Intensional view of General Single Processor Operating Systems

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Abstract

Operating systems are currently viewed ostensively. As a result they mean different things to different people. The ostensive character makes it is hard to understand OSes formally. An intensional view can enable better formal work, and also offer constructive support for some important problems, e.g. OS architecture. This work argues for an intensional view of operating systems. It proposes to overcome the current ostensive view by defining an OS based on formal models of computation, and also introduces some principles. Together these are used to develop a framework of algorithms of single processor OS structure using an approach similar to function level programming. In this abridged paper we illustrate the essential approach, discuss some advantages and limitations and point out some future possibilities.

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1 Introduction

The purpose of an operating system (OS; plural OSes) is often stated as: “To provide a convenient interface to the user, and manage the available hardware resources.” [1], [2], [3], [4]. This is an ostensive definition of an OS since “convenience” and “interface” are understood by examples and “management” is specific to hardware resources. This paper describes an attempt to develop an intensional view of an OS. The approach is targeted to system programmers, academics and researchers by eliminating the ostensive view of OSes.

This work bases OSes on basic mathematical models of computation and explores the consequences. It induces some principles based on practice, and shows that for single processor OSes these offer a unified framework to view the structure of OSes. This work will be useful to diffuse the traditional boundaries between OS kernels and system software. We do not aim for soundness or completeness in our approach; instead we view it as initial steps toward an eventually sound theory of OSes.

2 Motivation and Approach

The ostensive character of the description of an OS in section 1 influences the theory and practice of OSes in a number of ways. First, different groups of people see an OS differently. OS programmers provide a “convenient” system call interface to system programmers. System programmers provide a “convenient” interface via techniques like libraries and system software tools to the application programmers. Application programmers provide a “convenient” interface – via the command line or graphical icons – to the end users. To a system programmer convenience could be about the variations supported for resource management, e.g. FCFS or RR scheduling. To an applications programmer convenience could be about the variations available in system abstractions, e.g. finite precision arithmetic or arbitrary precision arithmetic. To an end user convenience could be about the usability abstractions, e.g. presence or absence of virtual desktops. An OS means different things to different groups.

Secondly, the ostensive nature of the definition affects the practice of development and use of OSes. As systems evolve over time the conveniences may filter from the end user level down to system level. Thus, for instance, we find file encryption user utilities gradually move down to the system level where file systems offer encryption capabilities. Groups like OS programmers, system programmers and application programmers then need to face the task of cooperatively modifying their interfaces to accommodate the filtering down effect without affecting other parts of the overall structure. Furthermore, a migration duration – during which the new coexists with the old – is typically offered to ease the transition from the old architecture to the new. The ostensive view of an OS does not offer any help in guiding the collective modification and migration management efforts. It would be useful to separate the affected context from the unaffected ones to deal with such architecture restructuring efforts. It is also useful for other problems like the development of virtualization strategies and formal verification efforts. There is a need to examine if there are any unifying principles that can help define clear segregation and aggregation of the work across groups.

Third: An ostensive definition of an OS makes it hard to develop any theory of an OS. OSes are primarily regarded as a technological problem. The techniques and algorithms have evolved over the years in response to technological challenges and user needs. The central concern – providing a convenient interface and managing the hardware resources – is only intuitively clear. The ostensiveness percolates down to many other critical concepts in an OS. For example, a process is described as an instance of a program in execution.

Researchers typically see OSes as abstract machines. The absence of an intensional definition of OSes makes it hard to identify general abstract machines although subsystems can be, and have been, studied. Perhaps that is why we see most OS research is, to quote Yates et. al., “very systems oriented and results driven” [5]. Bergstra and Middelburg have recently pointed out that there appears no insight into what an OS is and perhaps therefore there may be no formal view of OS [6]. Middelburg in his survey observes that (a) there is only one more or less abstract model by Yates et.al. [5], (b) there does not exist a theory based on that model, and (c) that the OS community “has paid little attention to clarifying what an OS is and giving motives for introducing OSes” [7]. There is a need for an effort toward an intensional view of OSes.
Clear intensional definitions offer a solid base to OS researchers so that they may define their abstract machines precisely. They offer clear and constructive goals to system programmers for building their systems. We hope that the principles we offer support efforts to develop more intensional approaches to problems like architecture restructuring and formal efforts for describing OS behavior as well as OS verification. Toward that end we show that a systematic framework for single processor OSes is possible given the definitions and principles. The current work describes the essential framework due to space limitations.

2.1 Approaches used in Literature

2.1.1 Origin of ostensive definitions
Early work has naturally viewed OSes ostensively and that view has fossilized over the years. Solntseff succinctly captures the OS evolution in terms of era like the initial “topsy” period where everything not directly produced by the user was considered part of the system [8]. Denning in an early review paper, offered a definition of an OS in terms its seven supervisory and control functions [9]. An interesting footnote in the paper observed that a process is a “direct generalization” of procedure in execution, but later work did not build on it. The review went on to identify five abstractions – programming, storage allocation, concurrent processes, resource allocation and protection – that could form the basis of a “theory” of OS. Dennis and van Horn was an early attempt at figuring out the semantics of OSes [10]. A later reprint of the paper defined an OS as an high level abstract machine using data abstraction concepts [11]. While a lot of work has been done since then, the core ideas, definitions and algorithms of this initial era have largely remained unchanged.

