Local convergence leads to global polarisation

The software simulation Axelrod used has been replicated \[Eav99b\]. The agent to undergo the accretion was randomly chosen; the parameters of the simulations were initially:

- 5 features
- 10 traits per feature
- 100 agents
- 4 neighbours
- Topology was a square field

This is quite a testing culture. There are $\binom{10^5}{10}$ different individuals to choose from. A significant emergent property appeared that is typical of large systems:

A particular trait would become current within a group, this would make members of that group more attractive to one another and they would exchange more traits until their features were identical to one another. Should such a group encounter another group that had undergone the same process, it would be relatively improbable that they would be able to interact. In this way, islands of homogeneity emerged.

**Typical Culture** This can be seen in the following density and three–dimensional height plot, see figures 7.1 and 7.2 respectively, both of which are reasonably typical. The features have been mapped to a continuous valued metric using the function given by (7.5) and then logged to the base $n$ so that the metric is linear, see (7.6):
\[ h(A) = n^0 \cdot a_0 + n^1 \cdot a_1 + \cdots + n^{n-1} \cdot a_n \]  
\[ \hat{h} = \frac{\ln h(a)}{\ln n} \] 

**Density plot** This is shown as a pair of plots in figure 7.1. It maps the identity metric to a red–green–blue colour–code. The location of an agent can be determined from the \( x \) and \( y \) axes. The colours form into blocks where the agents are similar. The upper plot is the state of the system before interaction commences, the lower when it has reached stasis and no more interaction is possible.

**Height plot** Colour density plots show where regions of identical agents have formed, but do not clearly show how incompatible the regions are. It is difficult to tell if a yellow region is incompatible with a blue. There may be hint of blue colour in the yellow or *vice versa*. This is even more difficult if the plots are only viewed in grey-scale.

Incompatible regions are easy to see using the height plot in figure 7.2. The \( z \) axis is marked \( id \) and the physical location of the individual is specified by the \( x \) and \( y \) axes as with density plots. The surface marked by the solid lines is the initial state. The surface marked by the dotted lines is the final state.

If the difference in height between two plateaus is greater than 1 unit then the regions are incompatible — if \( \epsilon = 0 \) and \( k = \frac{1}{n} \) in (7.4).

The two types of plot are complimentary. It is difficult to interpret one without the other. The density plot shows compatibilities clearly, the height plot incompatibilities. The distribution of the varieties is given in table 7.1.

### 7.1.3 Large–Scale Behaviour

The model is a Markov process with absorbing states [Pap84, p. 396, “Birth Processes”], so it should settle after some initial transient behaviour, but may, possibly, possess limit cycles.

In Axelrod’s analysis, these following points were considered important:
Figure 7.1: Density plots of the evolving culture of figure 7.2
Culture stabilization under Egoistic behaviour

Figure 7.2: Surface plot of an evolving culture at $t_0$ and $t_\infty$. 
1. How many areas of dissimilarity?

2. How many different areas of dissimilarity?

3. How large were they relative to one another?

4. How quickly did the system stabilise?

**Metrics**  Axelrod’s method of to determine the fluctuation of the areas of dissimilarity used time–series plotting and peak detection. A set of metrics were developed that more conveniently measured the qualities of regions. Some system activity metrics were also introduced.

\( \eta \) is an efficiency measure and is the ratio of the number of interactions to the number of selections in each period. This is used to measure system activity.

\( S(v) \) The entropy of the different varieties of agents on the field. This is a single metric for measuring variance, \( S(v) \) is a normalised entropy, \( i.e. 0 \leq S(v) \leq 1. \)

\[
S(v) = -\frac{1}{\ln N} \sum_{v}^{N} p_v \ln p_v \tag{7.7}
\]

\( p_v \) is the probability of selecting an agent having variety \( v \), simply \( \frac{n_v}{N} \); \( N \) is the maximum number of varieties that can exist simultaneously, which, in this case, is the same as the total number of agents that can exist simultaneously, in these simulations \( N = 10 \times 10 \). The variety entropy is the measure of the homogeneity of the agents in the population as a whole, when it is zero, the population has only one variety of agent and no further interaction is possible.

\( S(c) \) The compatibility entropy is a measure of how compatible the varieties are with one another. The probability on which the measure is based is that of an agent of variety \( u \) interacting with an agent of variety \( v \), denoted by \( u \wedge v \):
\[ P(u \land v) = P(u)P(v|u) + P(v)P(u|v) \]

where
\[ P(w) = \frac{n_w}{N} \]
\[ P(x|w) = \frac{n_x}{N - n_w} \]

The event \( u \land u \) is not acted upon, so it is removed from the probability space as are the events \( u \land v \) when \( u \) is not compatible with \( v \) — the agents can only interact with one another if they are similar in one feature and have at least one dissimilar feature. The events that form part of the entropy measure do not cover the entire event space, so they need to be normalised. Once that is done, the entropy can be formed in the usual way. The entropy metric is itself normalised using the factor \( \binom{N}{2} \), i.e. the maximum number of pairs of different agents it would be possible to have.

\[
S(c) = -\frac{1}{\ln \binom{N}{2}} \sum_{u,v} \binom{N}{2} P(u \land v) \ln P(u \land v) \tag{7.8}
\]

When the compatibility entropy is zero, every agent is of an incompatible variety with every other agent and no further interaction is possible. It is possible for a system to have a non-zero compatibility entropy and for no further interaction to be possible; this would arise if two (or more) “islands” of compatible agents are separated by a sea of agents with which they are incompatible.

**Stasis Condition**  Because the system may fall into a limit cycle, a condition needs to be put into place that will cause the simulation to terminate. Neither of the entropy metrics is useful for this, so a simple test is to see if the number of varieties has changed over a certain number of periods. (This actually needs to be improved upon, because under some short duration limit cycles the number of varieties does change. This is unavoidable, it will be argued later that this model shows chaotic behaviour and the length of limit cycles is a fractal number.)
Typical Metrics and some Characterisation  The plot of these metrics against time for the culture whose initial and final states are shown in figure 7.1 appears in figure 7.3. The horizontal axis, marked $T$, represents the number of cycles.

Neither the variety nor the compatibility entropy has reached zero, but after 25 periods of no activity and no change in the number of varieties, the system is static. Entropy drives activity, the higher the entropy of the system the greater the activity can be. One can divide the activity of the system into four broad epochs:

1. Grouping and Simplifying - Anarchy

Entropy is high and the activity $\eta$ rises quickly and is relatively constant for the first epoch $[0, 20]$; the entropies fall rapidly. The compatibility entropy is more or less synchronised with the variety entropy, meaning that as a new variety is formed it is compatible with the majority of other varieties (which one would expect, since there are so many varieties around.) The end of the anarchic epoch is characterised by an entropy dip. This is due to some traits being annihilated at the edges of the square. There is a lull in activity during this dip.

2. Migrating - Collectivism

During the epoch $[20, 40]$, the activity increases, but the entropies remain relatively constant. Critically, the compatibility entropy increases and is slightly advanced in phase relative to the variety entropy: implying that an interaction between two agents generates another agent having a different variety. The traits are migrating across the population.

3. Concentration - Oligarchy

Epoch $[40, 70]$ has a constant level of activity, but both entropies begin to fall: no more new varieties are being generated and varieties are forming into incompatible groups. The compatibility entropy now falls behind the variety entropy in phase and the difference between the two increases. This implies that when two agents interact the agent is either unchanged or becomes identical to the neighbour with which it interacted.
Figure 7.3: Entropies and activity for the evolving culture in figure 7.1
4. Isolation and Stasis - Authoritarianism

From [70, 90] the activity falls as do the entropies. The compatibility entropy falling behind in phase and having more pointed peaks than the variety entropy.

By period 90, the system is inactive.

At the end of the simulation there are 10 varieties: these are ordered and inter-related as shown in table 7.1. The first-ranked is incompatible with all the others and has a numeric majority over all the others combined. It is now a perennial dictator, it cannot be changed and has a numeric majority.

| Order | Identity | Number | Compatible with |
|-------|----------|--------|----------------|
| 1     | 1 8 3 5 8 | 56     | none           |
| 2     | 6 7 1 6 5 | 27     | 3, 8, 9, 10    |
| 3     | 8 5 6 6 7 | 5      | 7, 8, 10       |
| 4     | 7 2 2 4 9 | 3      | 5, 6           |
| 5     | 5 3 8 4 2 | 2      | 6, 7           |
| 6     | 3 6 8 4 5 | 2      | 4, 5, 9        |
| 7     | 9 3 5 8 4 | 2      | 3, 5, 8        |
| 8     | 2 7 6 8 1 | 1      | 2, 3, 10       |
| 9     | 6 8 1 1 5 | 1      | 2, 6, 10       |
| 10    | 6 7 7 6 7 | 1      | 2, 3, 8, 9     |

Table 7.1: Identities in an evolved culture

Some Expected Deductions  The activity plot in figure 7.3 shows that the system stabilised in 90 periods — each period allows up to a hundred interactions. Axelrod was able to substantiate some intuitive deductions:

1. More features, More interaction

The more features agents possessed the more likely they were to interact. The efficiency $\eta$ had a higher average. (There were no conclusions as to its expected distribution.)
2. More traits, Less interaction

The more traits per feature the less likely agents were to interact. The efficiency $\eta$ would be lower in this case.

3. Bigger neighbourhoods, More interaction

The larger the neighbourhood (that is, the number of adjacent neighbours), the more likely agents were to interact.

An Unexpected Deduction  The relative spread of regions of dissimilarity and their distinctness proved to be less intuitive. Axelrod found that the larger the system, the fewer the number of dissimilar regions. The explanation for this is rather subtle: traits migrate across the system on a random walk [Pap84, p. 389]; the more random the system is, the further they will progress, the system is random for longer if it is larger; therefore, the larger the system, the wider the spread of a particular trait, therefore the less likely it is that the trait will be confined to one isolationist group.

This result can be interpreted as a thermodynamic effect: the system is a hot liquid that is cooling, substances dissolve in it and are dispersed by Brownian motion; the greater the volume of liquid the more mixing takes place.

This observation also helps in understanding the variation in the number of distinct regions. On the whole, one variety will tend to dominate all others: it is probabilistically more likely to reach stasis in this way. If two blocks of varieties were to form which were, more or less, of equal size and they were identical in every respect except one, then a limit cycle would develop. At the border between the two blocks, some would accrete a trait and join the other block while a similar number would accrete the other trait and join the other block. Figure 7.4 shows a density plot which has three blocks surrounded by a fourth. The block of three are compatible with one another and differ very slightly from the block surrounding. Figure 7.5 shows the metrics over time, the system behaves very much as any other would up to period 200, thereafter it enters a cycle.
Figure 7.4: Density plot for competing varieties in a culture at $t_0$ and $t_{800}$
Figure 7.5: Entropy and activity for the evolving culture in figure 7.4
7.1.4 The Collective Choice Interpretation

Axelrod modified the cultural model in a number of ways and drew further conclusions which will prove to be useful later. The relationship between features and traits can be interpreted as a collective choice procedure.

Axelrod’s Investigations  Axelrod’s simple model does help to explain large-scale system behaviour given an intuitively appealing small-scale behaviour. Axelrod investigated the effects of different topologies and different stochastic inputs for selection — in particular, selecting central agents more often, because traits can be destroyed at the edges — and the initial allocation of traits — using a Gaussian distribution, to see how much the final varieties could vary from a variety of Gaussian averages.

Axelrod chose not to vary the rules agents used to accrete traits. This does affect how the model can be used to make a collective choice.

Collective Choice Interpretation  The earlier analysis of preference hierarchies and preference aggregation, see chapter 4, gives an insight into the operation of the cultural model as a collective choice procedure.

Assume there are three issues, $a, b, c$, a system must determine the relative strengths of each of them given that each agent (or voter) is allowed to express a preference ordering using, for simplicity, a strong ordering. The orderings, $D$, is the set given in (7.9).

$$D = \{ a > b > c, a > c > b, b > c > a, b > a > c, c > b > a, c > a > b \} \quad (7.9)$$

If the features are $F = \langle a > b, a > c, b > c \rangle$ and the traits for each feature are $T = \{1, -1\}$ then an agent preferring $a > b > c$ would have a feature set of traits: $\langle 1, 1, 1 \rangle$, and an agent having $a > c > b$ would have $\langle 1, 1, -1 \rangle$. If these two agents interacted they would quickly settle their differences on the relative merits of $c$ and $b$ and form a single variety of agent, similarly for agents preferring $b$ and $c$.

If an agent preferring $a$ were to interact with an agent preferring $b$ then $\langle 1, 1, 1 \rangle$ meeting $\langle -1, -1, 1 \rangle$ would allow them to exchange their primary preference and the
internal state of the receiver would become inconsistent, so the criterion for interaction is that the two agents must agree on two preferences before they can interact.

This interpretation is valid for a wider issue set and for weak orderings, the choice of the number of traits on which to agree does become more complicated. Referring to table 6.5, for three issues there are 13 different weak orderings of those issues with respect to one another. The features would be $F = (a > b, a > c, b > c)$ and the trait set would be $\{1, 0, -1\}$. An agent having a preference ordering: $a > b > c$ would have a feature set: $(1, 1, 1)$ and $a = b = c$ would be $(0, 0, 0)$.

It is possible to be more liberal in this interpretation. If one has $n$ issues and the number of orderings is $O(n)$, as given by table 6.5, if one then wants to simplify the orderings to some sub–set, then one should set the number of features $\#(F)$ and the number of traits $\#(T)$ so that $\#(F) \cdot \#(T) < O(n)$. The cultural model then acts as a genetic algorithm, but of a peculiar kind: it crosses varieties with one another, but does not mutate, and requires no global fitness function.

One must then impose some kind of topology that allows each variety to interact with every other. This need not be a mesh topology, because the traits only have to find a migration path. A spanning tree for the preference orderings will suffice and it is easy enough to set a size for a useful spanning tree using (7.10), where $n$ is, once again, the number of issues to be resolved.

$$\sum_{i=1}^{n} \binom{n}{i}$$ (7.10)

The cultural model can then be thought of as collective choice procedure that forms a spanning tree of a well–ordered graph. Unlike the techniques given in §6.5, it is a stochastically–driven heuristic method. It attempts to reduce a preference ordering search space of order $O(n)$ to a strongly–ordered subset of those orderings where some of the issues have been merged by allowing a weak–ordering.

(The fact that some of the feature sets produced during the operation of the cultural model may give rise to inconsistent states can be justified in the same way as it is with genetic algorithms. It is simply a transient state that allows new varieties to be developed. This is argued more persuasively in [Dav91].)
7.2 Formation of Cultures under Peer Pressure

Axelrod’s simple behavioural rule and the large-scale effects it appears to introduce is discussed first. A new rule is introduced and a system using it is simulated and the results analysed.

7.2.1 Egoistic Behaviour

The small-scale behaviour that agents follow is described in the title of figure 7.2 as Egoistic. Each agent can accrete a trait from one of its neighbours regardless of the state of its other neighbours.

Increasing Heterogeneity Some of the simulations conducted used a smaller playing field (5 by 5) with only 3 features and 3 traits per feature. These show that agents can quickly agree to not differentiate amongst themselves, see figure 7.6. (The axes are labelled in the same way as in 7.2: identity, id, on the vertical axis, location within the playing surface on the $x$ and $y$ axes.)

It is unlikely that a wholly homogeneous culture should arise with a larger more complex playing field, but it is usually the case that one variety of agent wholly dominates the others. It might be desirable to control the degree of variety.

Restricting the migration of traits Of particular interest for information security is how a small sophisticated group might be able to enforce a consensus that certain views should be globally accessible. Figure 7.7 illustrates this. Here, two agents placed at the origin and at $(4,0)$ have seen their principal traits migrate across almost the whole of the surface.

It would be desirable that there be distinct regions having access to particular views/traits, but it is not desirable that views/traits migrate indiscriminately across regions.
Culture stabilization under Egoistic behaviour

Figure 7.6: Culture that evolves to homogeneity
Culture stabilization under Egoistic behaviour

Figure 7.7: Culture unduly influenced by some agents
7.2.2 Peer Agreement

Another simple behaviour that could be employed by an agent is to require that one of its other neighbours also be compatible with the neighbour from which it would accrete the trait. Unfortunately, to make this rule more precise a modal logic is required. Modal logics are briefly discussed in appendix F.

