Hierarchical Complexity: Measures of High Level Modularity

Alex Fernández (alejandrofer@gmail.com)

January 20, 2013

Abstract

Software is among the most complex endeavors of the human mind; large scale systems can have tens of millions of lines of source code. However, seldom is complexity measured above the lowest level of code, and sometimes source code files or low level modules. In this paper a hierarchical approach is explored in order to find a set of metrics that can measure higher levels of organization. These metrics are then used on a few popular free software packages (totaling more than 25 million lines of code) to check their efficiency and coherency.

1 Introduction

There is a high volume of literature devoted to measuring complexity. Several metrics have been proposed to measure complexity in software packages. At the code level there is for example McCabe’s cyclomatic complexity [1]. Complexity in modules (sometimes equated to source code files, in other occasions low level aggregations of code) has also been studied, and its relationship to quality has been measured [2].

But modern software packages can have millions or tens of millions of source code; just one level of modularity is not enough to make complex or large software systems manageable. And indeed an exploration of large system development (made possible thanks to open development of free software) systematically reveals a hierarchy of levels that contains subsystems, libraries, modules and other components. But to date no theoretical approach has been developed to measure and understand this hierarchy. This paper presents a novel way to study this problem; the particular set of metrics derived can be seen as a first order approach, to be refined in subsequent research when the problem reaches a wider audience.

1.1 Contents

This first section contains this short introduction; the second is devoted to the study of hierarchical complexity and modularity from a theoretical point of view. Section 3 explains the experimental setup that will be used for measurements. In section 4 the source code of several software packages is measured to verify the theoretical assumptions, and the results are analyzed. Finally, the last section contains some conclusions.
that can be extracted from this approach, in light of the theoretical analysis and the experimental results.

1.2 Conventions

Portions of source code are shown in a non-proportional font: \texttt{org.eclipse}. File names are also shown in non-proportional type, and also in italics: \texttt{org/eclipse}. Commands are shown indented in their own line, like this:

\begin{verbatim}
find . ! -name "*.c" -delete
\end{verbatim}

Terms being defined appear within single quotes: ‘exponential tree’, while terms already defined in the text or assumed are in double quotes: “combinatorial complexity”.

2 Theoretical Approach

Complexity is the bane of software development. Large scale systems routinely defy the understanding and comprehension powers of the brightest individuals; small scale systems suffer from poor maintainability, and it is often cheaper to rewrite old programs than to try to understand them.

Against this complexity there is basically one weapon: modularity. No other technique (cataloging, automation, graphical environments) works for large system development, but our tools to measure it are scarce. In this section a new metric for complexity measurements is proposed.

2.1 Hierarchical Complexity

In 1991 Capers Jones proposed several measures of complexity for software \cite{3}. One of them was “combinatorial complexity”, dealing with the ways to integrate different components; another was “organizational complexity”, this time dealing with the organization that produces the software. But no attention was given to the fact that large-scale software is organized in multiple levels.

Several notions related to high level organization have since been advanced in the literature \cite{4,5}. However, when the time comes to measure complexity in a system it is still the norm to resort on measuring interfaces\cite{6}, code-level complexity \cite{7} or just lines of code per module \cite{8}. Given that the real challenge in software engineering does not currently lie in algorithmic complexity or cyclomatic complexity, but in the complexity of high level organization, some metrics to explore complexity in the component hierarchy should be a useful addition to the software engineering toolbox. The term “hierarchical complexity” seems a good fit for the magnitude being measured.

2.2 System and Components

A ‘system’ can be defined as a global entity, which is seen from the outside.

A ‘component’ (often called “module”) is an internal part of the system which is relatively independent, and which hides its inner workings from the rest of the system.
It communicates with the rest of the system via ‘interfaces’: predefined aggregations of behavior.

We can then redefine a ‘system’ as a collection of components and the interfaces that connect them. Underlying this definition is the presumption that a system has well defined components; as we will see, at some level it holds true for any non-trivial software system.

A system can also be divided in subsystems. A ‘subsystem’ is a high-level component inside a system. In turn, a component can be divided into subcomponents; for each of them, the container component is their “system”. In other words, any component can be seen as a whole system, which interfaces with other systems at the same level.