Processes were recognized as an abstract central entity within an OS in the 60s and the 70s. Denning also reviewed the definitions of a process and noted that although imprecise, they were sufficient for implementation purposes. Processes were defined in various ways, some indirectly. Holt viewed a process as an “agent” that causes state changes [12]. Dijkstra saw it as a “sequential automaton” [13]. Dennis and van Horn described it as a “locus of control” [10]. Denning presented the “instance of program in execution” view, and reviewed others [9]. Implementation techniques for managing memory, processes and devices were developed. See [9] for a review. We will view processes as formal computation and subsume these varied views.

The late 70s and early 80s saw the birth of personal computing, and a surge in innovations in hardware technologies. A significant part was the hardware support for OS operations, which in turn drove the systems research. Projects like Hydra [14], Amoeba [15], Medusa [16], Spring [17] and Accent [18] focused on the evolving challenges of multiprocessor and distributed systems. Others focused on individual sub problems in such systems. For instance, issues like programmability [19], monitoring and debugging [20], parallel scheduling [21] and multicore scheduling [22] have been addressed in the literature. Distributed systems are challenging and a clear statement of the formal intent is important to identify general formal issues among the specific problems.

2.1.2 OS architecture issues
Apertos (earlier Muse) attempted to bring in reflectivity (see [23]) primarily motivated by the advent of mobile computing [24], [25], [26]. The central thesis of this work is the separation of object level and meta level abstractions represented within the same framework. Núrnb erg et.al. elevated the view of Hypermedia from a paradigm of information organization to a view of a computing paradigm [27]. The separation of data, structure and behavior is an interesting idea in this work, and can be seen as the λ calculus in disguise. Factored OS (FOS) is a recent approach to deal with the growing complexity of OS [28]. It is based on factoring a component (service) into smaller ones and is motivated by the need for OSes to scale up for multicore systems. We will offer a principle that can guide the factorization. In contrast to these design time variations of the OS structure, approaches like Exokernels or SPIN investigated techniques of mutating the structure of the OS at runtime. Exokernels are the result of re-architecting traditional OS structure to safely expose physical resources to applications to allow application specific customization [29]. This is an
example of redefining the interface, or the abstract machine, that an OS presents to applications. The SPIN approach tries to employ the good properties of the Modula-3 programming language to obtain an extensible system from a core set of extensible services [30]. This safely changes the interface that an OS presents to an application. While individual issues to focus appear distinct, the common underlying concerns are about the approach to OS structuring. Our work offers some principles to guide such structuring efforts.

The growing complexity of the OS problem has greatly increased the turnaround time for building experimental systems and efforts to build such systems have reduced. Via the decade long K42 effort, Wisniewski et al. explore the facets of building a full OS and share the experience and insights [31]. They point out that some important practical questions, e.g. the useful lifetime of the GNU/Linux or Windows structures, are unanswered, and offer plausible reasons for the lack of whole-OS research efforts. Another approach to deal with complexity is to “go small”, and some efforts have investigated OS on single user systems. Stoy and Stratchey explored a different control structure through the OS6 which was an early attempt at virtual machines. They avoided a job control language through a hierarchical control structure for system use (as opposed to hierarchical resource allocation) [32], [33]. Single user OSES permitted easily removing the boundary between the OS and the user program [34]. Such attempts could have been useful to extract the essential abstractions, but further work needed has not been pursued. Whole-OS efforts, e.g. to describe the structure of an OS, are needed in addition to incremental work.

Ideas from programming languages have been used to investigate structure and structuring issues in OS. Clark discussed the use of upcalls to structure programs like an OS [35]. Kosinski identified eight important issues in expressing OS code, e.g. the need for parallel operation yet be determinate, or understandability (of OS code) in the large etc. [36]. He developed a data flow language based on function definition and composition, tried to identify minimal computational function, and used these to sequence computations. The Barrellfish effort developed the Filet-o-Fish language to construct a domain specific language (DSL) and employ it to generate low level OS code [37]. Back et al. use Java to explore the OS design space, and outline the major technical challenges [38]. They point out that adapting language technology to fit into OS framework could be used to deal with the challenges. Specifically, they show how garbage collection techniques can be used to support resource management. Flatt et al. demonstrate how key OS facilities are obtained through three key extensions – threads with parameters, event spaces, and custodians – to a high level programming language [39]. They summarize an important lesson in the title of their paper – “Programming languages as operating systems”. The bridging principle in the current work is useful to understand such approaches. Draves et al. apply continuations in a general purpose operating system kernel by redesigning the internal thread and interprocess communication facilities to use continuations as the basis for control transfer and demonstrate substantial improvements in system performance [40]. Using continuations allows them to portably implement new optimization, and to recast several optimizations found in other operating systems in terms of a single abstraction. Kiselyov and Shan show that delimited continuations offer a uniform view of many scenarios that arise in systems programming including an interesting one: a snapshot of a process [41]. They implement the zipper file system that explicitly uses continuations for multitasking and storage. Their work shows how delimited continuations are helpful, especially “in conjunction with types that describe the shape of data and effect of code in detail”. They use such types to sandbox processes, isolate transactions, prevent race conditions, improve scalability to multiple processors, and obviate the user-kernel boundary in hardware.