The model under which an agent \( x \) operates is denoted \( \mathcal{U} = \langle \mathcal{W}, \ldots, \mathcal{P} \rangle \). Containing a set of agents \( \mathcal{W} \), which are its neighbours \( \{y_1, \ldots, y_n, z_1, \ldots, z_n\} \) and a set of truths, the traits, distributed amongst the worlds, \( \mathcal{P} = \{P_0, \ldots, P_N\} \).

**Egoistic Behaviour** Firstly, egoistic behaviour can be more formally specified. The probabilistic fuzziness of \( U(0,1) \) in (7.4) is not given in this formal specification. The form is of a schema, the conditions above the line must appertain and the condition below the line can be enforced.

\[
\begin{align*}
\begin{array}{c}
\mathcal{U} \\
\end{array} & \models_x P_i \land \neg P_j \land \Diamond (P_i \land P_j) \\
\mathcal{U} & \models_x P_j
\end{array}
\]

\( x \) has been selected and holds the trait \( P_i \) but not \( P_j \). There is another agent in his neighbourhood where both \( P_i \) and \( P_j \) are held. \( x \) accretes \( P_j \) (Incidentally, \( i \) is not equal to \( j \) because \( P_i \land \neg P_j \) would be false.)

**Peer Agreement Behaviour** A form of peer agreement behaviour can be expressed thus:

\[
\begin{align*}
\begin{array}{c}
\mathcal{U} \\
\end{array} & \models_x P_i \land \neg P_j \land \Diamond (P_i \land P_j) \\
\mathcal{U} & \models_x (P_j \land \neg P_i) \lor \Diamond (P_k \land \neg P_j \land \Diamond (P_k \land P_j)) \\
\mathcal{U} & \models_x P_j
\end{array}
\]

\( ^1 \)The class of modal logic employed has to be irreflexive. In particular any axiom which prevents \( \Diamond (P_i \land P_j) = \Diamond P_i \land \Diamond P_j \), i.e. \( P_i \) and \( P_j \) must reside in the same agent.
The first condition is the same as in (7.11). The second has two parts, there is someone else in the neighbourhood who:

- Either: holds $P_j$ but not $P_i$.
- Or: could also accrete $P_j$, i.e. is compatible with $z$ in some other way.

This form of behaviour — implemented as the class PeerPossible in [Eav99b] — is effectively a membership rule. If $z$ is the holder of $P_j$ who also holds $P_i$, then $x$ proposes $P_j$ and someone, $y$, seconds it.

In the former case, if the number of neighbours is limited to four (as they are in the Axelrod square topology) then five may vote and a majority, $x$, $y$ and $z$, have stated that they are compatible with $P_j$ — $z$ votes “for” because it already holds $P_j$, the other two, $x$ and $y$, because they hold something that $z$ also holds.

### 7.2.3 Some Expectations

1. Slower Trait Migration and More Probable Limit Cycles

   Clearly, one can expect the rate of trait migration to be slower. A trait not already extant in a neighbourhood will have to wait for a trait that is extant to join it, before it can propose itself. If trait migration is very slow and in pairs, it might be the case that traits repeatedly cross and re–cross the field without actually appearing in the same agent together. This could lead to very long limit cycles.

2. Edge Effects

   Under egoistic behaviour, if a trait becomes isolated at an edge, it had one less degree of freedom in the direction in which it could migrate. Trait migration on a square field tends to be from the centre to the edges. Under PeerPossible behaviour it should be the case that traits will be more difficult to dislodge from the edges, because the neighbourhood they belong to has one less voter, but, as proposer and a seconder are still needed, three out of four must concur; at
the corners, the condition is even more stringent, requiring three out of three to concur.

3. Dormancy and Second Waves

The edge effects might lead to agents being able to preserve traits at the edges and corners so that as the system stabilises, and the traits held at the centre migrate outward, the traits held at the edges would overcome the traits that originated from the centre. This would lead to a second wave of activity.

7.2.4 Some Results

A set of simulations was undertaken using PeerPossible behaviour instead of Egoistic. The model is susceptible to the effects of different starting conditions — the initial allocation of traits to each individual, \( \binom{10^5}{100} \) different configurations — and the number of different sequences of interactions — 100\(^{200}\) for a typical 200 period run. Nonetheless, some useful results were observed. A typical pair of density plots and an activity plot appear as figures 7.8 and 7.9 respectively.

Large–scale behaviours PeerPossible is similar to Egoistic behaviour in that it gives rise to diverse populations which can either be ultimately quiescent or fall into a limit cycle. PeerPossible leads to limit–cycling populations more often than Egoistic — as was expected. Unlike Egoistic behaviour these can be predicted and can remain relatively stable. PeerPossible behaviour very often results in limit cycles between comparably sized groups, but these are more or less defined after 200 periods (this is discussed in more detail later.)

This can be summarised:

- If the system does stabilise quickly, it invariably results in one dominant variety.
- If the system takes longer to stabilise, then a limit cycle with a dominant variety varying in the number of members is the usual result.

An analogy to political systems might be useful here: systems that stabilise rapidly to an authoritarian regime are similar in behaviour to third world political systems
Figure 7.8: Peer Agreement Density Plot at $t_0$ and $t_\infty$
Figure 7.9: Activity and entropy for figure 7.8
— an immutable consensus emerges; systems that exhibit limit cycles are comparable to first world political systems — a variable consensus emerges.

Whether a population will stabilise quickly can be determined quite reliably by the changes in its entropy characteristics as it evolves.

Figure 7.8 shows different identities are usually attached to an edge. This is also true of cultures produced by egoistic behaviour, but it appears to be more marked for PeerPossible behaviour. This is a result that was also expected.

An interesting and useful side–effect of slower trait migration is that large–scale behaviour becomes more predictable because traits are more likely to cluster in their original locations and individuals at the edges tend to become the dominating variety. Referring to figure 7.8, there are two large distinct regions:

- The turquoise lower left–hand side
  The colours in the lower left–hand side corner of the initial state are more often of the turquoise hue that will prove to be dominant. There are some agents on the edge, at (0, 0), (0, 3) and (0, 7), that are already of colour that will prove to be dominant in that corner. Note that (0, 7) and (0, 10), already closely related to the dominant turquoise, have joined the red variety.

- The garnet upper right–hand side
  This area appears to have been constructed in response to the turquoise area. There are no explicitly garnet individuals in the initial populations, the final colour appears to be a blend of red and the light puce coloured individuals. Notice that the individuals in the upper corners are unchanged throughout the evolution.

**System Activity** Referring to the four epochs that were characterised for egoistic behaviour, there are some differences for PeerPossible:

1. Anarchy
   The anarchic period appears to last about twice as long as it does under egoistic behaviour, as one might expect, because the level of activity is about half. When
both entropies fall to 0.6 the collectivistic epoch commences. It also exhibits
the dip associated with traits being annihilated at the edges.

2. Collectivism

This is markedly different from egoistic behaviour. The entropy falls throughout
the collectivistic epoch — meaning that the system is organising itself faster.
Other than that, it behaves in a similar manner: the difference between the
variety and compatibility entropy reduces and the latter leads the former.

3. Oligarchy

Under egoistic behaviour, this epoch is marked by a fall in entropy, and an
increasing difference between variety and compatibility entropies which leads
to a phase lead becoming a lag. Under \textit{PeerPossible} behaviour only the phase
change is noticeable, because the entropy has fallen to critical during the period
of collectivism.

4. Authoritarianism

The authoritarian epoch is the same under both egoistic and \textit{PeerPossible} be-


Generally \textit{PeerPossible} behaviour has a level of activity that is 10% lower than
egoistic but takes about twice as long to stabilise. The latter is commensurate with
the requirement under \textit{PeerPossible} behaviour that an individual must gain a corrob-
orating neighbour — suggesting that two agents, probabilistically, take twice as long
to agree as one — but the level of activity is not half of what it was under egoistic
behaviour. This would suggest that \textit{PeerPossible} behaviour is more efficient — in
that, the interactions between agents are not as often undone.

\textbf{Limit Cycles} \textit{PeerPossible} behaviour, as predicted, does suffer more from limit
cycles. In a set of 32 simulations only 11 reached stasis. It would seem that the
limit cycle is the preferred global behaviour for local \textit{PeerPossible} behaviour. A good
Figure 7.10: Peer Agreement Density Plot at $t_0$ and $t_{1100}$
example of a limit cycle’s activity appears in figure 7.11. The state of the agents appears in figure 7.10.

Although the system cannot reach stasis, which is arrived at when the number of varieties is constant for 25 periods, the system has been more or less stable since period 200, which is quite typical of PeerPossible systems. Looking at the state of the agents, one variety has dominated the others and, because of the lack of variation of the variety entropy, has done so for some time.

One could be fairly confident in saying that when the variety entropy has fallen below 50% and the compatibility entropy is less than the variety entropy, a system is probably stable, in that the dominant variety will remain so.

It appears to be very rare for a system in a limit cycle with a dominant variety to further evolve so that variety is no longer dominant.

7.2.5 Some Conclusions

PeerPossible behaviour does seem to lead to more predictable systems which, more often than not, avoids an authoritarian terminal state and that trait accretions are less frequently reversed later.

7.3 Predictability of Large–Scale Behaviour

The simulation model has been used to determine emergent properties of large–scale behaviour given different small–scale behaviours. In §7.1.3 it was seen that larger playing fields led to more homogeneous cultures. The simulations used to demonstrate this property were highly stochastic: individuals were given random traits, they were then randomly located and then in each period randomly chosen to interact with one another.

It is also hoped that this analysis of the evolution of cultures can give us some assurance that, were a system allowed to organise itself, it would consistently arrive at more or less the same set of cultures if the individuals within it start with the same traits and behave in the same way. This would mean that a safe access control
Figure 7.11: Activity and entropy for figure 7.10
management system would arrive at very much the same allocations of access rights if the individuals start with the same interests.

In the context of the simulation model developed above, some assurance must be gained that the final state of the system is statistically independent of the location of the individuals and when they are chosen to interact with one another.

Before describing the experiments that were conducted to provide this assurance, some insight will be gained from the analytic research that has been conducted in this field.

### 7.3.1 Analytic Research

Essentially, some guidance is needed on how to construct a simulation model whose final state will be almost wholly dependent on the initial states of the individuals: their location with respect to one another and the sequence they interact with one another is not important.

#### Voter Models and Initial Distributions

Axelrod pointed out in his paper [AAEC96], that the simulation model is a variant of the voter model in which a particle aligns itself with its neighbours based on whether they hold the same value or not.

Consonant voting Bramson and Griffeath, [BG80], have made a comprehensive analysis of voter models having only one trait. They quote results showing that voters in one- or two-dimensional space tend to converge weakly to a majority, either for or against, which is dependent only on the initial ratio of voters for and against. The voter model they analysed was a consonant voter model meaning that a voter aligned himself to be the same as his neighbours.

Bramson and Griffeath’s main interest was to establish conditions under which the process would be ergodic, i.e. under what conditions limit cycles would not occur. They showed, analytically, that in one-dimensional systems the consonant voting
model for one trait individuals was ergodic, but for more than two or more dimensions, \( i.e. \) four neighbours or more, it was not ergodic.

They also showed that even though two– or more dimensional systems might not be ergodic, the ratio law still applied. In that, the probability of the system attaining a state where the ratio of for and against voters was reversed from the initial state of the system was ergodic: under a consonant voting model, the same simple majority will be maintained. There were a number of provisos to this. If the ratio was close to \( \frac{1}{2} \) there was as a possibility of short excursions when the majority would be reversed, but not indefinitely.

**Dissonant voting** Bramson and Griffeath’s paper also analysed dissonant voting models and discovered that they were unable to ascertain whether the ergodicity theorems they had developed could be shown or not. Their analytical technique was lacking because dissonance introduced cumulatively larger probabilities of dissimilarity. It appears that, under dissonant behaviour, chaotic behaviour can develop which can lead to very long limit cycles which may not hold an initial majority in place. This can be demonstrated with reference to another of Axelrod’s behavioural investigations.

The basis of Axelrod’s simulation is a simple behavioural interaction, which is best expressed in modal logic. The modal logic expression is a useful formalisation, but it has proved difficult to extend it to describe the dynamics of interacting systems. Axelrod’s cultural model was preceded by, and is, in some ways, an extension of, the Iterated Prisoners’ Dilemma — IPD, see [Stu97] for example. Each prisoner has one neighbour, so it a very simple model under Bramson and Griffeath’s analysis, but the dynamics can be very complex. An analysis of the simple interaction underlying the IPD was carried out by Mar [MD94]. He showed that this could lead to a system which possessed chaotic self–similar behaviour if one of the prisoners acted consistently *dissonantly*.

Unfortunately, consonance and dissonance become non–bivalent concepts when more than one trait is involved and the properties of the distance metric and the behavioural rule that uses it become important.
Because of this property, it is not possible to make any useful predictions about large-scale behaviour in dissonant systems. Axelrod’s cultural model can move from a disordered to an ordered state with predictable large-scale behaviour, but it cannot move from an ordered state to a more disordered one and remain predictable.

**The relative consonance of PeerPossible** Referring to the behavioural models that have been investigated: PeerPossible behaviour, it was noted in §7.2.5, gives rise to fewer trait reversals than Egoistic. This would suggest that PeerPossible is a more consonant rule.

**Topologies and Initial Distributions**

Bramson and Griffeath’s one trait voter models were immune to changes in topology. There was no difference in large-scale behaviour if the voters were laid out on squares, circles, cylinders, toroids or spheres. When the voters have more than one trait, superposition effects occur which make topology important. An analysis of the effects of topology leads to a concept called meta-behaviour and suggests topologies that will be more predictable.

**Meta-behaviour and Topology** As pointed out in the discussion of the PeerPossible behaviour, agents located at the corners are more intransigent than those on the edges who are more intransigent than those in the centre because corner agents have only two neighbours, edge agents three and inner agents four.

It may be that the limiting distribution of identities is towards their meta-behaviour determined by their intransigence which is, in turn, determined by the number of neighbours they have.

**Squares** This would mean that for a square topology, there would be three types of meta-behaviour. The corner agents separate the groups of edge agents from one another and *vice versa*; this would suggest a mean of nine varieties would evolve: four different corner varieties, four different edge varieties and one variety for the inner agents. The inner agents would outnumber the corner and edge agents when, for a
square having sides of length $L$: $(L - 2)^2 > 4(L - 1)$, *i.e.* $L \geq 7$ and the number of agents is 49.

The inner agents would align themselves to have one variety and would then separate the other types of agent from one another preventing them from coalescing.

A useful analogy to a political system might help here: the United States of America has more than 49 states and has a relatively stable political spectrum. Changes to the constitution of the United States must be ratified by 66% of the legislative assemblies of its constituent states. This closely approximates to the allocation of behaviours in the behavioural model.

**Circles** The number of meta–behaviours can only be changed by using a different topology.

A circular topology could be constructed as a coiled helix — like a string of beads. The two end–agents would have two neighbours. The edge agents would form one outer circle and the inner agents would be all the agents within that circle: giving rise to three meta–behaviours. There would then be four varieties: two types of end–agent, one type of edge agent (they are now connected) and one type of inner agent.

The two end–agents could then be connected to one another to give one agent with three neighbours, *i.e.* another edge agent. There would then be only two meta–behaviours. The number of inner agents would exceed the number of edge agents when $\pi(r - 1)^2 > 4\pi r$, *i.e.* $r \geq 4$ or the total number of agents is greater than 49. This topology has been called the *Möbian circle* by Axelrod in [Axe97].

The inner agents would align themselves to have one variety and would then be able to dominate the other group of edge agents. This circle is a more responsive topology than the square, because the edge agents would be in the majority given one defection by an inner agent. That is, it reduces to a simple majority voting model.

The Axelrod cultural model can thus reduce a random selection of behaviours to a choice between two aggregated behaviours:

- A conservative policy held by agents at the edge
A broad consensus policy held in the centre

Axelrod conducted a number of simulations to determine if this was the emergent property for circular topologies and the result was more or less in the affirmative, see [Axe97].