When the system is viewed in this light, a hierarchy of levels emerges: the main system is made of subsystems, which can often be decomposed into components, in turn divided into subcomponents. The number of levels varies roughly with the size of the system; for small software projects one or two levels can be enough, while large scale developments often have more than five levels.

2.3 Articulation

The way that these levels are organized is a crucial aspect of modularity. It is not enough to keep a neat division between modules; for robust and maintainable systems to emerge, connections between levels must follow a strict hierarchy. The alternative is what is commonly called “spaghetti code”.

There are many different names for components at various levels. Depending on the domain and the depth we can find subsystems, modules, plugins, components, directories, libraries, packages and a few more. It is always a good idea to choose a standard set of levels for a given system and use them consistently. The selection of names should be done according to whatever is usual in the system’s domain, e.g.: in operating systems “subsystems” are commonly used as first level, as in “networking subsystem”; while in financial packages “modules” is the common division (as in “supply chain module”). Finally, ambiguities should be avoided: e.g. in this paper “software package” is used in this paper in the sense of “complete software systems”, so when adding a component level of “packages” the difference must be noted.

In the lowest levels it is often the programming language itself that drives (and sometimes enforces) modularity. In object-oriented languages, classes are containers of behavior that hide their internal workings (like attributes or variables), and are in fact a perfect example of components. Procedural languages usually keep some degree of modularity within source code files: some of the behavior can be hidden from other files.

Functions are at the bottom of the hierarchy. A ‘function’ (also called “subroutine” or “method”) is a collection of language statements with a common interface that are executed in sequence. A function certainly hides its behavior from the outside, so it can be seen as the lowest level component, or it can be seen as the highest level of non-components. The first point of view will be chosen here.

Statements (or lines of code) are the low level elements, but they can hardly be considered components themselves from the point of view of the programming language:
they do not hide their internal workings, nor have an interface. There is however one sense in which they can actually be considered components: as entry points to processor instructions. A line of code will normally be translated into several machine-code instructions, which will in turn be run on the processor. The line of code hides the internal workings of the processor and presents a common interface in the chosen language; if a function call is performed, the language statement hides the complexity of converting the parameters if necessary, storing them and jumping to the desired location, and finally returning to the calling routine. Since in software development machine-code instructions are seldom considered except for debugging or optimization purposes, lines of code remain as “borderline components” and will be considered as units for the purposes of this study.

Lines of source code can be unreliable as economic indicators [9], but they are good candidates for the simplest bricks out of which software is made once comments and blank lines are removed. Source code statements are more reliable but the added effort is not always worth the extra precision. In what follows the unit for non-blank, non-comment source code line will be written like this: “LOC”, with international system prefixes such as “kLOC” for a thousand lines and “MLOC” for a million lines.

To capitulate, a function is made of lines of code, and a class is made of a number of functions (plus other things). Classes are kept in source code files, and files are combined into low level components. Components aggregate into higher level components, until at the last two steps we find subsystems and the complete system.

2.4 A Few Numbers

We will now check these theoretical grounds with some numerical estimations.

The “magic number” 7 will be used as an approximation of a manageable quantity; in particular the “magic range” 7 ± 2. It is common to use the interval 7 ± 2 in that fashion [10, 11], and yet Miller’s original study [12] does not warrant it except as the number of things that can be counted as a glance. Even so, it seems to be a reasonable cognitive limit for the number of things that can be considered at the same time.

The main assumption for this subsection is thus that a system is more maintainable if it is composed of 7 ± 2 components. In this range its internal organization can be apprehended with ease. Each of these components will in turn contain 7 ± 2 subcomponents, and so on for each level. In the lowest level, functions with 7 ± 2 LOC will be more manageable. In this fashion systems with 7 ± 2 subsystems, packages with 7 ± 2 classes, classes with 7 ± 2 functions and functions with 7 ± 2 LOC will be preferred. At each level a new type of component will be chosen; arbitrary names are given so as to resemble a typical software organization.

The problem can thus be formulated as follows: if each component contains 7 ± 2 subcomponents, what would be the total system size (measured in LOC) for a given depth of levels? Put another way, how many levels of components will be needed for a given LOC count? (Again, the lowest level containing LOC themselves does not count as a level of components.)