2.1.3 Formal modeling of OSES

On the formal side, attempts have been made to build models of OS – in whole or in part, develop languages to express them and verify them. Yates et al. developed a formal model of an OS as a system of distributed state machines [5]. They investigated two views of an OS: a user level model as an interface specification, and a kernel level model of the implementation that exposes the details hidden by the user level abstraction. They show that the kernel level model indeed implements the user level model, and hence both are functionally equivalent. Another example of the value of formal work in OS, or its parts, is the graph theoretic description of the deadlocks problem [42]. It brought a number of previous deadlock algorithms for prevention, detection etc. together into a simple neat structure. On the verification front, Barreto et al.
specified process management, IPC and file system components of an OS kernel in Z, uncovered errors and inconsistencies in the kernel and formally verified it by using a mechanical theorem prover Z-EVES on the Z specification [43].

The current work asks if an OS can indeed be defined intensionally. It offers such a view and explores its consequences via a focus on program execution as the central concept at which programming languages and OSes converge. A good model of OS structure that identifies the intensional concepts and uses them to devise the specific algorithms is also pedagogically useful and can help in activities like OS course design [44]. For instance, traditional memory management and file systems have redundancies that can be eliminated to effectively teach those algorithms [45].

2.2 Approach

The ostensive nature of the definitions used in OS practice can be overcome by connecting to theoretical computer science. Algorithms are the central constructive concept in computer science. They represent the part of our formal mental concepts that can be mechanized, i.e. concepts for which we can have a Turing machine. Their practice involves two major aspects – expression and execution. Programming languages concern themselves with the former, and OSes concern themselves with the latter. Each uses an underlying model of computation. As long as the models are equivalent, each can use a general, possibly different, model for its purposes. We examine the relationship between program expression and execution to identify some useful principles.

Once the definitions and principles are in place, we view an OS as a whole. As an algorithm it is statically structured out of a collection of algorithms that together yield a dynamic behavior at run time. The individual component algorithms can be selected and combined in a variety of ways to realize a given specification of an OS. The possible combinations form the design space of the algorithms and define the structure of an OS. An OS designer is concerned with developing a structure that meets the specifications. To obtain the various possible component algorithms we develop a framework to describe the structure of an OS based on the ideas of equivalence class partitioning of resource sets under OS operations. However the dynamic behavior of processes, e.g. critical sections and deadlocks, is beyond the scope of the current work which restricts itself to rather static structural aspects of OSes.

3 Definition and Principles

3.1 Definition of an OS

Programs are executed on, i.e. interpreted by, hardware. Hardware implementations of computing machines could be regarded as physical realization of some formal machines. Thus we could see the von Neumann model as a physical realization of the formal Universal Turing Machine (UTM). In principle, hardware implementations could choose one of the many equivalent formal machines like Turing machines, λ calculus (\( \lambda \)), Markov algorithms (MA) and partial recursive functions (PRF) [46] [47]. The structure and operations of the chosen formal machine form the instruction set of the system. The instruction set is the language to be used to express any algorithm and execute it too. Hence the formal machines must be one of the many general models of computation. We call this model of computation the low level machine. On the other hand, an end user desires a convenient execution system. Such a convenient system, the high level machine, must also execute any algorithm. Hence it must also be one of the many models of computation. Since the low level computation model need not be the same as the high level computation model, we introduce an algorithm over the low level machine that transforms the system into the high level machine, and call it the Operating System. An intensional definition of an OS is:

**Definition 1** An Operating System is an algorithm that implements a Turing complete model of computation, called the high level machine, in terms of another Turing complete model, called the low level machine.
The notion of an OS is now based on the theory of computation. It is an algorithmic proof of equivalence between the low level and high level Turing complete models of computation. The structural aspects of an OS are as a bridging algorithm between a pair of universal Turing complete machines. The operational aspects of an OS are all the possible ways in which the high level machine may interpret its programs. As an algorithm, an OS has to realize its operational aspects using the low level machine. Fig. (1) captures this intensional definition of an OS as the algorithm between a low level machine $L$ and a high level machine $H$. Further, this definition allows us to introduce another ostensive concept – the abstraction gap – that captures the intuitive difference between the two models of computation. The purpose of an OS is to bridge this abstraction gap.

Another interesting description of an OS emerges from the program expression point of view. As the high level machine of an OS is a universal machine, the OS accepts descriptions of one or more machines, i.e. programs, and executes them. The OS and its programs must be fully decoupled from each other. Programs may be defined at any time, any where and in any way possible. Once defined they may be executed any time, any where and in any way possible. An OS may therefore be described as a program whose one or more subprograms are fully decoupled from itself. In this sense, every program is a delimited continuation as suggested by Kiselyov et.al. [41].