### 7.3.2 Experimental Investigation

From the analysis above, it would appear that this model would lead to more predictable large-scale behaviour:

- PeerPossible small-scale behaviour
- Möbian circle
- More than 49 agents

The following experimental procedure was carried out in addition to Axelrod’s experiments: generate one set of agents and place them randomly on a Möbian circle and allow the system to interact. When stasis was reached, the final set of varieties of agent was recorded and the experiment repeated with another random allocation of the same agents.

**Regions** These results agree closely with those of Axelrod’s for the Möbian circle where the simulations produced just two varieties for 70% of the simulations and these simulations reached an authoritarian state. 20% of simulations resulted in either, three varieties which were all mutually incompatible and reached stasis, or, three varieties which remained compatible but the system did not reach stasis. When three varieties emerged it was invariably the case that two large varieties were incompatible and separated by a small buffer region occupied by the third small variety. This buffer region invariably contained the two agents that linked the outer edge with the inner core.

The remaining 10% of the simulations seemed to be a variant of the buffer region where there were two varieties in the buffer zone, which were incompatible with one of its neighbouring zones.
No simulation resulted in more than four varieties. Clearly, this is very consistent large–scale behaviour.

**Varieties** The simulations proved to be less decisive with regard to final varieties. The initial population of agents was seeded using a binomial distribution of twelve traits for half of their features and a uniform distribution of twelve for the remainder. The binomial distribution was a throw of two six–sided dice\(^2\). The conditions for the simulation were these:

- 144 agents were laid out in a Möbian circle
- **PeerPossible** behaviour for the agents
- There were twelve features, each having twelve traits
- \(n\%\), \(n \geq 50\%\) of the agents had their lower six features assigned traits using the binomial and the upper six features using the uniform distribution.
- The remaining \(100 - n\%\) had their upper six features generated using the binomial and the lower six generated using the uniform distribution.

It was seen that only when \(n > 66\%\), were the final varieties noticeably similar across simulations with different initial distributions of the same agents. When \(50\% < n < 66\%\), one or more arbitrary traits from the smaller group could establish themselves in the larger group. A similarity between the varieties remained which did indicate a consensus had emerged.

It should be noted that 66\% is a statistically significant number. It is one standard deviation of the normal distribution and the sum of a large number of binomial distributions approximates to the normal.

This agrees with the Bramson and Griffeath’s analysis: that the varieties that emerged from the larger group were consistently in the majority.

\(^2\)It was decided to operate in base twelve, because twelve has more divisors than ten which helped to simplify the calculations.
7.3.3 Sequences of Interaction

It appears then that with a suitable choice of topology and an intrinsic bias in the population a consistent consensus can be achieved. It was decided that an investigation into the effects of the sequence of interaction between agents was unnecessary. This may not be so easily dismissed in a real culture where the choice of agents who may interact with others may be biased towards particular individuals. This is worth further investigation, but, for the time being, it is assumed that the agents chosen to interact with one another can be safely assumed to be uniformly random.

7.3.4 Collective Choice

Referring to the discussion of the theory of collective choice §6.4.1, the Möbian circle topology has the attractive property of being able to reduce collections of issues to just two and thus appears to reduce choice systems to one of simple majority and thereby circumvents the limitations imposed by Arrow’s Impossibility Theorem, as summarised in [Eav99a].

Referring again to the political structure of the United States, it would appear to display the characteristics of this circular topology. There are just two dominant political ideologies and the states neighbour each other in different circular topologies on the different political issues presented to them. The net effect is a superposition of pairs of different behaviours all of which can be encompassed by the two political parties’ platforms. This construction bears a great deal of similarity to the dynamic analysis of the Tiebout model by Kollman et al. [KMP93].

7.4 Summary

Protocol adoption  This chapter has shown that large systems where individual agents make choices constrained by a simple, rational behaviour can lead to stable behaviour for the system as a whole. This result, it is claimed [Axe95], helps to explain the emergence of de facto standards. Axelrod’s analysis was prompted by the evolution of different Unix standards, but it might be applied to different Internet
protocols. For example, 90% of Internet traffic is carried over TCP connections rather than in UDP datagrams. TCP has very useful technical advantages over UDP: it, unlike UDP, is rate–adaptive, does not require an application programmer to fragment his own data, transparently recovers from IP packet loss and the arrival of IP packets out of sequence — in summary, it provides a relatively simply session layer. UDP is however to easier to manage: it requires no connection management — simply one listening endpoint from each party for each connection — it is therefore easily adaptable to multi–cast protocols and it is easier to define rules for screening firewall routers. Had it been the case that a sufficiently capable session layer were available to application programmers early in the development of the Internet, UDP might have become the de facto standard for IP communications rather than TCP. Similar arguments can be made for the domination of other protocols: the Sun Micro–systems RPC protocols based on the portmapper, could have been supplanted by the Domain Naming Service based Hesiod protocol from MIT.

**Protocol adoption and behaviour** The number of incompatible standards (meta–behaviours) that can emerge is a function of topology; how long the system takes to arrive at a stable set of standards is a function of the choices — features and traits — available. The behaviour that each agent employs when making choices controls the rate of migration of the traits and the number of conflicts over their selection: Egoistic behaviour allows traits to migrate quickly but introduces proportionally more conflicts to resolve, PeerPossible behaviour the converse.

It has also been argued that PeerPossible should be a more consonant voting behaviour than Egoistic and, when coupled with a Möbian topology allows very homogeneous cultures to evolve. This cultural system also has the attractive property that it does not remove any intrinsic bias in population.

**Engineering behaviours** A point that has not been addressed is how behaviours like Egoistic and PeerPossible would be engineered so that they may be used to simplify policy choices in working systems. A simpler example than access control policy evolution might be IP address allocation. Looking at figure 7.10, it could be the case
that a hundred small separate networks at $t_0$ have interacted with one another and joined each other’s networks to yield a few larger networks by $t_{1100}$. The criteria for the features they might employ would include some of the following:

- Connections to different types of carrier network: some networks may consist almost entirely of single-homed 100BaseTX on the same subnetwork; some may have a number of dual-homed routers with access to ATM or SDH leased lines linking to other subnetworks.

- Different protocols used for communication: some networks may make extensive use of multi-cast, point-to-point IP routes, or Generic Router Encapsulation (GRE) tunnels.

- Traffic types: some networks may be simply web-browsers; some may use remote file-store.

- Screening subnets: it may be the case that some networks must not be visible to one another.

There could be a very large set of traits for each of these and others.

For an operational protocol, one must consider resource-locking. Each individual would operate autonomously from every other, but would need to acquire locks on their neighbours when they are about to make the decision to change their configuration. This is quite a difficult lock-acquiring exercise since dead- and livelock are distinct possibilities.

**Population statistics** The key point about the behaviours Egoistic and PeerPossible is that they operate locally and can, consequently, adapt very quickly to their neighbours. The entropy measures that have been introduced are population measures and, in a working system, would be expensive to compute. They are, as has been seen above, a very useful guide to the operational state of the system — whether anarchic, collectivistic, oligarchic or authoritarian. A system administrator could use the entropy measures to determine if a system has simplified itself enough to be allowed to continue to fulfil its chosen function: more efficiently and with less conflicts
than before it organised itself. To obtain an accurate statistic, it may be necessary for the administrator to quell all interactions and request the status of all the individuals.

**Migration of access rights**  The results obtained in this chapter give us confidence that a self-organising system that allows access rights to be migrated from one individual to another should be predictable. Some of the metrics developed could be used to monitor the migration.

The cultural model gives us a reference model of behaviour. When one designs a system, one can attempt to reduce its operation to that of the simulation described in this chapter. This then gives us some expectations for its behaviour.
Chapter 8

Self–Organising Permissions Policy System

The findings of chapters 6 together with the small–scale behaviours investigated in chapter 7 can be used as the basis for a self–organising permissions policy system. In chapter 6, integrity checks and distance measures for preference hierarchies were introduced. In chapter 7, a cultural model illustrated how a system of interacting agents with a fixed set of choices using a simple behavioural rule based on a distance measure would have reasonably predictable large–scale behaviour so that agents within cultures should segregate themselves into large groups.

To assure ourselves that a system will behave like the cultures described in 7, it must have the same construction:

- A small–scale behavioural rule
- A fixed set of discernible features with traits
- A distance measure for two feature sets
- A fixed topology, preferably in two dimensions

Before discussing how a self–organising permissions system might work, a simpler example of a self–organising set of newsgroups will be developed.
8.1 Self–Organising Newsgroups

One application of this system as proposed would be a set of self–organising newsgroups or mailing lists. The problem with USENET newsgroups is they have a very low “signal to noise” ratio. There are lots of postings of dubious worth, some nothing more than advertisements. Very often the quality of debate degenerates to a squabble. Often cliques of users develop threads of discussion which are of no interest to anyone else. Cross–posting is another problem: subscribers send the same message to a number of newsgroups simultaneously.

Newsgroups could be self–organising: so that squabblers will be moved to their own groups as would persistent advertisers. Cross–posting will be limited by using managers who may choose to refer a posting to another group rather than have it posted in their own.

There are three types of newsgroup management in place for the USENET.

**Moderated** every posting to the newsgroup is vetted by a moderator.

**Managed** subscribers are only allowed to post if they have applied for permission to do so from the newsgroup manager. The newsgroup software then checks if each posting comes from an allowed subscriber.

**Unmanaged** Access is completely open.

Moderation is usually too burdensome. Managed newsgroups are quite rare (but common for mailing lists), so the usual form is an unmanaged newsgroup. The system proposed will be a sophisticated managed newsgroup.

To put newsgroup postings under some sort of control, a preference hierarchy needs to be developed from some norms. This would then be used to partition the subscribers to the newsgroup into sub–groups and to rank the newsgroups with respect to one another. This section will continue with a description of how such a self–managing newsgroup protocol would work and an analysis of it as a cultural model like that in chapter 7.
8.1.1 Newsgroup Operation

How it might work

Newsgroups are organised by a set of news administrators who require a group of people to issue a charter and have a number of newsgroup subscribers sign it before a group is propagated within the USENET hierarchy. Discussions around an operating system, such as Linux, in the comp.os hierarchy has been split into these groups:

- comp.os.linux.advocacy
- comp.os.linux.announce
- comp.os.linux.hardware
- comp.os.linux.software
- comp.os.linux.setup
- comp.os.linux.networking
- etc.

Within the comp.os.linux.advocacy newsgroup there will be a number of postings comparing Linux with the Microsoft Windows operating system. The Linux vs. Windows debate is an interest which all of the comp.os.linux newsgroups share, but only comp.os.linux.advocacy would usually discuss it, but a debate comparing Windows network interface card driver support vis à vis that of Linux would be of interest to the comp.os.linux.networking newsgroup.

A self-organising set of newsgroups for comp.os.linux should finally evolve a structure similar to that above, but it would use who takes part in which debates to evolve the structure, rather than having one imposed on it.

The operation of a self-organising newsgroup has only a small amount of information to use: postings from subscribers to particular threads. There are four procedures involved in self-management:

1. Initial group allocation
2. Posting using subscriber referral and access management
3. Generating group allocations
4. Posting using group referral and access management
5. Repeat from $\exists$

**Protocol** A protocol of some kind has to be imposed on the newsgroup to yield more information from the postings.

- When a subscriber initiates a thread, it must be followed up for it to considered.
- A subscriber cannot follow up himself.
- A follow–up must be followed-up to be considered.
- A follow–up is closed if it is acknowledged by the subscriber who initiated the thread.

This set of rules makes for civilised debate, a simple example of which might be:

1. $p$ initiates thread $a$
2. $q$ follows up $a$
3. $p$ acknowledges $q$

$p$’s initiation of the thread $a$ counts as a statement of his preferences because $q$ followed it up. $q$’s follow up is counted as a preference, because $p$ acknowledged it. A more complicated scenario might be:

1. $p$ initiates thread $a$
2. $q$ follows up $a$, creating $a'$
3. $r$ follows up $a'$
4. $q$ or $p$ acknowledges $r$ on $a'$
5. $p$ acknowledges $q$ on $a$
Probably, the simplest discipline is to allow the initiator to acknowledge all contributors, except those he considers irrelevant. If any of the contributors follows a thread that the initiator feels is irrelevant then that subscriber who followed up the irrelevant thread can acknowledge it and form a new thread. So, in the interaction above, if \( p \) does not acknowledge \( r \), then \( q \) must acknowledge his contribution and their contributions count to the sub-thread \( a' \).

**Initial Grouping**

This is the first phase of generating a preference hierarchy. It is used to derive a partitioning of the subscribers to the newsgroup. As each subscriber posts to a thread, it generates a preference. If, for example, there are three threads: \( a, b, c \) and an apathy thread is added to this so that all the threads can be related, call it \( \emptyset \), then if a subscriber posts one or more times to threads \( a \) and \( b \) and not to thread \( c \) then the preference ordering is \( a = b > c = \emptyset \).

**Newsgroup partitioning by thread interest**  A preference hierarchy for each of the subscribers would be generated. It would then be aggregated using the techniques described in §6.6.3. The preference hierarchies would be just two-ply — those subscribed to and those not — but it might be the case that global indifferences emerge from the \( I \)-graphs. For example, everyone who posts to \( a \) will always post to \( b \). Thread \( a \) would then be merged with \( b \) and would form a new sub-newsgroup.

In the aggregation there would almost certainly be cycles — a cycle such as \( a > b = c = \emptyset, b > a = c = \emptyset \) and \( c > a = b = \emptyset \) could arise. These would have to be removed by merging threads or by removing subscribers who introduce cycles. Using some set nomenclature, \( \{ s \mid < \text{ordering} > \} \) is a statement of set membership for subscribers \( s \) who have ordered the preferences in the specified way. For the example of three initial threads, all of the possible new sub-newsgroups that could emerge are given below:
\[ g_a = \{ s | a > b = c \} \quad \text{and} \quad g_{ab} = \{ s | a = b = \emptyset > c \} \quad \text{and} \quad g_{abc} = \{ s | a = b = c > \emptyset \} \]
\[ g_b = \{ s | b > a = c = \emptyset \} \quad g_{ac} = \{ s | a = c = \emptyset > b \} \]
\[ g_c = \{ s | c > a = b = \emptyset \} \quad g_{bc} = \{ s | b = c = \emptyset > a \} \]

(8.1)

There are only 7 rather than 13 groups that Table 6.5 would suggest. This is because the simplification discussed in §7.1.4 has been used. These 7 groups represent all the valid shades of opinion there might be. This has been achieved in the newsgroup system by only allowing two-ply preferences for the subscribers.

In more colloquial terms the subscribers have been partitioned into “one interest only”, “two-interests” and “interested in all” groups.

**The Entry Group** This group is used by all groups to post new threads and by people who wish to join the newsgroup to see what threads are being discussed. A thread that is never followed up would stay in the entry group, when there is a follow-up, it would move to one of the sub-newsgroups. The group is called the *entry* group.

Every subscriber is a member of the entry group. Every subscriber may initiate a thread in the entry group.

**Ordering Subscribers and Appointing Managers** For each sub-newsgroup generate an ordering of the subscribers based on the number of times they have posted to the threads of their sub-newsgroup. Form the most active members into a collective that acts as the sub-newsgroup’s access managers — it might be the top 5% of subscribers for each group, for example. (This, incidentally, is one of the problems of this system’s design: a sophisticated group of subscribers can make themselves managers of groups by answering each other’s threads. This is similar to tactical voting. It will be seen that an entropy measure can be used to determine how much support managers have.)
New postings

When an existing subscriber initiates a new thread, it would be posted to his sub–newsgroup and also to the entry group. Followups to the new thread would appear only in the sub–newsgroup. If a subscriber in another sub–newsgroup wants to follow a new thread in a sub–newsgroup, he would be able to review the postings for that new thread but not make any.

If he did want to make a posting to that thread, his mail would be sent to the access managers. They would then decide whether to permit the posting and would thus grant to the new subscriber membership of their sub–newsgroup. He would then be allowed to initiate a thread in that sub–newsgroup as well as submit postings.

Group Preference Hierarchy

After a number of new threads have been started, the subscribers can be re–partitioned and, additionally, a hierarchy of the groups can be generated. This hierarchy expresses a norm of behaviour between the groups.