Let us first study the nominal value of the range, 7. For only 3 levels of components,
a reasonable amount for a small system, the total LOC count will be

\[
7 \text{packages} \times 7 \frac{\text{classes}}{\text{package}} \times 7 \frac{\text{functions}}{\text{class}} \times 7 \frac{\text{LOC}}{\text{function}} = 2401\text{LOC}.
\]

When there are 4 levels of components, including in this case “subsystems”, the result is

\[
7 \text{subsystems} \times 7 \frac{\text{packages}}{\text{subsystem}} \times 7 \frac{\text{classes}}{\text{package}} \times 7 \frac{\text{functions}}{\text{class}} \times 7 \frac{\text{LOC}}{\text{function}} = 16807\text{LOC}.
\]

For bigger systems a new level of “modules” is added:

\[
7 \text{subsystems} \times 7 \frac{\text{modules}}{\text{subsystem}} \times 7 \frac{\text{packages}}{\text{module}} \times 7 \frac{\text{classes}}{\text{package}} \times 7 \frac{\text{functions}}{\text{class}} \times 7 \frac{\text{LOC}}{\text{function}} = 117649\text{LOC} \approx 117\text{kLOC}.
\]

A respectable system of 100kLOC is already reached with 5 levels. At depth 6 (inserting a level of “libraries”) the total LOC count will now be:

\[
7 \text{subsystems} \times 7 \frac{\text{libraries}}{\text{subsystem}} \times 7 \frac{\text{modules}}{\text{library}} \times 7 \frac{\text{packages}}{\text{module}} \times 7 \frac{\text{classes}}{\text{package}} \times 7 \frac{\text{functions}}{\text{class}} \times 7 \frac{\text{LOC}}{\text{function}} = 823543\text{LOC} \approx 824\text{kLOC}.
\]

The limit of reason ability can again be estimated using the “magic number” as 7 levels, adding a last level of “subprojects”:

\[
7 \text{subsystems} \times 7 \frac{\text{subproject}}{\text{subsystem}} \times 7 \frac{\text{libraries}}{\text{subproject}} \times 7 \frac{\text{modules}}{\text{library}} \times 7 \frac{\text{packages}}{\text{module}} \times 7 \frac{\text{classes}}{\text{package}} \times 7 \frac{\text{functions}}{\text{class}} \times 7 \frac{\text{LOC}}{\text{function}} = 5764801\text{LOC} \approx 5765\text{kLOC} \approx 5.8\text{MLOC}.
\]

There are of course systems bigger than 6 million lines of code. A few ways to extend LOC count can be noted:

- Some particular level might contain quite more than 7 subcomponents. For example, when classes are counted some of them (those in auxiliary or “scaffolding” code) can be left out, since they do not belong to the core of the model and do not necessarily add complexity.

- We have seen that LOCs are not components, so the $7 \pm 2$ rule of thumb would not apply at the lowest level. Having e.g. 21 LOCs would yield a total three times higher for every depth.

- Using the high value in the “magic range” $7 \pm 2$, 9, total size goes up considerably. At the highest depth considered above, with 7 levels, size would be $9^8 = 43046721$, or about 43 million LOC.
• The “magic range” can also apply to the number of levels, yielding a total of 9 levels of components. In this case, $7^{10} = 282475249$, yielding about 282 million LOC. In the most extreme high range we would have $9^{10} = 3 \cdot 10^9$ or 3486 million MLOC, as the most complex system that could be built and maintained.

• Lastly, it is quite likely that systems bigger than five million LOC are indeed too complex to grasp by any single person (or even a team). A system with five million LOC is already a challenge for anyone.

It must be noted that the “magic range” does not apply to depth as such for two different reasons. First, a limit should be sought rather than a range. Small systems cannot be expected to fall within the range, if they don’t have enough components as to warrant a minimum of 5 levels. Therefore values below the range are acceptable too; it is the upper end of the range where it becomes relevant.