### 3.1.1 Correspondence with practice

The low level machine language may not always be suitable for program expression purposes. In practice we often introduce another computation model, usually Turing complete, that is used to design the program expression system. We call the instruction set of this model of computation as the high level language (HLL). More than one HLLs may exist in a system. Fig. (1) expresses this idea and $P_1$ and $P_2$ may denote two HLLs. For example, $P_1$ may be the HLL defined by the system services of typical Unix style OS kernel, $P_2$ could be the HLL defined by a typical program development HLL, say C.

Fig. (1) shows that an OS as a concept is a bridge between a low level machine and another high level machine. It may be regarded as a whole entity or may be composed of an OS component and a system software (SS) component. As shown for machine $P_2$, the $OS_2$ may be composed of $OS_1$ and a system software component for expression $SS_2$. Note that $OS_2$ need not be so composed and can stand alone.
Additional system software, $SS_3$—usually the software tools, can be used to reach the level of machine $H$. Whether the high level machines are $H$ or $P_1$ or $P_2$, an OS is essentially the bridge between them and the low level machine $L$.

**Notation:** Let $^{LS_I^S}^H$ denote that a concept $S$, e.g., an OS or system software $SS$ or language HLL, be expressed in a language $I$ to raise a low level machine $L$ to a high level machine $H$. Thus $^{LOS_I^H}$ is an OS expressed in some language, denoted by $I$, that raises the low level machine $L$ to a high level machine $H$. Similarly, $^{CSSC_{\lambda}^A}$ denotes system software expressed in $C$ to obtain a $\lambda$ calculus machine over a given $C$ machine. The notation is adapted from the T diagram introduced by Bratman in [48] and used by Aho et al. in [49].

Designing HLLs, i.e. program expression systems, involves defining frameworks over a chosen model of computation. Frameworks may introduce arbitrary rules over the model to ease program expression, but that may not affect the computation power of the model chosen. For instance, the C programming language introduces a rule that the occurrence of a function call at runtime directly corresponds to its syntactic occurrence in the source code. This does not affect the ability to express any computation sequence but may make expressing some of them inconvenient. For instance, consider the **signal** abstraction to express response to events. The signal handler call is tied up to event occurrence and not with the syntactic occurrence of the handler in the expressed C programs. $P_1$ and $P_2$ in Fig.(1) are often frameworks over some formal machines.

In general any OS, $^{LOS_I^H}$ or $^{LOSS_{P_1}^H}$ or $^{LOSS_{P_2}^H}$, may not restrict program definition and execution in any way. However, the generality of the algorithms in an OS that manipulate the state and control flows determine the extent of the restrictions on program execution. An OS that uses coroutines style approach to control flow and state manipulation can at best support non-preemptive multitasking.

### 3.2 Procedures and Processes

A process is often defined as “an instance of a program in execution”; see [9]. The definition is esoteric since a process is understood *a posteriori*, i.e. after one has some experience with the ideas of a “program instance” and its “execution”. Dennis and van Horn define a process in an *a priori*, but more abstract, way as: “A process is that abstract entity which moves through the instructions of a procedure as the procedure is executed by a processor.” [10]. Both these definitions are also contingent ones and do not clearly capture the mechanical aspects that are required for formal work as well as for implementation. A mechanical view of process would capture the operational meaning of “instantiating a program” and “executing it”.

To obtain a mechanical view we use the intuition behind interpretation as formally defined in elementary proof theory (see [50], for example). Intuitively, interpretation is the ability to extract the value bound to a given symbol. A computing machine interprets the symbols of its programs given a set of values bound to them. These bindings are the state, or an environment or context. A process is, therefore, the formal computation (see [47] [46] etc.) by a computing machine when a set of symbols of a program and an associated context are presented to the interpreter.

**Definition 2** Given a program and an associated environment for interpretation, a process is the formal computation by a formal machine, e.g. a Turing machine.

We will refer to the set of symbols—program and the associated context—as a **procedure**. A procedure is a process when interpreted by a machine. A process induces state changes in the system and is an active entity [9], [12]. A procedure is a passive entity when not interpreted by a machine. When passive we will refer to it as a **file**. A procedure is a structural aspect of an OS, and forms the basic unit of manipulation by the algorithms of an OS. It is the final goal of program expression while a process is its specific formal computation. This distinction between the procedure and its process helps to avoid the contingent aspects. “Executing a program” is the formal computation of a procedure. “Instantiation a program” is creating the procedure, i.e. the program and its associated interpretation context. It gives a clear algorithmic goal for system programmers who devise system software, e.g. loaders. For them, a procedure is the structural entity that must be switched between active and passive states.
The procedure in the above definition corresponds exactly to the input to a Universal Turing Machine (UTM). This notion of a process as formal computation is also invariant over all the computer organization and computation organization strategies, whether single processor machines or distributed systems. It only requires a suitable underlying formal model of computation.