Norm of behaviour  It is best to explain this by example: if a member of sub–newsgroup $g_a$, the one containing all those who chose $a > b = c$, chooses, via the entry group, to join group $g_b$ for two threads, $b_1', b_2'$ and only takes part in one thread in his own group $a_1'$ then he has the following preference orderings:

- An ordering between threads as before: $a_1' = b_1' = b_2' >$ any others
- An ordering between sub–newsgroups: $\text{group}(g_b) > \text{group}(g_a) > \text{group(} \text{others})$.

The latter preference is formed because the subscriber has posted twice to threads originating in group $g_b = \{s | b > a = c = \emptyset\}$ and only once in $g_a = \{s | a > b = c = \emptyset\}$. The ordering between threads will be only two–ply, as before, but that between newsgroups can be as long a chain as there are newsgroups.

The ordering between threads represents a subscriber’s current interests and the ordering between newsgroups relates his current interests to his past interests. (The
relative strengths of his interests are not used in forming his preference hierarchy, these are used in the aggregation across the newsgroups.)

This forms a norm of behaviour. One would expect a subscriber in group $g_a$ to post subsequently solely to that group, but if he posts to $g_b$ as well, this would suggest he should join $g_{ab}$.

For all the members of a particular newsgroup, the ordering between sub–newsgroups is aggregated using the maximum likelihood preference ordering procedure described in §6.8.3. This yields an ordering across the newsgroups that is specific to each newsgroup. The newsgroup effectively decides who its neighbours are. If one considers a three thread system, the arrangement of the newsgroups will develop from that given in figure 8.1.

![Figure 8.1: Newsgroups: implied topology](image)

New postings with a group hierarchy

When a subscriber posts a new thread in his own group, it will be sent to the access managers of the groups adjacent to his own group in the preference hierarchy of groups. They can then choose to accept it or not. If they do, then the interested members in the neighbouring groups will post to the new thread and make their group more similar to the thread initiator’s group.
8.1.2 Summary

The preference hierarchy generated decides the order in which the groups refer to one another in figure 8.1. There is an order imposed: when a subscriber posts to both $g_a$ and $g_b$ he indicates that he would prefer to join a group $g_{ab}$.

The access managers are the most frequent message posters to their own groups and they are responsible for vetting the subscribers allowed to join a debate and thus a newsgroup. In this way, very active subscribers to a particular set of threads will find themselves acting as access managers for groups that discuss mostly their sort of interests.

The groups derived from the first set of postings are not tied to discussing debates concerning the subject or subjects they first expressed an interest in. Each group will be constantly redefining itself: both in the subscribers it has and the issues it discusses.

The use of automatic referral between newsgroups adjacent in the hierarchy makes access management easier and allows for the migration of traits. Using the entry group to initiate a thread will be relatively rare.

This system is self-organising in a rather subtle way. The access managers are representative of the subscribers to the group. In the example of a permissions' policy management system, it will be seen that this authority by which subscribers are allowed to join a group can be determined from another preference hierarchy.

8.1.3 The Cultural Model and Stability

Now the self-organising newsgroup system has been defined, a structural isomorphism has to be made to ascertain which entity in the newsgroup system fulfils which function in the cultural model.

When that is done it will be possible to make some predictions about the behaviour of the system using the analysis of the dynamics of the cultural model.

The Cultural Model Referring to Axelrod’s model in §7.1.2 and figure 8.1, the simulation model has only three entities — agents, features and traits. An agent has
a set of features, each feature can take any one of a number of different trait values. (Each trait is therefore an object of a particular feature class.) The set of traits for the different features is the identity of the agent.

\[
\begin{align*}
\text{Agent} & \xrightarrow{\text{has}} \text{SetOfFeatures} \\
\text{Trait} & \xrightarrow{\text{is-example-of}} \text{Feature} \\
\text{SetOfTraits} & \xrightarrow{\text{is-kind-of}} \text{Identity}
\end{align*}
\]

These are equated with entities in the newsgroup system in the following way.

\[
\begin{align*}
\text{Newsgroup} & \xrightarrow{\text{has}} \text{SetOfInterests} \\
\text{Posting} & \xrightarrow{\text{is-example-of}} \text{Interest} \\
\text{SetOfPostings} & \xrightarrow{\text{is-kind-of}} \text{Identity}
\end{align*}
\]

The agents would be the newsgroups referred to in (8.1) not the subscribers. They are located with respect to one another given by figure 8.1.

**Interests as meta–threads as features** One might ask what is an interest in the context of the newsgroups. An interest within a newsgroup manifests itself as a thread of discussion and a thread of discussion is nothing more than a set of related postings — they are related by their common interest. All the newsgroups do have the same set of interests, whether they foster any interest in any particular subset is what the postings determine.

**Distance Function** The access managers of the group and the existing subscribers determine which postings to accept within a newsgroup. The access managers accept new threads, the existing subscribers choose whether to follow them up. Together they act as the distance function does in Axelrod’s model (7.3): The mechanics of the distance function are very different: the access managers and the existing members vote and the maximum–likelihood preference ordering is used to determine which of its neighbours each newsgroup is compatible with.
**Topology**  There are a number of possible topologies for the system. It can be either as in figure 8.1, which for three interests gives each one three neighbours and the central point six. This could be simplified to that given in figure 8.2.

![Figure 8.2: Newsgroups: implied topology with fewer neighbours](image)

This latter topology implies that subscribers to the single interest group only become interested in all three issues after they have become interested in two of them. The number of neighbours is two, three and three for the single-interest, two-interest and every-interest groups. It is a more appealing topology because it gives each agent fewer neighbours and can easily be formed by using a binary tree.

**Dynamics**  The system described in figures 8.1 and 8.2 is not particularly complex. Following the argument given in §7.1.4, if one only allows seven different opinions to be held regarding the preferences across three meta-interests then one need only set \( \#(F) = 3 \) for the meta-groups \( g_a, g_b, g_c \) and have a trait set of \( \#(T) = 2 \). The playing field can have only 7 different newsgroups, using (7.10). This would mean that every subscriber would be allocated to one primary group which could be either a single–, dual– or every interest one.

This is a fairly simply model and it does usually reduce to just two or three varieties regardless of which of the two topologies is used. The more connected graph,
figure 8.1, usually reaches stasis faster. It hardly ever develops a limit cycle. Typical patterns are fairly predictable, whichever variety starting at \( g_a, g_b, g_c \) asserts itself in the middle point \( g_{abc} \) usually asserts itself over at least one other interest, so, for example, if the variety starting at \( g_a \) reaches \( g_{abc} \) first, it might arise that \( g_b \) takes on the same variety so that, effectively, \( a = b \).

**More typical systems** Usually newsgroups will have more than three interests, looking at the *comp.os.linux* hierarchy, the newsgroup administrators were expecting to keep debate focused on about six broad subjects. This is a more complex system, but easily derived using the spanning tree construction of §7.1.4 (which was used for figure 8.2). The size of the playing field would be 62: \( \sum_{i=1}^{6} \binom{6}{i} \). These 62 newsgroups represent all the different shades of opinion there are allowed to be.

With a feature set of \( \#(F) = 6 \), we might say that subscribers have 3 interests (they are hoping to pair the six meta–threads to form the simpler spanning tree), this would give them a trait set of \( \#(T) = 13 \), from table 6.3, if we ask them to state their preferences on the three pairs they have chosen using a weak ordering. This would mean that when re–partitioning the subscribers, the preference ordering would be a chain that is three–ply in length: \( i.e. a > b > c \).

This then gives quite similar parameters to the Axelrod cultural model analysed in chapter 6 and the dynamic behaviour can be expected to be the same.

**A PeerPossible System** Peer-Possible behaviour can be implemented in effect in the newsgroup system. As each subscriber makes a posting, if he is not already a member of the group with the thread, it must be shown that he is a member of a neighbouring group to the one he wishes to make the posting in.

This makes the access managers’ job easier and should lend to the system some of the properties that PeerPossible behaviour was deduced to possess in the cultural model.
8.2 Self–Organising Permissions Policy System

It now remains to apply what has been learnt from the newsgroups example to a system to simplify preference hierarchies for access control systems to produce a self–organising permissions policy system for healthcare.

8.2.1 Newsgroups: Summarised

The newsgroups example had the following similarities to the cultural model.

• The subscribers were not the agents that interacted in the cultural model, but rather the groups that they belonged to.

• The individual subscribers acted as traits for a feature. A group collected members which formed its identity.

8.2.2 Rôle–based Access Control System

Little mention was made in the newgroups example of the target technology for the access control system to the newgroups. In this discussion of the self–organising permissions policy system a rôle–based access control system will be the target technology. This is because it can be adapted to suit all types of access–control system in current use and its information model, §2.4, has the key entities needed to manage the system: the rôles and constraints objects.

8.2.3 Healthcare

Within the healthcare sector, the collegiate organisational model described by Anderson [And96b] applies. Within each college — that is, every clinic or surgery — the security rights are well–defined, but they will almost certainly not be consistent across the colleges.

An example: receptionists in different practices The rights given to receptionist in one general practice may only entitle them to view the records of patients
who are visiting their general practitioner on that day — such a system might be wholly electronic with access policies defined within a relational database that holds all patient records; another surgery may allow their receptionists to see all records of all patients at all times — a paper–based system where the receptionist is given a key to the records room.

The difficulty here is that within their own colleges, the receptionists have been assigned the same nominal rôles, but the rôles have different rights and privileges within each college.

It would probably be the case that the surgery that has the paper–based system needs more trustworthy receptionists because they would have access to so much more information. Consequently, the qualifications and experience of the receptionists would need to be qualitatively better than those of receptionists working in the surgery that has a better protected electronic system. Because these better qualified receptionists are considered more trustworthy, they might be given more rights and privileges in other colleges.

**Simplification of the Rôle Space**

A system administrator, if he were to define this rôle across the practices, would need to know what the rights and privileges associated with the rôles are and the quality of the people assigned the rôle before he can determine who should be given the federal rôle. The system administrator would find it expedient to divide the rôle of receptionist into a number of other sub–rôles. Some rôles would require that an individual assigned to the rôle must meet certain requirements that would give one more confidence that the individuals will be trustworthy.

A rôle, as a data structure, is probably best represented as an ordered pair $\langle r_{\text{initiator}}, r_{\text{acceptor}} \rangle$ — the rôle of the initiator and the rôle of the acceptor. The total number of rôles in the federation is $N_r = \sum_{i=1}^{N} c_i$, where $c_i$ is the number of rôles in each college.

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1 Anderson makes it clear that this scenario is not one that would arise: the receptionist rôle would be constrained to allow only access to records in the receptionist’s own practice. This scenario is though, in miniature, the problem that would be faced in allocating access rights across all parts of the healthcare sector.
one college of the $N$ there are. The total number of federal rôle pairs will be less than $N_r^2$. The hope is that by simplifying them and eliminating the irrelevant alternatives, it may be possible to reduce them to a more manageable number.

**Rôles and Interactions**

When one analyses the operation of the newsgroup system, one sees that each posting to a newsgroup by a subscriber is an interaction between newgroups: the newsgroup that the subscriber belongs to and the newsgroup the subscriber posts to.

Within healthcare, interactions are between individuals in one of their defined rôles: when a general practitioner refers a patient to a consultant, he is known as the *referring physician* and the consultant is the *consulting physician*; within a hospital a doctor present at the treatment of a patient by another doctor is fulfilling the rôle of *attending physician*. There are a number of other such rôles played by physicians within hospitals; these are currently being codified for the proposed HL7 standard [Unk01b]. HL7 also defines rôles that are not medical: administrative, auditing and clerical rôles are also defined.

In addition to the rôles defined within HL7, there are other rôles that do not fall into its remit, but one would expect them to be defined within the federal system: in particular, medical researcher and comptroller.

With regard to the referral process: an interaction takes place when a general practitioner refers a patient to a consultant, whether his referral is accepted or rejected, an interaction has taken place. Similarly, when a medical researcher requests access to a set of records in a database, this constitutes an interaction.

**Distance Measure** The HL7 rôles are already well–defined, they would in fact form part of the distance measure between rôles and would be axiomatic pre–conditions for an interaction.
**Features, Traits and a Data Structure**

Figure 8.3 illustrates a proposed data structure for a patient record. Its design is intended to illustrate an instance of one of the four broad classifications of access that were introduced in §2.1.

They are constituted in the following way using three branches of the patient record tree: *naming*, *history* and *status*. These correspond to synonymous, anonymous and eponymous in the following way. Synonymous information is any combination of facts from the *naming* branch of the tree that would allow a patient to uniquely identified. The anonymous branch, *history*, contains the history of the patient: these records are all of the same type which is generically called *event*. The eponymous branch, *status*, contains summary statements — age group, sex, diabetic, allergies, body–mass index and so forth. It should not be possible to identify a patient uniquely using sets of anonymous and eponymous information. This means that the inference threats that Denning describes in [DSW90] are protected against, probably by a query system enabled in the way Denning describes.

A fourth class of access is synonymous: this is viewed as being knowledge of a set of anonymous facts and a set of eponymous facts, *but* it is also possible to uniquely identify the patient in question. This would be used by another physician to ask the custodian of the patient’s record for additional information. This is typical of the referral process that physicians employ; they initially discuss a patient under an assumed name, passing on what they consider to be salient facts before the consulting doctor assumes responsibility and is told the patient’s identity.

Finally, the reason for choosing a numbered tree structure is that every entity — be it a field or linked historical record — can be given a unique vector relative to the *id*. The type of a linked record is given a unique vector identifier; this is concatenated with the *id* of the record of having the contents. The *id* fields in linked records would be informative. They might specify a date, in which case it would be possible to limit historical access to dates within a range. Essentially, the tree structure is a linked structure of all the normal forms\(^2\) of the records in a database that pertain to

\(^2\)A record is decomposed into a composite record with links to records in other files. Each of
a patient.

Between different rôles under different contexts different views of patient records will be granted. As patient record views are defined they can be compared with one another as trees: when one rôle grants access to another they agree on a standard view; one of those rôles may in a later interaction with another rôle decide that the current rôle is entitled to the same view as the previous one. They may choose to standardise or diverge, but a number of standard representations in different contexts will emerge.

The definitions of anonymous, eponymous and synonymous access will differ for each rôle. Their meanings in each context will be refined and generic types will emerge between rôles.

The set of facts permitted for each class of access constitutes a trait for that feature. This is the first set of features and traits defined for the permissions policy system.

**Ontological Features and Traits**

In addition to the views that are granted between rôles, the context in which the interaction takes place must be defined: these are the ontological features:

**Administrative** Some of these may be administrative: working in the same clinic, the same hospital, health district and so forth.

**Discipline** In healthcare, this would usually be derived from the medical clinic: pædiatric, oncological, genito–urinary and so forth. It may also be derived from affiliations to professional organisations.

**Procedural** The procedure that is being followed. Whether a referral, consultation, prescription, treatment and so forth. Many of these procedures are defined within HL7.

these should be in a normal form which depends wholly upon each primary key for that file; all of fields within the record are either atomic or a link to another record, see [Wie83] for a discussion of normal forms and the construction of database keys. The key would be the id field described in the text.
Figure 8.3: Tree structured patient record with features for classes of access
It may well prove expedient to introduce others.

Inconsistencies and Distance

In more conventional database access control systems, the problem that a security rights administrator faces when a new object is put under his jurisdiction is whether to grant to existing groups rights to access that object or whether to sub-divide those groups to form a new group and grant access rights only to it. The choice is usually determined by whether an inconsistency results: if the right granted to an existing group gives them information that would allow them to compromise the existing group structure then they should not be granted that right. For example, if the right to grant read access is given away too freely, then a number of groups might disappear because they effectively become the same group. Or, it might be the case, that one group is denied access to a object it cannot function without.

For the tree data structure described above, it may prove the case that one individual in one rôle grants access to a view which would make the system inconsistent in a similar way. This can be determined by using the take–grant method of analysis introduced in §3.1.4.

If such an inconsistency would result, then this should contribute to the distance measure and would introduce an axiomatic inferred rule to its evaluation. (One might assign an unbroachable distance to it.)

Another contributing factor to the distance measure might be statistical belief in the authority of an identity. This can be quantitatively stated using the methods proposed by Maurer [KM00, Mau96].