A more important objection is that the “magic range” was introduced above as a cognitive limit for things which have to be considered at the same time. But component levels are introduced precisely to avoid considering too many components at the same time; much less levels of components. There is no real reasoning where all levels of components have to be considered at the same time, other than to catalog them; therefore, systems with more than $7 \pm 2$ levels of components do not have to be intrinsically harder to manage than systems with less, other than they become really big at that depth.

2.5 Generalization

Let $d$ be the depth of the component hierarchy (i.e. the number of levels of components), and $c(i)$ the number of elements at level $i$; for $i > 0$, $c(i)$ is also the number of subcomponents. Then the total size $S$ (in LOC) will be

$$S = \prod_{i=0}^{d} c(i),$$

where $c(0)$ is the number of LOC per function and $c(1)$ the number of functions per file. Assuming that $c(i)$ is always in the magic range:

$$c(i) \approx 7 \pm 2,$$

from where

$$S \approx (7 \pm 2)^{d+1}.$$

Table 1 summarizes the estimated number of LOC that result from three values in the range $7 \pm 2$: both endpoints and the mean value. They can be considered to be representative of trivial (5), nominal (7), and complex systems (9). Several depths of levels are shown.

A system whose code is nearer the trivial end will be easy to understand and master; not only at the lowest code level, but its internal organization. On the other hand, a complex system will take more effort to understand, and consequently to maintain and extend. This effort is not only metaphorical: it translates directly into maintenance costs. An effort to first simplify such a system before attempting to extend it might be worth it from an economic point of view.
| depth | trivial (5) | nominal (7) | complex (9) |
|-------|-------------|-------------|-------------|
| 3     | 0.6kLOC     | 2.4kLOC     | 6.6kLOC     |
| 4     | 3.1kLOC     | 16.8kLOC    | 59kLOC      |
| 5     | 15.6kLOC    | 118kLOC     | 531kLOC     |
| 6     | 78kLOC      | 824kLOC     | 4783kLOC    |
| 7     | 391kLOC     | 5765kLOC    | 43MLOC      |
| 8     | 1953kLOC    | 40MLOC      | 387MLOC     |
| 9     | 9766kLOC    | 282MLOC     | 3486MLOC    |

Table 1: Number of LOC that corresponds to several depths of levels. For each depth the low, mean and high values of the “magic range" $7 \pm 2$ are shown; representative of trivial, nominal or complex systems.

2.6 Measurement

Lines of source code (however imperfect they may be) can be counted; function definitions can be located using regular expressions. But it is not easy to get an idea of the number of components in a system. The basic assumption for the whole study is that source code will be structured on disk according to its logical organization; each directory will represent a logical component.

An exact measure of modularity would require a thorough study of the design documents for the software package: first finding out the number of component levels, then gathering the names of components at each level and finally counting the number of components. Unfortunately, such a study cannot be performed automatically; it would only be feasible on small packages or after a staff-intensive procedure.

A metric based on directories has the big advantage of being easy to compute and manipulate. It has the disadvantage of imprecision: to some degree developers may want to arrange files in a manageable fashion without regard for the logical structure. Developers may also have an on-disk organization that does not encapsulate internal behavior and just keeps files well sorted according to some other formal criteria. Alternatively a software package might be organized logically into a hierarchy of components, but lack a similar on-disk organization.

Finally, it is of course perfectly possible to rearrange the source files in new directories to make the code look modular, without actually changing its internal structure; organization in directories would allow trivial cheating if used e.g. as an acceptance validation. Since this measure is not in use today this last concern does not apply, but it should be taken into account for real-life uses. In software developed commercially component hierarchies should always be documented, and automatic checking should only be used as an aid to visual inspections.

3 Methodology

The study is performed on several free software packages. Ubuntu Linux is used for the analysis, but about any modern Unix (complemented with common GNU packages) should suffice. For each step, the Bash shell commands are shown.
3.1 Package Selection and Downloading

Several free software packages are selected for study. The requirement to choose only free software is intended to make this study replicable by any interested party; source code can be made freely available. The selection of individual packages was made according to the following criteria:

- Every package should be relevant: well known in a wide circle of developers and users.
- Every package should be successful within its niche; this ensures that only code which is more or less in a good shape is chosen.
- Every package should be big enough for a study on complexity; only software packages bigger than half a million lines of source code were selected. On the other hand measures should cover about an order of magnitude. Therefore the selected packages will be in the range 500kLOC to 5000kLOC.
- At least two packages for each language should be selected.
- Only packages with several authors should be chosen, so that individual coding styles are not prevalent.