### 3.3 Some useful principles

Principles capture invariants of a problem that can be used to develop a structure, i.e. the steps and their permutations that satisfy the specification, of the solution. The questions that help capturing them for the OS problem as given by definition 1 are: (a) What invariants can be induced?, (b) How can we identify the steps required by an OS to bridge two models of computation?, and (c) Given the steps what determines their correct arrangement?

#### 3.3.1 First classness

Our definition 1 offers an invariant. An OS must be free to execute a set of one or more procedures with the least restrictions, i.e. anywhere, any way and any time. For each procedure it must define two states: active (or running), and passive (or ready to run). To realize execution with the least restrictions, procedures must be switched between these two states in any desired manner, i.e. procedures must be first class entities. Procedures are first class since as files they can be a member of a set used to select for scheduling. They are also a parameter to decision functions that fix the schedule, or a return value of selection functions that pick a file to schedule. They become processes when subject to interpretation. The first classness of procedures must be an invariant property.

**Principle 1 (First classness)** Procedures in an OS must be first class.

First classness of procedures is necessary to allow an OS to evolve their execution in any pattern. Now the possible execution patterns are the number of distinct ways in which an OS may switch between active and passive states of each procedure in the set.

#### 3.3.2 The Bridging Principle

To realize, i.e. design and implement, an OS as a bridge between the two levels of machines, a designer usually introduces intermediate but intuitively clear levels of abstraction. Each of these levels preferably captures one step towards the eventual high level machine. Each intermediate level must also be Turing complete since each subsequent level must be able to express all algorithms. The question is: how do we identify these levels?

We now add a program expression system that is used to express an OS between a low level machine and a high level machine. This system, although a framework as a whole, is defined by some underlying formal computation machine. We will call this framework as the $E$ machine, the expression machine. There are three cases: (a) $L \neq E \neq H$, e.g. $\lambda\text{OS}_C^{MA}$ (b) $L = E \neq H$, e.g. $^{TM}\text{OS}_C^{\lambda}$ and (c) $L \neq E = H$ e.g. $^{\lambda}\text{OS}_C^{TM}$.

In each of the three cases an OS has to necessarily bridge any gap between the $E$ machine and the high level machine. The details of the three cases differ in the techniques to bridge the gap between the low level machine and the $E$ machine so as to achieve execution with least possible restrictions. In case these two are different, then the OS has to first implement the low level machine completely using the $E$ machine. In the case when the $E$ machine is the same as the low level machine the OS may have to implement algorithms to overcome the restrictions by parts of the HLL framework. Thus, given $C$ as the chosen HLL an OS has to overcome the restriction of stack based activations and implement more general activation mechanisms like event based activation (i.e interrupts) or multiplexed activations across processes for system calls. In

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1The notation (see page 7): $^{\lambda}\text{OS}_C^{MA}$ denotes an OS that realizes a Markov Algorithms (MA) based high level machine over a $\lambda$ calculus based low level machine, with the development hosted on an Turing machine based HLL expression system, say $C$.  

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the case when the $E$ machine is the same as the high level machine the OS may have little to bridge except algorithms to overcome the restrictions by parts of the HLL framework.

Given the chosen level of program expression the three bridging possibilities yield the bridging principle below. It identifies the origin and the nature of the abstraction gap alluded to by definition 1. It provides a mechanism to obtain the necessary steps to reach the high level model defined for the OS.

**Principle 2 (The Bridging Principle)** An OS must necessarily bridge any difference between the $E$ machine and the high level machine, and it must necessarily overcome any restrictions introduced by the $E$ machine over the low level machine.

To illustrate the bridging principle, consider the second case above $T^M\text{OS}_{C^{\lambda}}$ where we have the C $E$ machine used to implement an OS that bridges a von Neumann low level machine and a $\lambda$ calculus high level machine. With reference to Fig. (1), we have $L$ as the von Neumann machine, $H$ as the $\lambda$ calculus based machine, and $P_2$ as the C HLL that realizes the C semantics. To reach the full $\lambda$ machine level, the $SS_3$ component is necessary. It includes realizing the abstraction that are missing from the C HLL as well as the abstractions that need to be generalized to overcome the framework in C. C does not have automatic memory management, and its stack based activation needs to be generalized. On Unix like systems $SS_3$ is often a set of programs and libraries that provide a functional interface that hides memory details and also introduces composition capabilities. The creation of generalized activation mechanisms is moved into the kernel, e.g. per process u area to realize multiplexed system calls.

To identify the intermediate abstraction levels, including the limitations of the framework, for $T^M\text{OS}_{C^{\lambda}}$, we look at the abstraction levels of program expression. Fig. (2) arranges them to correspond to the intuitively increasing sense of the abstraction levels. The figure makes the point that the arrangement captures a gradual transformation from a Turing machines based computation model towards eventual functional one. On the right is a set of levels of expression and on the left are example languages that support them. They are arbitrarily arranged to appear to increase upwards from the bottom. One may either translate expressed programs down to the low level interpreter machine as shown by the arrow on the left or raise the interpreting machine up to the level of the expressed programs as shown by the arrow on the right. They gradually achieve the functional programming model of computation by creating better name spaces (e.g. mnemonics, variable names, function names), state spaces (e.g. types), automatic memory
management (e.g. garbage collection), and interleaving executions (e.g. closures and continuations).