8.2.4 Collective Choice Expert System

The operation of the permissions policy system is that of a collective choice expert system\footnote{This is a relatively new software system, Hubermann’s Beehive system, [HK96], is one such example.}. Whenever an interaction takes place, one rôle grants a data view to another, the cultural model is constructed and is allowed to evolve as a statistical experiment.
to determine how stable it is; a desirable outcome may be specified and a sample of outcomes might lead one to conclude that the proposed data view should or should not be granted, depending on whether it is more or less likely that a desirable consistent configuration would be statistically likely to arise.

**Modelling, Statistical Experiment and Comparison**  The model is constructed using the current attributes of the individuals in the healthcare business sector: their rôles and business relationships are analysed and a set of rôle assignments is made.

The data view is imposed on the model and it is allowed to evolve under stochastic inputs. A sample of evolutions would be used to analyse the behaviour of the system. The trajectory of each cultural evolution experiment would be recorded. The parameters measured for the trajectory would be the variety and compatibility entropies: $S(c)$ and $S(v)$, §7.1.3, their rates of change, their phase difference and the activity of the system. These trajectories of the different samples could be compared to one another. They would also be recorded for comparison with the real system as it evolves.

With this knowledge, it should be possible to show that, for a large enough group of rôles, a degree of stability could be reached and the data views would not allow inconsistencies and that the system could be shown to be near pareto–optimal in moving to its next operational state.

**Final States**  The cultural model statistical experiments will either degenerate and develop an inconsistency or become static or continue to evolve in a limit cycle. All of these outcomes can be determined from an analysis of the cultural model’s global state and statistics of its evolution under the stochastic input. The frequency distribution of stable to unstable outcomes is indicative of the stability of the real–world system.

The state that would normally be considered to be most satisfactory is a static condition, such as that shown in table 7.1, where the majority group is incompatible with all the others, their rôle is isolated, but the other groups are able to continue to migrate views across one another. The majority group here might be the comptroller rôle which is unable to obtain anything more than accounting details in aggregate
from any of the other rôles.

A limit cycle condition may also be a desirable, if the dominant rôles are policy-making ones: high-level custodians such as ethics committees for hospitals and the professional organisations of physicians, as well as representative bodies for groups of accessors\footnote{It may well be the case that cultural systems having limit cycles are exhibiting another behavioural phenomenon examined by Axelrod, the \textit{Tribute} system, \cite{Axe97}.}.

**Dynamics**  Hopefully there will be a similarity in the trajectories of the cultural model evolutions. The rate of change of the entropies and their rate of change with respect to each other is an indicator of when the final state will appear. These metrics may also serve as an indicator of how complex that final state might be.

The rates of change of entropy can be measured in the permissions policy system as it evolves; it might then be possible to show that it is following a similar trajectory to a cultural model experiment.

That cultural experiment could then be re-run with revised starting parameters to see how it evolves. The process of analysis and comparison could be repeated with more statistical certainty.

**Generating Rules**  If it becomes apparent that a large rôle will be dominant and will be isolated from the others then it could be imposed as an axiomatic data view within the system and be enforced through the distance function.

**Second and Subsequent Phases of Resolution**  The process could then be repeated with the large isolated majority group’s rôle eliminated from the cultural model, but its presence within the system contained as a constraint on the distance measure. It would then be possible to repeat the process with another series of cultural model experiments until all of the rôles are clearly defined with respect to one another.
8.2.5 Comparison with Newsgroups Operation

The operation of the newsgroup system was as follows:

- Membership of a group entitled its members to make postings to that group.
- All subscribers belonged to an entry group.
- Subscribers were assigned to the group that they contributed to most often.
- Access Managers determined if a new subscriber could contribute to a group and therefore be a member of it.
- An access manager was given his position within a group because he contributed most often to a group.
- A finite number of interests were assumed to be expressed.
- The length of the preference ordering across those interests determined how many different opinions would be allowed.

In the newsgroup example, only three interests were chosen to make illustration easier and a preference ordering that was only two–ply limited the number of varieties of newsgroup to 7 (of a total of 13). It was seen that it could be easily extended to cover six interests, but the preference ordering was limited in length to three ply, which meant, in effect, that only 62 (of 4683) varieties of opinion were allowed.

The system was bootstrapped by allowing the subscribers to make some initial statements of interest and they were then allocated to a group. After that, they were moved from group to group and groups could refer members to one another.

Access Rights for Rôles  Access rule generation is very similar using the collective choice expert system to assign rôles and define the inter–rôle data views.

- The accessors will be placed in access rôles. These rôles will be the interacting agents of the system. A rôle is entitled to claim certain views from other rôles.
• All accessors will have an entry rôle — unprivileged enquirer.

• Accessors will be assigned to the rôles which would give them the most utility, 
  *i.e.* access to as much information as they can.

• Interactions take place as custodians determine if an accessor can be assigned 
a rôle by determining what data view they may have.

• Custodians will be appointed by the subjects of the views available in a given 
rôle — they are not chosen from the accessors.

• A finite number of ontologies will be allowed to be expressed. The number of 
  plies for the preference ordering of the rôles that accessors have been assigned 
  by the custodians must also be set.

The treatment of the accessors is identical to that of subscribers in the newsgroups 
example. It is the appointment of custodians which is different. Custodians do not
have to be chosen from the accessors, they are already in place.

A very important difference in the operation of the two systems must be made 
clear: in the permissions policy system being a member of an access group does not
entitle the member to use all of the views the other members of the access group have
acquired, it makes it more probable.

An Example of the Bootstrapping Procedure  If accessor *a* makes an access
request for a particular view of a database then if the custodians *C* of that database
view grant the access request, they collectively become the custodians of a rôle created
uniquely for that accessor. Call the access group *C(a)* meaning custodians *C* for *a*.

If accessor *a* makes another access request for a different view, then the custodi-
ans of that data, *D*, are also able to take into consideration *C(a)*. With this, the
custodians could make the following access rule:

\[ x : C(x) \Rightarrow D(x) \]  (8.2)
Re-organisation There is however no explicit need for the custodians to make such a rule explicit because it is already implicit in the system. When the rôles are reorganized, rôles $C(a)$ and $D(a)$ would be merged, because they have no other members, so it just an inconvenience to have them appear distinct, but if another accessor were to be granted access to $C(a)$ but not to $D(a)$ then the groups must be made distinct. This would also imply that there is an ordering between the groups, $C(a) > D(a)$, meaning that membership of $C(a)$ grants more access than $D(a)$.

To fully exploit the implicit rules, it must be possible for the system to accurately compare the trustworthiness of the two accessors without having to call upon the custodians repeatedly. In the newsgroups example, this was achieved in a democratic way by having the access managers of the newsgroup be chosen from the subscribers. In the permissions policy system, the custodians are outside of the system, but are able to compare accessors. As was explained in chapter 2, each accessor would have acquired certificates from other permission policy systems and these could be compared. These other policy management systems would also be able to order the rôles the accessors were members of.

It would thus be quantitatively possible to compare the amount of trust that has been placed in two different accessors based on the rôles that have assigned to them.

Large-scale behaviour The net effect of this procedure will be that accessors will be classified accurately and will be expected to behave in a particular way and they can be reasonably safely compared. This will make the generation of explicit access rules much easier. Explicit access rules will usually be more abstract but essentially of the same form as (8.2). The explicit access rules would in fact be specified in the system’s operation and would take on the character of axioms of the system.

Safety It is the responsibility of the custodians to ensure that accessors do not belong to any access groups which they should not ethically be members of. The self-organising permissions system only simplifies the management of access rights for accessors; it does not itself apply the principle of least privilege. It should not contravene it though. It is therefore important that some meta-data rules be specified
which state a preference ordering across views.

There is an implicit ordering across database views if they were classified as in table 2.1. In more concrete terms, one could say that a view that contains an indication of a subject’s age is more confidential than one that does not and, therefore, anyone who has access to such a view has had more trust bestowed upon them that someone who does not.

**Summary**  It should be apparent now how different permissions policy hierarchies inter-work to generate implicit access rules. The custodians are able to compare accessors by using the permission policy orderings generated in other systems. This is the procedure that underlies much of modern business where it is often required that companies have to prove creditworthiness to one another by using bank statements and asset holdings. The procedures described above simply apply this principle on less quantitative information than money.

### 8.3 Conclusions

It has been seen in this chapter that self-organising systems can be easily specified and designed and should display the useful self-stabilising dynamics of the Axelrod cultural model of interaction. In the following chapter, the permissions policy management system will be discussed in relation to the other requirements given in this dissertation.
Chapter 9

Discussion, Future Work and Conclusion

In this final chapter, the systems described in the preceding chapter will be more critically assessed against the requirements. Future work to validate the concepts discussed in this dissertation will be outlined and a final conclusion on its usefulness will be given.

9.1 Discussion

It has already been made clear that the permissions policy system makes use of other permissions policy systems preference hierarchies to be able to compare accessors against one another. The broad goals of the requirements chapter — the duties of custodians to their subjects — cannot be directly met by this procedure but it does make it possible to detect any infringements by the custodians since they too should conform to a norm of behaviour which could be placed in a preference hierarchy.

An outstanding question is how safe are the decisions that are made. This hinges upon the granularity of the grouping. If there are too many groups, then it will not be possible to establish a reliable norm of behaviour from a preference hierarchy based upon it. If there are too few groups, the preference hierarchy will not be able to
generate enough implicit rules and to produce a useful organisation. It is worthwhile restating the key relationship upon which self-organisation is based.

**Ontologies** The number of ontologies is fixed at the first organisation of the accessors. In the newsgroup example, the number of interests (or meta-threads) was fixed at 3 because that made illustrations easier. It could easily be set to any arbitrary number.

**Variety** Once the number of ontologies has been fixed, one must then decide how much variety is allowed. For the newsgroup example, three ontologies could be combined in seven different ways. But for larger ontologies the number of combinations becomes very large. For the example of six newsgroups, the variety was limited by restricting the number of newsgroups expressed across a smaller playing field of choices. The number of which is given by \((7.10)\). The assumption in this enumeration of choices is that they are grouped by varying degrees of indifference and this leads to a binary tree structure.

The underlying relationship between the topology of agents and the complexity of the preference orderings they hold is the key to understanding organisational phenomena.

In chapter 7, an observation of Axelrod’s in [AAEC96] led to a series of investigations of behaviour, topology of proximity and system size. It was concluded that some topologies gave rise to more stable and predictable behaviours.

In the discussion above, it was made clear that the only configuration parameters for a self-organising permission system seemed to be the size of the issue space and its internal connectedness. A spanning tree leads to systems which can simplify complex issues very quickly. This is the basis of the work carried out by Miller *et al.* [Mil95], but it is well-known from political theory that binary-tree systems can be easily subverted [Bla58, Far69].

To make a system safe, it should not be possible to subvert it, but it is well-known that no collective choice procedure can be fair (and therefore safe) from Arrow’s *Impossibility Theorem*. Arrow gives a possibility theorem, but it may now be possible
to have a confidence level for a collective choice procedure based upon the entropy of the preference hierarchies. What is a significant level of entropy is difficult to decide, but the analysis of evolving cultures shows that it may be the point where the phase reverses between the variety and compatibility entropies of an evolving population.

The design of the self–organising permissions policy system only showed how much interconnectedness is needed to make useful decisions on a quantitative basis about abstract concepts, such as “trustworthiness”.

9.2 Future Work

There are four outstanding problems with the design of self–organising preference aggregation systems:

1. Critical entropy for fair collective choice
2. Topologies for self–organising systems
3. Entropy measure for spectral analysis of votes
4. Cross–certification metrics

The last of these has not been discussed at any length within this dissertation, but it would be fundamental to a high–security system. It requires that different preference hierarchy systems be able to cross–validate one another. There is already a means whereby X.509 certification authorities can validate one another, but they all have the same degree of mutual trust. Recently, research by Maurer [KM00] suggests that this may be quantified reliably.

A prototype database management system has been presented in this dissertation which could make use of X.509 certification, chapter 4, and a practicable system for self–organisation of access was proposed in §8.2. There should be further practical investigation into the following types of system.

- Secure self–organising mailing list
• Licencing, surety and insurance systems

• Permissions policy system based on insurance

The self-organising mailing list has already been presented and it would be a good proving ground for analysing some of the methods described in this thesis. The cross-certification metrics would ultimately have to be based on risk and the evaluation of risk demands that liability can be limited. This would require that licences and sureties be obtainable in the same way as information, \textit{i.e.} electronically. Finally, a self-organising permissions policy system could be implemented using risk as the basis for grading accessors.

Finally, an interpretation of the principles proposed by Anderson [And96a] as economic goals should be made. The system that Anderson proposes for resolving the access decision issues of a collegiate healthcare sector is a widely applicable model of an economic market. They are essentially \textit{fair}, which might imply they are pareto-optimal. A pareto-optimal system cannot be said to exist by Arrow’s impossibility theorem, but Arrow’s analytic choice system is based upon a memoryless system. It may be the case that a pareto-optimal system exists if a best-of-$N$ vote is allowed. There are some interesting games theory scenarios that suggest this may be so [BCP94].

\section{9.3 Conclusion}

This thesis has looked at the problem of providing a secure environment for collaborative computing. This reduced itself to the problem of providing safe and secure access to databases. Secure access is already mature technology, but safe access relies upon access control. This can only be decided with foreknowledge of the information flow. The information flow can only be determined by classifying all subjects and objects within the system. Such an information system would be very large and it could not be reliably managed without using some self-organising technology. This would require an adaptive discretionary control mechanism.
The method proposed in this dissertation would be based on aggregating the information flows specified by different subjects for the objects they own. Such a system has been shown to be self-organising because it is essentially a voter model: these have been analytically proven to be ergodic for one-ply information flows and simulations indicate they are also self-stabilising for an arbitrary number of plys, but take exponential time to stabilise.

It is well worth continuing the investigation of organisational structure using quantitative techniques based on the degree of information flow. This is fundamentally an entropy measure where the degree of uncertainty about an individual’s behaviour is the random variable in a maximum likelihood estimate.
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Appendix A

Glossary

Pareto–optimal An allocation of goods amongst consumers which possesses the property that should any one consumer change his consumption level, then the effect upon all other consumers is undifferentiated, they may all gain or may all lose, but, with respect to one another, they are unchanged. Pareto–optimality can be developed quantitatively \cite{Bal97} and used as a measure of fairness.

Possibility and Impossibility Theorems These have been well–known in quantitative disciplines and are, respectively, the proof of the existence of a mathematical function and its non–existence. In this dissertation, the most important possibility and impossibility theorems are due to Arrow \cite{Arr63}: in which he shows that under a weak–ordering there is a “fair” means of choosing between two different policies, but there is no “fair” means of choosing between three or more policies. The former is a possibility theorem, the latter an impossibility one.

Preference Relations A partially ordered set, poset, where the relations between entities are $>$, $<$, $=$. Whether $=$, used as an indication of indifference, is permitted is a specification of the ordering of the poset. A poset is the mathematical structure best used to represent authorisation chains or lattices, which are fundamental to access control systems.

Strong and Weak Ordering A strong ordering does not permit indifference, only
$a > b$, $b > a$ are valid expressions in a two–policy system; under a weak ordering $a > b, a < b, a = b$ are all valid expressions. A weak ordering is more expressive, less decisive and, because it introduces so many more permutations of preference, harder to analyse.

**Normality** In a statistical context: normality implies that the sum of a set of independent identically distributed random variables will have a aggregate distribution that will tend toward the Normal Gaussian distribution $N(0,1)$ — when properly scaled. This is the basis of statistical quality control and least mean square estimation. A least mean square estimation assumes normality. Normality can usually be assumed when the mean and the standard deviation are related as in the Tchebysheff inequalities.

**Maximum Likelihood and Entropy** Maximum likelihood is a method of statistical analysis which can be used to fit data to frequency distributions where the sample mean is not normally related to the population mean. It is consequently “non–linear” because it cannot make the assumption that the relation between the mean and the standard deviation that the Tchebysheff inequalities require. Essentially, the underlying probability distributions are either not independent or not identical or both. It is possible to decompose many probability distributions based on posets into the sum of a set of uniformly distributed indicator probability distributions. This then allows one to assume that all constituent probability distribution functions are sufficiently similar that only interdependence cannot be disregarded.

**Maximum Likelihood Preference Relations** An aggregation of similarly formed — weakly or strongly ordered — preference relations of voters is said to be maximally likely if the hamming distances between each and every set of individual preference relations with respect to the aggregate is symmetrically distributed.