Overall, packages should be written in different languages, so as to have a varied sample of programming environments.

Once selected, for each package a fresh copy was downloaded in October 2006 to February 2007 from the public distribution. Those packages that are offered as a single compressed file are downloaded and uncompressed in their own directory. Some packages have their own download mechanisms. For the GNOME desktop, GARNOME was used [13]: it downloads the required tools and builds the desktop.

3.2 Basic Metrics

The first step is identifying what the target language is, and keeping just files in that language. It is difficult to find a software project this size written in only one language; for this study the main language of each package (in terms of size) was selected, the rest were discarded.

The file name is used to identify source code files. For C we can choose to keep just those files ending in \*.c, what is usually called the “extension”. C header files (with the extension \*.h) are ignored, since they are usually stored along with the equivalent C source code files. Table 2 shows the extensions for all languages used in the present study. Then the rest of the files can be deleted:

```
find . ! -name "*.c" -delete
```

This command removes all files not in the target language; it also removes all directories that do not contain any target language files. This step is repeated as needed in case deletion was not strictly sequential (i.e. a directory was processed before the items it contains), until no more directories are removed. Then directories are counted:
find . -type d | wc -l

All files in the target language are counted too:

find . -name "*.c" | wc -l

Lines of code are counted removing blanks and comments. C++ and Java are derivatives of C, and therefore share a common structure for comments. Note that lines consisting of opening and closing braces are excluded too, in order to remove a certain degree of “programming style” from them.

find . -name "*.c" -print0 | xargs -0 cat \
  | grep -v "^[[:space:]]*$" | grep -v "^[[:space:]]*\$" \
  | grep -v "^[[:space:]]*{^[[:space:]]*$" \
  | grep -v "^[[:space:]]*}\^[[:space:]]*$" \
  | grep -v "^[[:space:]]*//" | wc -l

The results obtained with this method are not perfect, but they have been found to be a reasonable fit. Similar expressions are used for Lisp and Perl taking into account their respective syntax for comments. For the actual results presented in this study several equivalent regular expressions are used to remove comments, with slightly more accurate results.

The number of functions is also counted using full-blown regular expressions. Table 2 shows the regular expressions used for each language to locate function definitions in the code.

| language | extension | function definition |
|----------|-----------|---------------------|
| C        | "c"       | (\w+)\s*([[:space:]*,]\&\*\*\*)\s*; |
| C++      | "cpp",".cxx",".cc" | (\w+)\s*([[:space:]*,]\&\*\*\*)\s*{ |
| Java     | "java"   | (\w+)\s*([[:space:]*,]\&\*\*\*)\s*{ |
|          |           | (?=throws)\s*\w+(?:\s*\\\s*\w+)*\s*{ |
|          |           | \s*\w+)*\s*{ |
| Lisp     | "el"     | (\w+)\s*{ |
|          |           | (<=sub)\s*\w+)*\s*{ |
| Perl     | "pl",".plx",".pm" | (\w+)\s*{ |
|          |           | (<=sub)\s*\w+)*\s*{ |

Table 2: File extensions for different languages. The right-most column shows the regular expression used to find function definitions for each language.

A Python script iterates over every directory and file with the correct extension, and counts the number of matches for the appropriate regular expression. Again, the results have been inspected for correctness. They are not perfect; for example, some C++ function definitions may call parent functions, and when they contain typecasts they will not be registered under this definition. C++ template code is not considered either. They are however a good enough compromise; not too slow but not too precise.

Note that C and C++ headers are not used to find function definitions. There are several reasons for this decision. First, header files usually contain only function definitions, while function declarations are in source files (except for inlined functions). And second and most important, it is hard to distinguish between C and C++ headers since they follow the same pattern (both share the extension “.h”), so they would get mixed
in the process for projects that contain code in both languages. In field experiments the results are not affected by this omission.