The preceding discussion suggests that techniques of computing closures and continuations generally must be borrowed into the our specific OS example problem since the C HLL based expression model supports only stack based activations. Also the algorithms that would eventually create implicit memory for the high level model from explicit primary memory of the low level model are also necessary. The bridging principle thus helps an OS to identify the intermediate levels necessary to bridge the two models of computation. However, since the idea of ordering the abstractions in Fig. (2) is currently intuitive, the bridging principle is ostensive and contingent.

3.3.3 Binding and Interpretation

Having identified the intermediate steps between the low level and high level machines, we organize them in a sequence that satisfies the specification of an OS. The design space is formed by the number of allowed ways in which the given set of steps may be permuted. The binding principle that follows is the decision rule to decide if a given permutation of the identified steps is acceptable or not.

Given that interpretation is the ability to extract the value bound to a given symbol, the central construct required is binding symbols to their values. The interpretation system is discrete and takes one symbol at a time for interpretation. For successful interpretation we need the following, stated as the principle of binding:

**Principle 3 (The Binding Principle)** *The binding of a value to a symbol may be established at any instant before the instant of interpretation.*

The bridging principle helps introduce the intermediate steps which can be permuted in any way. The binding principle is the rule that defines acceptable permutations. Together they can yield an approach similar to the def-use chains in data flow analysis that yield compiler optimizations like constant propagation and common subexpression elimination. Since interpreters are acceptor machines, the binding principle captures the need to establish the binding before use. Given a sequence of symbols for interpretation, the principle forms the base of the tool chain approach of establishing binding analogous to compilation phases. Bindings that can be computed earlier are moved to the earlier phases of the tool chain, e.g. libraries. Fig.(3) captures this idea for a typical compilation sequence.

![Figure 3: Temporal sequence in which bindings are gradually established by the translation technique.](image)

Given that the bridging principle helps to identify the necessities, the binding principle helps to identify the correct possibilities of placing them. It helps to identify the design choices required to map the low level
machine to the high level machine. For instance, since framing the main memory, i.e. binding frame numbers to fixed size memory regions, is independent of dividing a program into pages (i.e. binding page numbers to fixed sized program chunks), both can be established independently and anytime before the page table that binds pages to frames is built. As another example, the file system layer within a monolithic kernel can be viewed as a set of bindings of the file system abstractions to memory devices moved into the kernel space. On the other hand, if the device abstractions ensure disjoint regions then the file system abstractions for each region may be moved into user space too. The impact of this principle for conceiving and building system software will be discussed in another work.

4 Resource Management Algorithms

The detailed version of this paper works out the equivalence class partitioning idea, and illustrates a complete paging and segmentation based memory management algorithm. It is based on partial recursive functions model of computation and uses a Lisp like notation to better describe the formal structure. The description below sacrifices little accuracy for brevity of illustration of the approach. For example, it allows signature inconsistency in composition.

For an OS a procedure \( p \) is characterized by two parameters: \( p \equiv p(s, t) \), where \( s \) is the memory size and \( t \) is the CPU time. An OS is given a (assumed finite) set of procedures, \( P = \{ p_1(s_1, t_1), p_2(s_2, t_2), \ldots, p_n(s_n, t_n) \} \), of \( n \) procedures. Memory resources are sets of finite and reusable units while CPU time is infinite and not reusable units. The set of memory units, \( M \), and the set of CPU time instants, \( T \), are examples of resource sets that we generically denote as \( R \). In general, resources are countable sets of units, \( R = \{ r_1, r_2, \ldots \} \). To each element of a resource set \( R \) we define a function \( addr \) that associates a unique natural number called the address of the element of the resource set. \( addr \) can be used to order the elements of \( R \) monotonically, and we assume that they have been so ordered. A contiguous subset \( S \subseteq R \) is specified by two addresses – the start address of the subset and the end address of the subset.

The structural algorithms of an OS are about managing the resources like memory and CPU time. We see these algorithms as operations that induce an equivalence class partitioning of the resources. To obtain specific algorithms, we look at the different sets (e.g. \( P \) of procedures or \( R \) of resource units), their structure, and different possibilities of binding resource sets to specific resources.

The resource allocation problem is: given the required quantity \( q \) of the resource to extract a non-intersecting subset of \( S \subseteq R \) of contiguous elements of \( R \) such that \( \#S \equiv (addr(\text{end}) - addr(\text{start})) = q \). The required quantity \( q \) is obtained by selecting an element from \( P \), and projecting out the required parameter. Thus if \( R \) denotes the memory, then \( q \) denotes the projection of the size parameter \( s_i \) of the \( i \)th procedure in \( P \). The \textit{select} operation that selects an element of a set is any algorithm that returns a member of the set.