---

1 See [Pap84], pp. 540.
2 See [Pap84], pp. 535.
3 See [Pap84], pp. 540 and pp. 113. Non–linearity is an artifact of the form of the moment–generating function’s.
Preference relations of the individuals in a population of voters on issues are usually not formed independently from one another. Consequently, the techniques of statistical estimation based on normality are not valid. Thompson and Remage [TR64] developed a method for determining maximum likelihood preference relations.

**Entropy or negentropy** Originally developed as a statistical measure of the order within a system; most famously embodied by Schrödinger in his function giving the quantum energy available within an atomic nucleus. This statistical measure has since been applied fruitfully in many fields and is the basis of information theory developed by Shannon. The most pertinent applications of entropy for this dissertation are topological entropy [AKM63] and maximum likelihood estimation [TR64]. Within information system design, entropy can be thought of as the degree of confusion within the system. This manifests itself in an information system when it becomes less and less decisive [SBM97]. Irrelevant alternative policies proliferate introducing instability: behaviour is not conventionally predictable — it cannot be assumed to be statistically deterministic or markovian.

**Collective Choice Expert System** An information system designed to aid group decision–making. A collective choice expert system would have many of the same functional requirements as a conventional expert system — the ability to provide a justification and determinacy under the same fact set, for example [Unk01a]. It would be developed as a cross–disciplinary study of decision theory [Fis91], information theory, games theory and information technology.

**Access Control Systems** There are variety of these: mandatory access control, lattic–based access control and discretionary access control mechanisms. All of these systems are modelled to comprise objects, which are accessed, and subjects, who access them. Each access attempt is mediated and a decision as to whether access should be granted is based upon a lookup in an access control matrix.
Mandatory  Under mandatory access control. Each object has a pre-defined access control matrix, each operation, (read, write, execute etc.) is a row, each subject has its own column, but subjects are defined in a linear hierarchy, so that the form of the matrix can be made upper-triangular. Objects can be similarly organised into an hierarchy.

Lattice-based Is an extension of mandatory access control. The subjects and objects are arranged in a tree hierarchy and the access control matrix used to determine access is formed from the least-upper bound of the subject and the object in the tree hierarchy.

Discretionary This is the most flexible and the most common access control mechanism. Subjects are allowed to grant access rights to other subjects for objects they own. The access control matrix is constructed as the system operates.

Role-based Access Control Systems These were formalised by Sandhu [San98]. They differ from other access control mechanisms because they have a more sophisticated information model: rather than just have subjects and objects, rôle-based systems allow subjects to take on a number of rôles simultaneously within a session and a rôle is a defined interface onto an object. These constructs allow some of the vagaries of discretionary access models to be more precisely specified and managed. In particular, it is possible to define a different rôle for a subject when she administers the access rights of objects she owns, when she uses an object of her own and when she creates and destroys them. Sandhu presents a number of rôle-based systems which provide mandatory access control, lattice-based and discretionary systems.

Collegiate Structure Used by Anderson [And96b] to describe the organisation of the healthcare sector with respect to the allocation of access rights. Rights allocated within one college for a particular rôle are respected in other colleges. This is achieved by mapping a rôle defined within one college to a different rôle within another. This requires a federal superstructure that defines the rôles
and fairly administers them. Anderson argues that although individual colleges may apply any access control scheme they wish, the federal system will be a discretionary one: it is argued in this dissertation that the discretionary access model used within the federation will be a rôle–based model with constraints: rôles defined within each will map to a set of abstract rôles within the federation.

**Rôle–based access control with constraints** Rôles provide a convenient means of implementing constraints which are context–sensitive. These constraints can be used within collegiate structures of access systems. For example, general practitioners are entitled to prescribe drugs to any member of the general public; but a receptionist working in a general practice, although able to access medical records for patients within her own practice may not access medical records for patients in another practice. The general practitioner rôle has the right to prescribe in any general practice — an unconstrained permission; the receptionist rôle only has the right to inspect records in her own practice — a constrained permission.

**Custodian, Subject, Accessor and Owner** Rôles that are defined within the federal superstructure of a collegiate structure of organisations. These are abstract rôles which are used to define the relationships between members of different colleges. A preliminary information model is given in §2.5. In the example of a general practitioner prescribing drugs and a receptionist accessing records: the general practitioner is acting as an owner, creating drug prescription records which are then associated with subjects who have custodians. The receptionist of the general practitioner acts as an accessor, but is constrained to only those subjects’ records the general practitioner she works for is the custodian of.

**Ontologies** Within a collegiate access control structure, ontologies are the naming systems used to define objects and subjects and define what rôles subjects can take and objects can offer. An ontology must be respected within two colleges before rôles in each college can be aligned to a rôle with federally defined constraints. In the general practitioner and receptionist example, the doctor’s
right to prescribe is federal, the receptionist’s right to interrogate a record is only enforceable in her own college. An example of an ontology in a field outside of medicine might be the Library of Congress cataloguing system. Within medicine the classification of diseases by the World Health Organisation is such a universally recognised classification system. Other classifications such as those developed for hospital administration — the HL7 attribute model — will prove invaluable in establishing a common understanding of rôles across medical specialities.

**Federation** A concept similar to the collegiate structure proposed by Anderson, but used in the discussion of the design of information processing systems [ISO95b].

**Institutional Design** A branch of quantitative political science that aims to produce a set of government institutions which are optimal for the operation of a federation of entities submitting to a collective will. The methods of institutional design can be used to produce constitutions which specify the institutions of government [Kni92], whether they are collectively–managed (a cabinet) or solely–managed (a president’s office). Other codes of practice that are considered are: federal and state inter–relationships; bi–camerality; requirements for holding office; rights of appointment and right of veto to an appointment; duration of office and sequencing of elections; requirements for rescinding an appointment. Modal logics, in particular deontics, have been used to analyse ways in which institutions interact [BC90, RL95]. Econometric analysis and adaptive systems have been developed which show that different institutions emerge given different conditions [Tie56, KMP95], but a consensus forms around meta–norms of what are considered irrelevant alternatives. In this dissertation, it is hoped that a properly designed set of deontic interaction protocols can be used to *evolve* a fair federal superstructure for a collective access control system.

**Irrelevant Alternatives** In the theory of collective choice, this is one of the susceptibilities a collective choice function may suffer from. The problem is that the presence of a particular policy generates confusion over the ordering of is-
sues. This is, it is argued, the principle *confusing* factor in the operation of an information system and can be thought of as an increase in the disorder, the entropy, of the system.

**Entropy and Consensus** One of the difficulties in collective choice is that an aggregate social choice of $a = b$ may indicate either most individuals have stated $a = b$ or that many individuals have chosen $a > b$ and an equal number $b > a$. In the former, where $a = b$ is the choice of many, there is a consensus and, in a statistical experiment of selecting one voter and comparing his choice to the social choice, the outcome is predictable, so entropy is low, the system is highly-ordered. In the latter, where an equal number have chosen $a > b$ and $b > a$, the outcome is not predictable, the system not highly ordered. Low entropy indicates a high degree of order, and therefore consensus, within a population.

**Colliding Particle Systems** A useful model for the operation of a complex system originally developed to solve problems in statistical thermodynamics. The model of the system is of interacting particles which exchange some quantity between themselves. Heat conduction is a well-documented area in which this model is used. Colliding particle systems can be either consonant: the particles collide and become more like one another; or dissonant: colliding and becoming more unlike one another. In consonant systems, entropy decreases, the system becomes more ordered and may stabilise; in dissonant systems, entropy increases and the system is unlikely to find a stable state that is not some kind of limit cycle. In this dissertation, the colliding particle model is used as the basis for the simulation of the evolution of cultures: cultures that evolve around different norms of behavior — norms of behaviour for the use of medical records. Analysis of colliding particle systems is very difficult \cite{Mat77}; consequently, *Monte Carlo* simulations using cellular automata are often more insightful in real systems.

**Cellular Automata** Originally proposed by von Neumann \cite{VN66}, these computational entities are now part of the field of evolutionary computation, see for
example [MD94]. An intuitive description of the different methods of evolutionary computation can be found in [Dav91], a précis of which follows: the problem a statistician faces, in curve–fitting to empirical data, is comparable to finding the highest point in Australia using only kangaroos (sic).

**steepest ascent** requires that the statistician trains the kangaroos to climb the steepest obstacles the kangaroos find themselves presented with.

**simulated annealing** asks the kangaroos to do the same, but under the influence of alcohol, the effects of which wear off gradually.

**genetic algorithms** asks the kangaroos to find high places; they are expected to interbreed and migrate. The algorithm periodically culls all those kangaroos below a certain altitude.

**cellular automata** Following this analogy, one could argue that the cellular automata method operates in the same way as a genetic algorithm, but, as well as interbreeding, the kangaroos cull one another, with success more likely for those who live uphill. In this dissertation, a cellular automata playing field is developed which measures the degree of homogenisation within a consonant colliding particle system — of very simple kangaroos whose interaction protocols are defined within complete a modal logic.

**Modal Logic and Kripke’s semantics** A modal logic introduces to first order existential logic a degree of relative existence — a statement of prepositional logic shows that something exists, a statement in modal logic says that something exists somewhere. Modal logics are widely used within computer science. Stirling [Sti95] has developed a temporal modal logic which can be used to determined if a state exists at a certain point in the execution of a program. A modal logic is the basis of one of the most useful methods of formal proof of authentication protocols [GNY90], which concerns itself with the relative position of secrets at different points in the execution of a protocol. Recently, authorisation mechanisms have been based on modal semantics [ABLP91, Dul01]. The Kripke semantics [Kri63] provide a more intuitive way of visualising modal
systems that can be more easily applied to distributed systems: the semantics are of a connected graph, where a modal truth is immediately recognised as an existential truth possessed by a neighbour node in the graph. The two modal systems described in this dissertation are egoistic and peer pressure. Both of these have very precise Kripke representations and have been implemented, operated and evaluated in a common programming language.

**Egoistic interaction protocol** This protocol is used within a cultural playing field to form a consonant colliding particle system. A cellular automaton accretes a characteristic that one of its neighbours possesses only if a Hamming distance measure reports they are already relatively consonant. Egoistic systems converge rapidly; rarely fall into limit cycles; but their final state is not readily predictable from their initial one. Within modal logic they can be characterised as permissive. An egoistic interaction protocol allows each cellular automata to evolve a norm of behaviour. Similar automata emerge and their norm of behaviour becomes more common.

**Peer Pressure** This is an alternative to an egoistic interaction protocol. A cellular automaton accretes a trait from a neighbour, only if another neighbour possesses the same characteristic. Peer pressure systems are slower to converge; often fall into limit cycles; but seem to be easier to predict than egoistic ones. Within modal logic they can be characterised as permissive, but a peer veto is respected. A peer pressure protocol forces cellular automata to evolve a norm of behaviour in the context of a meta-norm of behaviour enforced by their peers.

**Norms and Meta-norms** These are best explained with an example: the tragedy of the commons. In Britain, after the acts of enclosure, most villages were given a piece of land which was a common grazing area. There were no explicit regulations that limited the amount of grazing a particular farmer could do on the common land. The norm of behaviour that emerged was to graze as much as one could, because someone else was almost certainly going to do the same. Consequently, common grazing land was constantly overgrazed and
quickly became a liability: the tragedy of the commons. If a punishment system is introduced, but there is no obligation to punish, then systems emerge which either punished a great deal or not at all, but were still unfair in the use of the common land. If a further punishment were introduced which allowed farmers who did not punish to be punished for not doing so, then and only then did a system emerge which achieved a degree of fairness in the use of the common land. Systems display one of three emergent properties [Axe97]:

- Overgrazing with very little informing — farmers mutually agree to not make use of the punishment system.
- Unfair grazing with much informing — farmers who overgraze a lot punish farmers who overgraze a little.
- Fair grazing with little informing — farmers seem to respect one another and do not overuse the punishment system — this meta-norm emerged only when the secondary punishment was introduced.

In the cultural playing field model developed in this dissertation, the meta-norm is enforced by the interaction protocol, which is either an egoistic one or one that is subject to peer pressure.
Appendix B

Aidan Project Software System

B.1 Aidan Project Software System

This appendix describes the software that was prototyped as part of the Aidan project. The project’s goals appear at [ECJT95]. The software used and developed is archived on CD-ROM.

Software Documentation

1. A Process is an instance of an application program.

2. If a something is a prototype, it is under development and may only have a skeleton implementation.

3. Classes, and objects, are marked in the following manner:

   - Imported Style: when the implementation has been imported, it is a standard Java or Jigsaw object, or class for an object, then it is marked thus: ▼ Database-Manager.
   - Exported Style: when the implementation can be exported, it has been developed for the Aidan project, ▼ Database-Manager.

This should help in finding documentation for the classes. There is no documentation for exported classes.
4. Attributes are marked in the following manner: \texttt{Age}. There are some properties that attributes can possess.

- **class**: This type of attribute belongs to the class and there is only one instance of it for all objects instantiated from that class.

- **object**: This type of attribute belongs to each object and each object has an instance of it.

- **persistent**: This type of attribute can be either class or object and indicates that the attribute can store its changed value on destruction of the object or unloading of the class.

5. Environment variables are presented thus: \texttt{CLASSPATH}, and can have mixed case.

### B.2 Application Programs and Their Configurations

#### B.2.1 Web-server

The web-server used was \textit{Jigsaw} [Jig]. On-line documentation is available. The following are outputs of the configuration information obtained by printing the \textit{Jigsaw} frames.

1. Version Information, see figure [B.1].

2. \textit{Aidan} Directory Resource, see figure [B.2]

   - \texttt{Putable} is the directory containing the results of user enquiries. One directory for each user.

   - \texttt{QueryByName} is the only database enquiry resource. It allows queries to be submitted to the database using surname and, optionally, a fore-name.

   - \texttt{Reference} is an unused directory resource.
### Attributes of General

|   | w3c.jigsaw.http.GeneralProp |
|---|----------------------------|
| identifier: | general |
| w3c.jigsaw.server: | Jigsaw/1.0a5 |
| w3c.jigsaw.checkSensitivity: | true |
| w3c.jigsaw.root: | /user/eepg/eepgwde/src/java/Jigsaw/Jigsaw |
| w3c.jigsaw.host: |   |
| w3c.jigsaw.port: |   |
| w3c.jigsaw.root.store: | true |
| w3c.jigsaw.root.name: | root |
| w3c.jigsaw.publicMethods: |   |
| w3c.jigsaw.trace: | true |
| w3c.jigsaw.docurl: | /User/Reference |

|   |   |
|---|---|
| w3c.jigsaw.resources.DirectoryResource: |   |
| Putable: |   |
| QueryByNames: |   |
| Reference: |   |
| ResourceAdder: |   |
| UserRepository: |   |
| eg-1.html: |   |
| ladies.html: |   |
| new.html: |   |
| tester.html: |   |

|   |   |
|---|---|
| w3c.jigsaw.resources.DirectoryResource: |   |
| Putable: |   |
| QueryByNames: |   |
| Reference: |   |
| ResourceAdder: |   |
| UserRepository: |   |
| eg-1.html: |   |
| ladies.html: |   |
| new.html: |   |
| tester.html: |   |

### Table B.1: Version Information

### Table B.2: Aidan Directory Resources
- **UserRepository** This is the database that contains the names of all the legitimate Aidan users and control information about them.

- **ResourceAdder** is a prototype resource that is intended to allow different database resources to be added and generate a new **QueryByNames**.

- The files suffixed HTML are test files and can be ignored.

3. **QueryByNames** Resource, see figure [B.3](#).

| Attributes of QueryByNames Resource | Aidan |
|-------------------------------------|-------|
| Parent: Aidan                        |       |
| Resource url: /Aidan/QueryByNames    |       |
| identifier: QueryByNames             |       |
| quality: 1.0                         |       |
| title:                               |       |
| content-language: text/plain         |       |
| content-encoding:                   |       |
| content-type: text/plain             |       |
| last-modified: Sat Dec 05 17:38:00 GMT+0 1997 | |
| icon:                               |       |
| maxage: false                        |       |
| filename:                            |       |
| putable: false                       |       |
| override: false                      |       |
| convert-get: true                    |       |
| DatabaseURL: jdbc:postgres95://h2ws-03.brunel.ac.uk/aidan;user=eepgwde | |
| View: select * from patients_view    |       |
| Owner: eepgwde                       |       |
| Table Caption Fields: SURNAME FORENAMES |       |
| Table Title Fields: SURNAME DATE_OF_BIRTH FORENAMES | |

Table B.3: Database Enquiry Resource

- **aidan.jigsaw.AidanQuery** is the name of the class on the **CLASSPATH** of the Java compiler.
• **Resource url** is the location of the resource relative to the root of the HTTP server.