3.3 Average Directory Depth

A first approximation to complexity is to find out the depth of each source code file, and compute an average. This operation can be performed using a sequence of commands like this (for C code):

```
tree | grep "\.c" | grep ".--" | wc -l
```
```
tree | grep "\.c" | grep ". .--" | wc -l
```
```
tree | grep "\.c" | grep ". . .--" | wc -l
```
...

thus getting the source file counts for level 0, 1, 2... and computing the differences to obtain the number of files at each level of directories. An average depth can then be easily computed, where the depth for each file is the number of directories that contain it. Table 3 shows the number of source files at each level for a few packages.

| package     | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   |
|-------------|------|------|------|------|------|------|------|------|------|------|
| Linux       | 297  | 2474 | 4451 | 1050 | 142  | 0    | 0    | 0    | 0    | 0    |
| OpenSolaris | 0    | 2    | 1529 | 3686 | 5082 | 1850 | 340  | 104  | 10   | 3    |
| Eclipse     | 2    | 0    | 89   | 228  | 2045 | 4136 | 4674 | 2973 | 407  | 0    |

Table 3: Depth of source code files for selected software packages.

Figure 1 shows the previous distribution graphically. Each set of depths can be approximated by a normal distribution.

This approach has several problems. Many packages contain directories with only one subdirectory, e.g. a directory called `source` or `src` which contains all source code; this is an artifact of the source distribution and should not be taken into account. In other occasions folders are repeated across the board, as in Java packages: the convention here is to start all packages with a prefix that depends on the organization that develops the code, and continue with the name of the organization and possibly some other fixed directories [14]. E.g. for Eclipse all packages should start with `org.eclipse`, which results in folders `org/eclipse`; this structure is repeated inside each individual project within the Eclipse source code. Visual inspection of the result is therefore necessary to disregard those meaningless directories.

The results are less than satisfactory. In what follows an alternative approach will be explored.

3.4 Average Number of Items per Directory

The target of complexity measurements is to find the number of subcomponents per component. From the number of archives and the number of directories a rough approximation to modularity can be computed, as the ratio between files and directories. But directories can also be contained in other directories, counting as subcomponents.
Let \( T \) be the total number of source files, and \( D \) be the number of directories. Then the average number of items per directory \( a \) can be computed as

\[
a = \frac{T + D}{D + 1},
\]

(2)
counting one more directory in the denominator for the root directory. It is a measure of the average number of subcomponents per component.

### 3.5 Average Exponential Depth

Once the average number of items per directory is known, another approach to compute the average depth can be used.

An ‘exponential tree’ is a tree of directories that has the same number of items at every level. The last level contains only files; all the rest contain only directories. Figure 2 shows two examples of exponential trees: one with 3 items per directory and 2 levels, for a total of \( 3^2 = 9 \) source code files; and one with 2 items per directory and 3 levels, yielding \( 2^3 = 8 \) source files. The root directory is not counted.

Symbolically:

\[
T = a^l,
\]

(3)

where \( T \) is the total number of files, and \( a \) the number of items per directory. The number of files in the tree grows exponentially with its depth \( l \).

If the tree of source code files and directories is approximated by an exponential tree, then at each level \( i \) the complexity would be constant: \( c(i) = a \). If such a tree has
Figure 2: Two examples of exponential trees. The number of items (directories and files) per directory at each level is constant throughout the tree.

If levels, then equation\[3\] can be written as:

\[ T = \prod_{i=2}^{l+1} c(i) = a^l, \]  

where levels are counted from 2 to \( l + 1 \) because level 1 is for functions inside files.
The component hierarchy will actually have \( l + 1 \) levels. With some arithmetic we get:

\[ l = \frac{\ln(T)}{\ln(a)}, \]

which considering equation\[2\] can be restated as

\[ l = \frac{\ln(T)}{\ln(T + D) - \ln(D + 1)} \]  

and which can be computed just knowing the number of source files and the number of directories.