A simple example of \textit{select} is the projection function that given a natural number \( i : 1 \leq i \leq \#R \) returns the \( i \)th element of set \( R \). The elements of a set \( R \) may be reorganized using an \textit{organize} operation that rearranges the elements of \( R \). The \textit{organize} operation operates on \( R \) before the \textit{select} operation. A simple example of \textit{organize} operation is the identity function that given a natural number \( i : 1 \leq i \leq \#R \) returns the \( i \)th element of set \( R \). Another example of \textit{organize} operation is the fixed size partitioning algorithm that first organizes the resource units into fixed sized allocation units, and then selects an allocation unit according to an \( addr \) defined over them. Composing the specific \textit{select} and \textit{organize} operations on some resource \( R \) yields a family of algorithms. For instance, the first-come-first-served algorithm is simply: \textit{identity} (identity \( R \)), where we have used the identity function as instances of both, the \textit{select} and the \textit{organize}, operations. The buddy allocation algorithm may be considered to be composed of a tree traversal based selection that operates on a resource set organized into a binary tree.

The set \( P \) may also be subject to reorganization independent of any organization of the set \( R \) of resource elements. The shortest-job-size-first algorithm is: \textit{identity} (sort \( (P, s_i) \)), where \( s_i \equiv \text{project} (1, \text{project} (i, P)) \), projects out the first parameter, size, of the \( i \)th procedure from \( P \). The shortest-job-time-first algorithm is: \textit{identity} (sort \( (P, t_i) \)), where \( t_i \equiv \text{project} (2, \text{project} (i, P)) \), projects out the second parameter, CPU time, of the \( i \)th procedure from \( P \). The \textit{sort} operation reorganizes \( R \) and the \textit{identity} operation selects an element from the reorganized set. If each element of \( P \) is arbitrarily associated with an externally specified natural
number, the priority of the procedure, we have priority based procedure selection. Since a high priority process must also be allocated memory resource (i.e. $R \equiv M$), we compose the manipulation of $P$ and the manipulation of the memory resource $M$. If we use buddy allocator for manipulating $M$, we have a high priority procedure allocated using buddy methods. The binding principle demands that the priority selection mechanism and the buddy organization mechanism may be established in any order before combining them.

Until this point we have assumed that procedures are indivisible in the sense that their resource needs are either to be completely satisfied or not at all. However, it is possible to partially satisfy the resource needs by dividing the needs into smaller chunks. If the chunking is variable sized, e.g. due to cognizance of the internal structure of the procedure, we have segmentation algorithms for memory, and I/O-bound–CPU-bound algorithms for CPU time. If the chunking disregards any internal structure and partitions the resource needs into equal chunks we have paging algorithms for memory resource and round robin algorithm for CPU time resource. Additionally, we have assumed that the cardinality of sets, like $P$, is constant. Using a countably infinite set $P$ yields a more realistic OS that keeps executing processes as they are fired. Also the size of the elements of the sets, e.g. a procedure in $P$, is also constant. Varying sizes of procedures allows mechanisms like plugins. These variations must be designed in accordance with the binding principle.

Another implicit assumption is that a specification of a set, say $R$ of some resource, is bound to the corresponding physical resource. This can be relaxed to yield an interesting possibility. If $R$ is instead bound to another set $R'$, and $R'$ is then bound to the actual resource, we have resource virtualization. This is used in segmentation and paging methods in OSes. The primary memory resource specification is bound to a set $M$ over which segmentation is defined. $M$ is then bound to the physical primary memory $M'$ over which paging is defined, with $\#M' \neq \#M$ as a possibility.

Finally, we have implicitly assumed that the subsets of resources are always disjoint. The disjointness will always hold for the non-reusable CPU time resource on single processor computing systems. However, for the reusable memory resource this disjointness may not hold. If two distinct subsets have a non-empty intersection, we have resource sharing, and write accesses to the shared area must be temporally sequenced. This is the critical section problem, and its temporal nature cannot be adequately captured by our structural approach.

To preserve space, we have presented the essential approach to resource management algorithms using subsets. The details examine the various implicit assumptions as indicated above, and relax them to obtain the framework. Also included are other properties of resources like finiteness and reusability (e.g. memories) that lead to deallocation algorithms and non primary property of secondary memories for swapping techniques. Swapping is viewed as a mechanism to extend the primary memory using a fraction of the secondary memory given that procedures must be swapped back to primary memory for execution. Security issues are also not shown since they are influenced by external environment of the computing system that drives the definition of resource subsets. However, they may be considered as inducing equivalence class partitioning based on externally defined criteria like ownership.

Our approach of describing resource management views the problem as a binding problem between a procedures set $P$ and a resource set $R$. Resources management operations induce an equivalence class partitioning of the sets, and the variations in binding the members of the two emerge from the manipulation of the sets and their elements. Various algorithms that perform the generic operations like select and organize, and their compositions according to the principles in section 3.3 yield the various specific structural algorithms of an OS. This approach thus unifies the algorithms into a systematic framework. However, our approach does not yield algorithms that need to consider process behavior, e.g. deadlocks and synchronization.