• **DatabaseURL** this is the resource locator for the database. This is a relatively rare form of URL and can be read as follows: use protocol “JDBC” with sub-protocol “Postgres95” on host “h2ws-03.brunel.ac.uk”, use database “aidan” and operate under user “eepgwde”. A password could also be passed.

• **View** This is the view that will be used by object, when instantiated.

• **Owner** Owner of this class.

• **Caption Fields, File Title Fields** These are used for formatting the output.

• Other attributes are inherited from the superclass and are either generated automatically or can be left unspecified.

4. **UserRepository** Resource, see figure B.4.

• **aidan.jigsaw.UserRepository** is the name of the class on the CLASSPATH of the Java compiler.

• **Table** This the table containing the user information.

• **RealmDirectoryName** This is the name of directory that will contains the directory having the name UsersDirectoryName.

• **UsersDirectoryName** This the name of the directory that the will contain users’ directories.

• **headers** These are accessible but currently are not used.

• Other attributes are as for ▼ **QueryByNames**.

5. **filter-0** Resource, see figure B.5. This is a class that, when instantiated, can be used to provide filter requests using the basic authentication method of HTTP.

• **group** This is the name of a group within the realm.

• **realm** This is the name of the super-group.
### Attributes of UserRepository

| Attribute          | Value                                                                 |
|--------------------|----------------------------------------------------------------------|
| Parent             | Aidan                                                                |
| Resource url       | /Aidan/UserRepository                                               |
| identifier         | UserRepository                                                       |
| quality            | 1.0                                                                  |
| title              | Database Resource Listing Aidan Users                               |
| content-language   | en                                                                   |
| content-encoding   |                                                                      |
| content-type       | text/html                                                            |
| last-modified      | Sat Dec 06 17:49:59 GMT+0 1997                                       |
| icon               |                                                                      |
| maxage             |                                                                      |
| DatabaseURL        | jdbc:postgres95://h2ws-03.brunel.ac.uk/aidan;user=eepgwde            |
| Table              | users                                                                |
| Owner              | Walter.Eaves@brunel.ac.uk                                            |
| RealmDirectoryName | Aidan                                                                |
| UsersDirectoryName | Putable                                                              |
| Realm              | Aidan                                                                |
| headers            | user-agent accept referer Authorization ChargeTo                    |

Table B.4: Database of Users

### Authorisation Filter

| Filter          | Value |
|-----------------|-------|
| filter-0        |       |
| Parent          | root  |
| w3c.jigsaw.resources.DirectoryResource |       |
| Identifier      |       |
| realm           | Aidan |
| shared-cachability | false |
| private-cachability | false |
| public-cachability | false |
| users           |       |
| groups          | main  |

Table B.5: Authorisation Filter
• Other attributes are as not, as yet, relevant.

6. eepgwde is an instance of the user class used by the GenericAuthFilter. Figure B.6 just illustrates that user information can be edited remotely. Users are added to a realm, so the realm information for this user is known.

| Attributes of eepgwde |       |
|----------------------|-------|
| identifier:          | eepgwde|
| email:               | Walter.Eaves@brunel.ac.uk|
| comments:            | Researcher|
| ipaddress:           |       |
| password:            |       |
| groups:              | main  |

Table B.6: A user account

• ipaddress Users can be limited to logging on from a web-browser running on a particular machine — or through a particular firewall proxy host.

• groups The groups to which the user belongs.

• Other attributes are self-evident.

B.2.2 Database

Databases are added in the same way as other resources.

B.2.3 JDBC Driver

JDBC drivers are added as resources as well.
Appendix C

Relations

These definitions are mostly from [GKH77], except the some of the relation types which are from [Aqv84].

Definition C.0.1 (Relation). A relation $R$ on a set $S$ is a set of ordered pairs of elements of $S$. If $(a, b) \in R$, one also says that $R$ holds for the ordered pair $(a, b)$ and sometimes one writes $a R b$.

Definition C.0.2 (Support, Range, Domain).

Supp $S \triangleq \{ x \in S | (x, y) \in R \text{ for at least one } y \text{ in } S \}$  
(Range)

Ran $S \triangleq \{ x \in S | (y, x) \in R \text{ for at least one } y \text{ in } S \}$  
(Domain)

Dom $R \triangleq \text{Supp } R \cup \text{Ran } R$  
(Domain)

Dom $R \subseteq S$

Definition C.0.3 (Simple Types of Relations). These are standard definitions of a relation $R$. The variables $x$, $y$ and $z$ range over a non-empty set $W$. The statement $x R y$ means that the the tuple $(x, y)$ exists in the relation $R$. The symbols $\lor$ and $\land$ are logical symbols meaning disjunction and conjunction of the logical existence conditions (not of underlying sets). $\neg$ means non-existence. Order of operators is
(highest) \(\neg\), then \(R\), then \(\lor\) and \(\land\).

\[
\forall x \exists y (x R y) \quad \text{(Serial)}
\]

\[
\forall x, y, z (x R y \land y R z \Rightarrow x R z) \quad \text{(Transitive)}
\]

\[
\forall x, y, z (x R y \land y R z \land x \neq z \Rightarrow x R z) \quad \text{(Weak Transitive)}
\]

\[
\forall x, y, z (x R y \land x R z \Rightarrow y R z) \quad \text{(Euclidean)}
\]

\[
\forall x (x R x) \quad \text{(Reflexive)}
\]

\[
\forall x (\neg (x R x)) \quad \text{(Irreflexive)}
\]

\[
\forall x, y (x R y \Rightarrow y R y) \quad \text{(Almost Reflexive)}
\]

\[
\forall x, y (x R y \Rightarrow y R x) \quad \text{(Symmetric)}
\]

\[
\forall x, y (\neg (x R y \Rightarrow y R x)) \quad \text{(Asymmetric)}
\]

\[
\forall x, y (x R y \land y R x \Rightarrow x = y) \quad \text{(Anti-symmetric)}
\]

\[
\forall x, y, z (x R y \Rightarrow (y R z \Rightarrow z R y)) \quad \text{(Almost Symmetric)}
\]

\[
\forall x, y, z \exists w (x R y \land x R z \Rightarrow y R w \land z R w) \quad \text{(Incestuous)}
\]

\[
\forall x, y (x \neq y \Rightarrow (x R y \lor y R x)) \quad \text{(Connected)}
\]

\[
\forall x, y, z (x R z \land y R z \Rightarrow x = y) \quad \text{(Left Unique)}
\]

\[
\forall x, y, z (x R y \land x R z \Rightarrow y = z) \quad \text{(Right Unique)}
\]

It might appear that, in effect, a Euclidean relation is the same as a transitive. This not so. For a group of three, \(X\), \(Y\) and \(Z\), with an initial topology that \(X\) can see \(Y\) and \(Y\) can see \(Z\), then for a transitive relation \(X\) must be given a view of \(Z\) as well; for a Euclidean relation there no change is needed.

If \(X\) can see \(Y\) and \(Z\), then to be Euclidean, \(Y\) must be able to see \(Z\) and \(Z\) must be able to see \(Y\). For a transitive relation no change would be needed.

**Definition C.0.4 (Equivalence Relation, Partition, Class).** An *equivalence relation* on a set \(S\) is a relation that is reflexive, symmetric, transitive and has a support \(S\) — also just reflexive and Euclidean. An equivalence relation \(R\) on \(S\) induces a partition of \(S\) into classes, which consist of those elements between which the relation
holds. A partition if a set $S$ is a family $P$ of non-empty subsets of $S$, called the classes of the partition, with the following two properties:

1. Any two distinct classes are disjoint

2. Every element of $S$ line one class

**Definition C.0.5 (Quasi-, Partial and Total Ordering Relations).** A relation $R$ on a set $S$ is called a quasi ordering on $S$ if $R$ is reflexive and transitive; partial if it also anti-symmetric and, if $R$ is also connected, it is called a total or linear ordering.
Appendix D

Current Technology

D.1 Distributed Processing

D.1.1 Computational Design Guidelines

These are common design guidelines, which one should bear in mind when considering how set of entities in a system interact. Protocols are designed at a computational level, but usually must consider the engineering and technological dimensions.

Any emphasised phrases, such as binding, are defined in [ISO95a].

Domains (or Paradigms) A client or a server is a computational object that represents an end-user in a processing domain. A processing domain is determined by the resources it uses. A “costed” domain — access to objects is costed — uses money; a confidential domain uses keys — access to objects is granted on presentation of a key. The computational object is an abstract object that behaves in a certain way in one domain. Where it is located is an engineering issue, how it is implemented is a technological issue. The computational object has to resolve the engineering and technological conflicts in the computational domain before performing a computation in its own domain.

Properties This is the set of properties that clients and servers are defined by.
**Association** A binding between client and server. At a high-level it may be something like an account number, which both share. At lower-levels, cryptographic keys and session numbers. Goodness of maintaining associations means that the client or server can be relied upon to instantiate a binding without have to create it again. The most important entities shared between clients and servers are names.

**State** A binding with the environment. It may include all previous associations if the object having this state is operating under a name that has existed before. The environment binding is usually the end-user (for clients) and is effectively the identity of the end-user in processing system domain. Goodness of maintaining state means that the clients or servers can be relied to have the same state from instantiation to instantiation in the domain. There is an initial state which exists prior to an object making any bindings. There is often a default state which usually forms the initial state.

**Interface** A means of accessing an object that may change the state of an object. Interfaces are expected to be invariant if the implementation changes.

**Implementation** A piece of technology that implements the expected behaviour of an interface.

**Role** If an object provides an interface, it assumes a role in a system, which is a prescribed behaviour.

**Autonomy** An object that is autonomous is accountable for its behaviour to itself alone. An object that is not autonomous has at least one controller. It is generally desirable for that object to have just one controller — to avoid conflicts in policy.

**Relocation** If an entity relocates, it moves from one environment to another. This is rarely done while computations are in progress, but it may be demanded in some domains.
Clients  Observations about the nature of clients. Clients . . .

1. outnumber servers.
2. are technologically heterogeneous in implementation.
3. do not align implementations with one another.
4. do not align interfaces with servers or with one another.
5. are autonomous.
6. freely relocate.
7. are specific to a user not one role.
8. have at least two roles: user as personal role, user in professional role.
9. are bad at maintaining state.
10. are bad at maintaining associations.

Servers  This is a set of observations, which one would hope a server should comply with. Servers . . .

1. are less numerous than clients.
2. are technologically less heterogeneous
3. do align implementations with one another
4. must align interfaces with one another
5. perform a specific role.
6. are not autonomous.
7. are good at maintaining state.
8. are good at maintaining associations.
Agents

Are essentially servers to clients and clients to servers. The point of an agent is to group clients and couple them to servers. Agents . . .

1. can be as numerous as clients.
2. are technologically less heterogeneous than clients.
3. have two roles: server to the client and client to a server.
4. are not autonomous.
5. are bad at maintaining state when acting as a client, because they track their clients, but are good at maintaining state for their clients.
6. are good at maintaining associations.
Appendix E

Graph–Theoretical Treatment of Preference Lattices

This appendix describes how preference lattices can be represented with graphs. It follows the treatment given by Miller in [Mil77]. Only the descriptive parts of Miller’s text is used. His treatment is based on that given by Harary et al. [HNC65]. It also refers to Christofides’ compendium of algorithmic methods [Chr73] and to Skiena’s very practical treatment [Ski90] for use with Mathematica [Wol99], which was used to test some of the methods employed. Skiena’s nomenclature is used for Miller’s descriptions.

E.1 Definitions

Definition E.1.1 (A Digraph and its Components). A directed graph or digraph is a collection of “points” — also nodes or vertices — and of “directed lines” — also arcs or edges — between these points. A graph that allows a number of edges between vertices is a multi–graph and the directed form is a multi–digraph.

Vertices $V$ is the set of vertices, \{x, y, \ldots, z, t, \ldots, w\}.

Edges $E$ is the set of edges, which are expressed as tuples between vertices: \{(x, y), \ldots, (t, u), \ldots, (t, w)\}. 
Definition E.1.2 (Domination). If there is a directed edge from vertex \( x \) to vertex \( y \), this can be written: \( x > y \), \( x \to y \) or \( \vec{x}y \); and one says that \( x \) dominates \( y \).

The set of all vertices that \( x \) dominates is written \( D(x) \).

A vertex \( x \) is undominated if no other vertex dominates it.

Definition E.1.3 (Paths, Cycles and others). Some common definitions:

- **Path** is a sequence of vertices and directed edges from vertex to another: \( x \to y \to z \to \cdots \to t \). The length of the path is also called its cardinality. A path of cardinality zero is a path from the vertex to itself and is also known as a self-loop.

- **Complete (or Hamiltonian) Path** includes all the vertices in a digraph.

- **Reachable** A vertex \( y \) is reachable from another vertex \( x \), if there exists a path from \( x \) to \( y \). Associated with each vertex is a reachable set, the set of all vertices that can be reached from that vertex.

- **Source** A vertex \( x \) is said to be a source if every other vertex is reachable from \( x \).

- **Sink** A vertex \( x \) is said to be a sink if every other vertex can reach \( x \).

- **Cycle** A pair of paths are said to form a cycle if, for a pair of vertices, \( x, y \): \( y \) is reachable from \( x \) and \( x \) is reachable from \( y \).

- **Complete Cycle** is a cycle that visits all the vertices of the graph.

- **Semi–path** is a path if the graph were undirected. That is, some of the directed edges point the wrong way, \( \text{viz. } x \to z \leftarrow v \to y \) is a semi–path from \( x \) to \( y \).

- **Semi–cycle** is a pair of semi–paths from one vertex to another and back.

  NB. If there is a path from \( x \) to \( y \), \( x \) only dominates \( y \) if the path has one edge, \( i.e. \) the two nodes are adjacent.

Definition E.1.4 (Types of Digraph and their properties). Definitions of common properties of graphs and digraphs:
**Connected** a digraph is said to be *connected* if there exists a semi-path between every pair of vertices.

**Tree** a digraph is said to be a *tree*, if it has one source and no semi-cycles or, equivalently, one vertex is undominated and every other is dominated exactly one.

**Complete** a digraph is *complete*, if every vertex is adjacent to every other.

**Asymmetric** a digraph is *asymmetric*, if for every pair of vertices, $x$ and $y$, if $x \rightarrow y$ then not $y \rightarrow x$.

**Tournament** is a digraph that is both complete and asymmetric.

**Transitive** a digraph is *transitive* if, $x \rightarrow y$ and $y \rightarrow z$ it is also true that $x \rightarrow z$.

**Strong Ordering** If graph is transitive and has no cycles, it is a *strong ordering*.

**Definition E.1.5 (Indifference).** In addition to specifying that one vertex dominates another, it is possible to specify that a pair of vertices do not dominate one another, by stating that one is jointly indifferent to them: $x = y$.

Indifference is symmetric and a graph that is transitive, has no cycles is a *weak ordering*.

**Definition E.1.6 (Partially Ordered Set or Partial Order).** If a set of elements is in some way ordered, then the set is *partially-ordered*.

The set can be represented as a graph and may prove to be either strongly or weakly ordered.

**Definition E.1.7 (Transitive Closure).** The *transitive closure* $C(G)$ of a graph $G$ contains an arc $\{u, v\}$ whenever there is a directed path from $u$ to $v$ in $G$.

Graphs can be simplified by condensing them. Usually, the condensation takes sets of connected vertices and treats them as one vertex.
Definition E.1.8 (Condensed Graph). A condensed graph reduces a set of vertices to one “super-vertex”.

Definition E.1.9 (Independent Set). An independent set of a graph is a subset of the vertices such that no two vertices in the subset represent an edge in the graph. The maximum independent set is a maximal set of vertices that meet this criterion.

E.2 Conditions and Deductions

Theorem E.2.1. A digraph with no undominated point has a cycle.