This value represents the depth that an exponential tree would need to have in order to produce the observed number of source code files; the approximation is evidenced by the presence of fractional depths. If the overall number of levels follows the 7 ± 2 rule, the value for exponential depth should cluster around 6, since it does not take into consideration the lowest function level. Symbolically:

\[ l = d - 1 \approx 6 \pm 2. \]

3.6 Pruning

Consolidation can play an important role in some source code layouts. Each subsystem may have its own hierarchy of directories like src; they add to the count of directories
but do not really add either complexity or modularity. This effect can be exacerbated in some Java projects (particularly those organized around Eclipse projects), where the common hierarchy of packages (like `org.eclipse...`) is repeated for every sub-project, inside the `src` folder. Directories should be consolidated removing repeated occurrences prior to measuring, but this operation requires intimate knowledge of the structure of the software and will not be done here.

A more practical approximation to consolidation can be done by pruning the source code tree. A certain amount of pruning has already been done in subsection 3.2: non-source files and empty directories have already been pruned, but a more aggressive approach is required. The number of reported directories is in many instances not consistent with.

‘Trivial’ directories are those containing just one meaningful item: either one code file or one meaningful directory. (A ‘meaningful’ directory is one which contains source code at any level.) These trivial directories cannot add to the component hierarchy, since a component with one subcomponent is meaningless; therefore they are not counted as directories. Figure 3 shows an example of pruning a source code tree.

In practice, a small Python script (available upon request from the author) is used to count source files and directories, discount trivial directories, recalculate the values for $T$ and $D$, and recompute the average number of items per directory.

Again, the results are not perfect since pruning does not yield the same results as consolidation: some internal structure can be lost in the process, so this time it tends to underestimate the number of directories, albeit in a smaller percentage. Figure 3 shows an example of pruning compared to consolidation.

Nevertheless, pruned values seem to follow code organization more closely than in the original model, so they will be used in the final results.
4 Results

The following tables summarize the results for a selected range of software projects.

4.1 Basic Metrics

Table 4 shows the results of computing some basic metrics against the selected software packages.

It must be noted how non-modular the code of Emacs really is, evident even in these direct measurements.

4.2 Average Items per Directory

These basic metrics allow us to compute some basic complexity metrics. Table 5 shows LOC per function (an indication of the lowest level of articulation), functions per file (the first level of components) and items per directory (all the remaining levels of components).

Both LOC per function and functions per file are shown separately from the remaining levels, items per directory. And indeed we find a bigger disparity in LOC per function than in the remaining metrics; from the 8.6 found in JBoss or NetBeans to the
Table 4: Lines of code, function definitions, source files and directories for selected free software packages.

| package                | language | kLOC  | functions | files | directories |
|------------------------|----------|-------|-----------|-------|-------------|
| Linux 2.6.18           | C        | 3388  | 134682    | 8414  | 902         |
| OpenSolaris 20061009   | C        | 4299  | 120925    | 12606 | 2525        |
| GNOME 2.16.1           | C        | 3955  | 163975    | 10025 | 1965        |
| KDE 20061023           | C++      | 2233  | 172761    | 11016 | 1602        |
| KOffice 20061023       | C++      | 511   | 31880     | 2204  | 375         |
| OpenOffice.org C680_m7 | C++      | 3446  | 114250    | 11021 | 1513        |
| SeaMonkey 1.0.6        | C++      | 1180  | 69049     | 4556  | 884         |
| Eclipse 3.2.1          | Java     | 1560  | 163838    | 14645 | 2334        |
| NetBeans 5.5           | Java     | 1615  | 187212    | 16563 | 6605        |
| JBoss 5.0.0.Beta1      | Java     | 471   | 54645     | 9504  | 2478        |
| Emacs 21.4             | Lisp     | 473   | 18931     | 759   | 18          |
| XEmacs-Packages 21.4.19| Lisp     | 926   | 37415     | 2133  | 285         |

35.6 in OpenSolaris. In functions per file both procedural and functional languages (C and Lisp) appear to be similar to C++; only Java shows lower values.

In the remaining metric, items per directory, only two packages are above the “magic range” 7 ± 2: Emacs and Linux. Emacs stands out as the less modular of all packages with difference, which is consistent with its long heritage: it is an ancient package which has seen little in the way of modern practices, and which is not really modularized. The modernized version, XEmacs, shows a profile more coherent with modern practices, although only the separate packages are measured. Linux, on the other hand, is a monolithic kernel design with a very practical approach. This seems to result in source code which is not always as well modular as it might be. JBoss is also out of range by a very small amount, but this time it is the low end of the range (4.84 items per directory). Its code is very modular, so much so that with only half a million LOC it has the second highest directory count. The first position goes to NetBeans, with 3.51 items per directory; it has by far the highest directory count.