5 Application to a Unix like OS

So far we have intensionally defined an OS, induced some useful principles, and formally described the resource algorithms using subsets. We now discuss their impact on the architecture of a Unix like OS whose kernel is as described by Bach [51]. An example is the GNU/Linux OS, which is made up of the kernel and other system software. The definition 1 requires a well defined high level machine. The $\lambda$ calculus model is a good high level machine for an OS. It is an intuitively simple view for an end user since it strips
off all the unnecessary details. After all, an algorithm needs the ability to identify its distinct component objects, prescriptions that describe transformation of some objects into others, and an ability to apply a prescription to the components of the algorithm. The rules of the $\lambda$ calculus capture this intuition. A computer user is typically concerned with obtaining the results of applying some transformation on some objects. Technological details like the representation of the components, their storage and retrieval, or the variety of ways in which they may be made to interact via applications are not relevant to the end user. The $\lambda$ calculus view of computation can be the candidate high level machine if the technical details are hidden away through techniques like file format standardization and implicit memory management. The user level view and the kernel level views in Yates et al. respectively can now correspond to the high level almost functional machine (the user view) and a low level imperative machine (the kernel view) [5].

The GNU/Linux is built over low level Turing machine like hardware with an empirically defined higher level. It is an almost $\lambda$ calculus type machine with sophisticated naming capabilities via icons, application capabilities via drag-and-drop techniques, and the compositional capabilities of the command line. It still has some way to go to reach full capabilities of the functional approach. For instance, anonymous $\lambda$ expressions are still to be realized, and still more simply not all programs return values called “exit codes” to the OS.

Despite these shortcomings we argue that GNU/Linux aims for the $\lambda$ calculus model as the high level computation model. The $\lambda$ calculus requires three abilities: naming, function abstraction, and application. As a candidate high level machine for an OS, the reductions are implicit within the OS. At the low level we are given an infinite countable tape – the primary memory, a head that captures the state transition abilities – the CPU ISA, and the basic read-write operations on the tape.

A name binds a symbol to an object in the system. Within GNU/Linux procedures are named using process identifiers, and files are named using strings. Other ways of naming files are through memory addresses (e.g. register names, memory location values, pointers), I/O ports (hardware or software enumerated), and device names. The abstraction level of names is elevated by using file systems that organize primitive names into path names that are bound to objects. In the primary memory, files are named using natural numbers called file descriptors.

A function application is expressed simply as program with arguments for operation, or even as a drag-and-drop operation. In response, an OS loads the program into primary memory as a file, completes any contextual bindings required, and obtains a procedure that can be scheduled. This is the conventional process.

To run a function application, a CPU time schedule must be determined. An OS has a set of one or more applications to run, and a CPU time allocation strategy. To switch between the function applications an OS computes the closure to capture the data state and the continuation to capture the control state. These may additionally be manipulated too. For example, an exec() call overwrites the closure and continuation of the parent with new ones.

Most current OSes distinguish between “executables” and “(data) files”, particularly for security and trust reasons. First classness shows that such distinction is not fundamental to OSes. The binding principle is used to determine the boundaries between the kernel, the system libraries, the system software and application software. A monolithic kernel can be viewed as a single set of bindings obtained by moving as many bindings as possible as early as possible into their expression. Exokernels support reshaping the bindings at runtime. Microkernels further refine the single set of bindings into multiple sets. System libraries may enhance the kernel bindings, e.g. socket abstractions for IPC, and language libraries may adapt bindings, e.g. fopen() over open(). Libraries can also extend the abstraction level of the OS, e.g. garbage collectors. While the bridging principle can identify the intermediates, the binding principle defines the allowed permutations.

An OS like the GNU/Linux can be viewed as an yet to be completed program to create a functional style high level machine over an imperative low level machine. It is difficult to express and execute higher order procedures, anonymous procedures etc. Lazy evaluation is also partial, e.g. Unix pipes.
6 Conclusions and future work

An intensional definition of an OS and procedures, and some induced principles is the main core of this work. This attempt yields an insight into the connection between the formal models of computation and OS practice. We separate the structural and behavioral aspects of OSes, and handle the structural aspects via equivalence class partitioning of resource sets. We present some principles that capture general properties, help identify the intermediate steps and define their correct arrangement during the bridging process. While some principles are directly useful in devising algorithms, some are still ostensive. Given a well defined purpose of a Unix like OS, our approach offers a high level understanding and can also point out some next technical directions.

The behavioral aspects of an OS need a suitable process algebra formulation. Other future work involves carrying out better studies of the abstract machines in an OS via techniques like ASM or abstract interpretation. In principle, adapting some program analysis formalisms (e.g., [52]) for OSes could be useful for exokernels, microkernels and architecture restructuring, but is a significant challenge. Another interesting possibility is a more declarative view of an OS with potential for generation of its imperative view and for formal verification problems. Parallel computing systems cannot be handled at the moment due to the lack of a good model to capture variations from co-processing to cluster computing to fully distributed computing.

We also envisage a more esoteric future work. The world view of the physical sciences expresses natural laws through Lagrangian or Hamiltonian formulations that are based on an extremum principle. Given a universal machine view of an OS, we may view computation as made up of a “kinetic” component – the process causing state transitions, and the “potential” component – the file that maintains the state. It would be interesting to explore for an extremum principle for computation.
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