Theorem E.2.2. Every tournament has at least one complete path and every tournament has an odd number of such paths.

Theorem E.2.3 (Decomposition of Partial Orders). For any partial order, the maximum size of the anti-chain equals the minimum number of chains which partition the elements of the partial-order [Di50].

E.3 Representations

E.3.1 Illustration

A set of preferences, see table E.1 can be mapped to a directed graph, see figure E.3.1, if indifferent then no arc, except for each policy with itself, i.e. the central diagonal. The figure contains three individual acyclic graphs which under simple majority rule form a cyclic graph for the society. Each diagram is a transitive closure of the preference relations.

\[^1\text{Ski90} \text{ p. 242.}\]
Table E.1: Preferences

| Voter | Ranking       |
|-------|---------------|
| A     | $a > b > c$   |
| B     | $b > c > a$   |
| C     | $c > a > b$   |

Figure E.1: Preferences as Graphs
E.3.2 Adjacency Matrices

Each one of the individual’s graphs can be transformed to a matrix representation using an adjacency matrix\(^2\), which simply states if two vertices are connected by a directed edge. For the graphs of figure E.3.1 these are:

\[
F_A = \begin{pmatrix}
1 & 1 & 1 \\
0 & 1 & 1 \\
0 & 0 & 1
\end{pmatrix},
F_B = \begin{pmatrix}
1 & 0 & 0 \\
1 & 1 & 1 \\
1 & 1 & 0
\end{pmatrix},
F_C = \begin{pmatrix}
1 & 1 & 0 \\
0 & 1 & 0 \\
1 & 1 & 1
\end{pmatrix}
\]

E.3.3 Transition Matrices

The system can be modelled using transition matrices. The preferences are as before, table E.1, but the direction of the edges of the graph is to the state most preferred (i.e. is reversed) and contains the probability with which that transition takes place. For this simple choice system, it is fairly clear what each voter’s preferred position is, but because of the transitivity, it is possible to go from the least-preferred vertex to either of the two more preferred, unfortunately one has to make a choice — or one is describing a different system — so the most preferred vertex is chosen as the one to transit to.

\[
F_A = \begin{pmatrix}
1 & 0 & 0 \\
1 & 0 & 0 \\
1 & 0 & 0
\end{pmatrix},
F_B = \begin{pmatrix}
0 & 1 & 0 \\
0 & 1 & 0 \\
0 & 1 & 0
\end{pmatrix},
F_C = \begin{pmatrix}
0 & 0 & 1 \\
0 & 0 & 1 \\
0 & 0 & 1
\end{pmatrix}
\]

E.3.4 Reachability and Reaching Matrices

Definition E.3.1 (Reachability Matrix). A reachability matrix, \( R \), is a square matrix having as many rows as there are vertices. The entry in the matrix at \( r_{ij} = 1 \) if vertex \( x_j \) is reachable from vertex \( x_i \).\(^3\)

\(^2\) Chr75, p. 13
\(^3\) Chr75, p. 18
Definition E.3.2 (Reaching Matrix). A reaching matrix, $Q$, is a square matrix having as many rows as there are vertices. The entry in the matrix at $q_{ij} = 1$ if vertex $x_j$ can reach vertex $x_i$.

E.3.5 Chains and Anti–Chains

(Note that Christofides uses the term chain for a semi–path.)

Definition E.3.3 (Chains and Anti–chains). These are complementary concepts defined on a partially–ordered set:

1. Chain

   A chain in a partially ordered set is a set of elements $u_1, u_2, \ldots, u_k$ such that $u_i$ is related to $u_{i+k}$, $i < k$.

2. Anti–Chain

   An anti–chain is a collection of elements no pair of which are related.

Chains partition the elements of the partially–ordered set. There may be a number of anti–chains as well, but they do not partition the set unless the set is in some way degenerate. Each element of each anti–chain will be contained in one (and only one) chain.

---

4 [Chr75], p. 18
5 [Ski90, p. 243] for the definitions and the method of finding the largest anti–chain.
Appendix F

Modal Logic

F.1 Overview

A modal logic can be used to express how truths are held between members of groups \cite{Che80}. Modal logics have been studied extensively and used for a number of purposes in computer science \cite{Sti95}.

Remark F.1.1 (Propositions). Modal logic usually concerns itself with propositional logic statements. These can be interpreted denoting the instantiations of variables, e.g. whether an entity like \text{cost}(x, y) is held at all, and, if it is, whether it has the same value as that held elsewhere.

When a set of variables has been instantiated, say \text{cost}(x, y) = 100, then this can reduced to a statement in propositional logic, \( A \), if need be using the following method. Firstly, a typing system needs to be established because the proposition involves a function; the function can be written as having four parameters: the function signature, \text{cost}, the result of the function call, 100, then parameters, \( f_1 = x, f_2 = y \).

A logical proposition \( A \) can then be defined as a statement in the type system of 2 argument functions: \( A \triangleq \langle \text{cost}, 100, x, y \rangle \); this in turn can be reduced to an untyped logical statement by stating: \( \text{type}(A) = \text{two argument functions, signature = cost, result = 100, arg1 = x, arg2 = y} \).

\footnote{This is a well-known technique in formal logic analysis which allows many seemingly more complex systems to be reduced to typed argument comparisons, see Hodges contribution to \cite{GG84}.}
Now $\neg A$ could mean any statement that is not $A$ in any way, for example: $\text{cost}(y, x) = 100$ or even $\sin(a) = \frac{b}{4}$. For the purposes of this discussion it is best to think of $A$ as being a typed statement from a class of function results, something like $\text{cost}(x, y)$, so that $\neg A$ would at least agree on the name of function, cost, which arguments $x$ and $y$, but not the result. As will be seen, the point is to provide a language that can ensure that different entities have the same instantiations of variables.

**Notation F.1.1 (Modal Operators).** These operators are:

- $\Diamond$ expressing the notion of *possibly*.
- $\Box$ expressing the notion of *necessarily*.

They can be explained, fairly informally, thus: an agent occupies a “world of beliefs and values” $x \in \mathcal{W}$ and can see other such worlds around him, $\mathcal{W}' \subseteq \mathcal{W}$. If the agent observes that the proposition $A$ is held in at least one world he observes, then $\Diamond A$ is true and if it is held in all worlds he observes, then $\Box A$.

Only one of the operators $\Diamond, \Box$ need be primitive, it can then define the other, thus: $\Diamond A \equiv \neg \Box \neg A$.

These operators will be used to define inference rules and whether $\Diamond$ or $\Box$ is specified is a matter of choice for system designers, the notation $[\Diamond | \Box]$ will be used to indicate this.

**Notation F.1.2 (Models).** The concept of a model $\mathcal{U}$ and the $\models$ operator needs to be introduced. The details of its definition can be found in [Che80]. For now, these examples and their meanings should suffice:

$$
\begin{align*}
\mathcal{U} & \models A \\
\mathcal{U}' & \models A \\
\mathcal{U} & \models A & \models A
\end{align*}
$$

(F.1) (F.2)

A model $\mathcal{U} = \langle \mathcal{W}, \ldots, \mathcal{P} \rangle$ contains a set of worlds $\mathcal{W}$ and a set of atomic propositions $\mathcal{P}$ distributed among the worlds. There can be different kinds of model and each model belongs to a class, such as $\mathcal{C}$, a class of models is differentiated from another class by the axioms that are in force.
1. (F.1)

(a) The first form means in model $\mathcal{U}$ in world $x$ proposition $A$ is held.

(b) The second form means in model $\mathcal{U}'$ in world $y$ proposition $A$ is held.

2. (F.2)

(a) The first form means: is valid everywhere in this model. $A$ is valid in all worlds because of the distribution of the atomic truths.

(b) The second form means is valid in all models of this class. This means that $A$ is an axiom or theorem of the model and is not dependent on the distribution of truths.

NB. The terminology of modal logic will be used, but bear in mind the application of the modal logic in this context:

1. Agent or Organisation = World

2. Supra–organisation = Model

3. Behavioural type of supra–organisation = Class

F.2 Values and Beliefs

Notation F.2.1 (Values and Beliefs). A proposition can be held in a number of ways in a modal logic:

Values These are propositions that are local to a world, $e.g. \models_x^u A$, $x$ believes $A$. These have no modal qualification in what is known as a normal form, $i.e.$ it is not possible to rewrite the truth as either $\Box A$ or $\Diamond A$.

Beliefs These are based on how neighbouring worlds report their values. These can be written in their normal forms, which can, on reduction, be one of either $\models_x^u \Diamond A$ or $\models_x^u \Box A$. 
Immutable Values

Propositions that are globally held. There are two forms of these:

1. \( \models u A \): propositions that are global to the model: these would be a set of atomic propositions which every world must possess and are immutable, and any theorems that are based solely on them.

2. \( \models C A \): these are propositions and axioms that are global to the class of models. There are just two propositions (the definitions of true and false), and a set of theorems, the axioms, that define the model, these may contain modal operators.

- Values are private, in that only the world holding them knows whether they are true or false.

- Beliefs are jointly held by the worlds that observe the same set of worlds.

One can also think of values and beliefs in terms of entity relationships between a subject and an object. “A subject has a belief about the value of an object” is diagrammed in figure F.1: the subject owns a value; the object owns another value. The subject has a belief about the value that the object holds. The belief is in the subject’s domain, but is associated with a value in the object’s domain.

A subject may never know the true nature of the value, but it can obtain corroborating beliefs from other sources, it can become more and more certain of the value the object holds. In figure F.2, the subject has obtained more beliefs — based on the beliefs of others — about the value the object holds.

Remark F.2.1 (Observation and Lying). Worlds that observe others can only observe what the observed world admits to. In short, the observer poses a question and the observed answers it. There are two problems:

1. The observed world has no a-priori value that it can return in answer to the question
Figure F.1: Relationship between a belief and a value
Figure F.2: Corroborating beliefs about a value
2. The observed world misrepresents itself and therefore:

(a) Claims to have no value, in which case apply [ ] above

(b) Negates the value it holds

There is no way in which the observing world can ascertain the observation it makes truly reflects the values held by the observed world without obtaining some corroboration from elsewhere. This point will be addressed in more detail later, but for the time being one can assume that worlds report their truths truthfully.

F.3 Deontics

Modal logic can be used to formalise laws of behaviour, in which case the logics are part of the field of deontics, see [Aqv84] for a summary.

- Prohibition
- Permission
- Obligation
Appendix G

KQML and KIF

G.1 Knowledge Query and Manipulation Language

KQML is an unusual language because it provides services with a means of interacting with one another that is similar to the way in which business is conducted amongst business organisations: with KQML services may advertise themselves, recommend one another and recruit one another. It also provides a high–level database access language, with primitives like insert, delete and so forth. It can also be used for low–level data streaming and redirection.

Performatives KQML is not a programming language or data access language, but a simple set of primitives that are used more for their semantic connotation than for their effect — an invocation language. A list of the performatives currently defined — and their meaning — is given in two tables: G.1 and G.2. Some entries refer to a VKB, which is a Virtual Knowledge Base, or a database of rules.

The performatives are invoked by a sender on a receiver. Performatives require parameters which are defined next.

Parameters The parameters to KQML performatives are fixed, their meanings are given in table G.3.
| Name        | Meaning                                                                 |
|-------------|-------------------------------------------------------------------------|
| achieve     | S wants R to do/make something true in its environment                  |
| advertise    | S is particularly suited to processing a performative                   |
| ask–about   | S wants all relevant sentences in R’s VKB                              |
| ask–all     | S wants all of R’s answers to a question                                |
| ask–if      | S wants to know if the sentence is in R’s VKB                          |
| ask–one     | S wants one of R’s answers to a question                                |
| break       | S wants R to break an established pipe                                  |
| broadcast   | S wants R to send a preformative over all connections                   |
| broker–all  | S wants R to collect all responses to a performative                    |
| broker–one  | S wants R to get help in responding to a performative                  |
| deny        | the embedded performative does not apply to S (anymore)                |
| delete      | S wants R to remove a specified sentence from its VKB                   |
| delete–all  | S wants R to remove all matching sentences from its VKB                 |
| delete–one  | S wants R to remove one matching response from it VKB                   |
| discard     | S will not want R’s remaining responses to a previous performative      |
| eos         | end of stream of responses to an earlier query                         |
| error       | S considers R’s earlier message to be malformed                         |
| evaluate    | S wants R to simplify the sentence                                      |
| forward     | S wants R to route a performative                                       |
| generator   | same as standby of a stream–all                                        |

Table G.1: KQML Performatives (A to G) for sender S and recipient R
| Name          | Meaning                                                                 |
|--------------|--------------------------------------------------------------------------|
| insert       | S asks R to add content to its VKB                                      |
| monitor      | S wants updates to R’s response to a `stream–all`                        |
| next         | S wants R’s next response to a previously mentioned performative        |
| pipe         | S wants R to route all further performative to another agent             |
| ready        | S is ready to respond to R’s previously mentioned performative          |
| recommend–all| S wants all names of agents who can respond to a performative           |
| recommend–one| S wants the name of an agent who can respond to a performative          |
| recruit–all  | S wants R to get all suitable agents to a performative                  |
| recruit–one  | S wants R to get another agent to respond to a performative             |
| register     | S can deliver performatives to some named agent                          |
| reply        | S communicates an expected reply to R                                  |
| rest         | S wants R’s remaining responses to a previously-mentioned performative  |
| sorry        | S cannot provide a more informative reply                               |
| standby      | S wants R to be ready to respond to a performative                      |
| stream–about | multiple response version of `ask–about`                                |
| stream–all   | multiple response version of `ask–all`                                  |
| subscribe    | S wants updates to R’s response to a performative                       |
| tell         | S admits to R that a particular sentence is in its VKB, usually issued in reply to an ask |
| transport–address | S associates a symbolic name with transport address                   |
| unadvertise  | a `deny` of an `advertise`                                              |
| unregister   | a `deny` of a `register`                                                |
| untell       | S admits to R that a sentence is not in S’s VKB, in response to an ask  |

Table G.2: KQML Performatives (I to U) for sender S and recipient R
Table G.3: KQML Parameters for Performatives

| Name            | Meaning                                                                 |
|-----------------|--------------------------------------------------------------------------|
| content         | the information for which the performative expresses an attitude        |
| force           | whether the sender will ever deny the meaning of the performative      |
| in-reply-to     | the expected label in a reply                                           |
| language        | the name of the representation language of the content parameter        |
| ontology        | the name of the ontology (e.g., set of term definitions) used in the content parameter |
| receiver        | the actual receiver of the performative                                 |
| reply-with      | whether the sender expects a reply and, if so, a label for the reply    |
| sender          | the actual sender of the performative                                   |

G.2 Knowledge Interchange Format

KIF provides a means whereby relationships and facts can be expressed as meta-knowledge which can then be translated and passed to executive agents - typically expert systems. Essentially KIF provides for: the representation of knowledge about the representation of knowledge; representation of non-monotonic reasoning rules; the definition of objects, functions and relations.

Its syntax is a cross between and Lisp and Prolog, but is used like Z, in that it is only used to define entities. It has as its verbs all of the logical and arithmetic operators.

Knowledge about the Representation of Knowledge KIF defines knowledge representation as lists.

\[
\text{(defobject read-request := (or (or (listof requestor target)) (listof requestor requestor-location target)))}
\]

Which defines an object that is a “read-request”, which is either a list of request-or identity and the target identity or the request-or identity, his location and the target.
Non-monotonic Reasoning Rules  Facts can be defined:

(believes http-agent '(valid-user sybase))
(believes http-agent '(non-interactive sybase))
(believes http-agent '(read-access-only sybase))

States that the HTTP-agent believes sybase is a valid user who will only operate non-interactively and will only make use of read-only access. Such facts can then be reasoned upon.

(=> (believes http-agent ?p) (believes page-agent ?p))

Which states that whatever the HTTP agent believes, the page agent believes.

Definitions  For example:

(defrelation grant-right-to-read (?x ?o ?g) :=
  (and (member ?x ?g)
       (forall (?m)
         (=> (member ?m ?g) (has-right-to-read (?m ?o)))))

Defines a relation that grants to an entity “x” the right to read an object “o” if all of x’s group are already able to read o. The relation “has-right-to-read” is defined elsewhere.