These first impressions are refined and expanded in subsection 4.6.

### 4.3 Average depth

Average depth is computed using two algorithms: average directory depth (see subsection 3.3) and average exponential depth (see equation 5 in subsection 3.5). Table 6 shows the average depth for the usual set of packages, calculated using both methods.

The biggest difference between both methods happens in KDE (3.2 vs 4.5), GNOME (3.8 vs 5.1) and Linux (2.8 vs 3.9). The values of directory depth for the first two packages involve heavy corrections due to directories with just one subdirectory in the tree; for Linux however there are no such corrections, but there is a big disparity between some directories which can contain up to 116 items, like “/fs”, and others with just one item. The rest of the packages are within a level in both measures. Exponential depth does not involve error-prone corrections and will therefore be used in what
Table 5: Basic complexity metrics.

| package                  | LOC/function | functions/file | items/directory |
|--------------------------|--------------|----------------|-----------------|
| Linux 2.6.18             | 25.2         | 16.0           | 10.33           |
| OpenSolaris 20061009     | 35.6         | 9.6            | 5.99            |
| GNOME 2.16.1             | 24.1         | 16.4           | 6.10            |
| KDE 20061023             | 12.9         | 15.7           | 7.88            |
| KOffice 20061023         | 16.0         | 14.5           | 6.88            |
| OpenOffice.org C680_m7   | 30.2         | 10.4           | 8.28            |
| SeaMonkey 1.0.6          | 17.1         | 15.2           | 6.15            |
| Eclipse 3.2.1            | 9.5          | 11.2           | 7.27            |
| NetBeans 5.5             | 8.6          | 11.3           | 3.51            |
| JBoss 5.0.0.Beta1        | 8.6          | 5.7            | 4.84            |
| Emacs 21.4               | 24.6         | 25.3           | 43.17           |
| XEmacs-Packages 21.4.19  | 24.7         | 17.6           | 8.46            |

Table 6: Average depth computed using directory depth and exponential depth.

| package                  | directory | exponential |
|--------------------------|-----------|-------------|
| Linux 2.6.18             | 2.8       | 3.9         |
| OpenSolaris 20061009     | 4.7       | 5.3         |
| GNOME 2.16.1             | 3.8       | 5.1         |
| KDE 20061023             | 3.2       | 4.5         |
| KOffice 20061023         | 2.5       | 3.1         |
| OpenOffice.org C680_m7   | 3.7       | 4.4         |
| SeaMonkey 1.0.6          | 4.8       | 4.6         |
| Eclipse 3.2.1            | 4.6       | 4.8         |
| NetBeans 5.5             | 7.5       | 7.7         |
| JBoss 5.0.0.Beta1        | 4.9       | 5.8         |
| Emacs 21.4               | 1.7       | 1.8         |
| XEmacs-Packages 21.4.19  | 3.0       | 3.6         |

This average depth of components does not take into account the lowest level of components that was considered in subsection 2.3 that of functions. To find out the real depth of the component hierarchy a level must therefore be added to the exponential depth. In fact, for C++ packages an additional level for classes might also be added, since they are allowed a further level of modularity inside source code files. This possibility will be discussed in its own subsection 4.7.

4.4 Pruning

After pruning the source code tree, disregarding all trivial directories (those containing only one file or directory), the results are those in table 7.

Comparing these results with those in table 5 it can be seen that items per directory
Table 7: After pruning trivial directories: pruned directory count, average items per directory and exponential depth.

| package                        | directories | items/directory | depth |
|-------------------------------|-------------|-----------------|-------|
| Linux 2.6.18                  | 774         | 11.9            | 3.65  |
| OpenSolaris 20061009          | 1276        | 10.9            | 3.96  |
| GNOME 2.16.1                  | 1075        | 10.3            | 3.95  |
| KDE 20061023                  | 1444        | 10.2            | 4.09  |
| KOffice 20061023              | 286         | 8.7             | 3.56  |
| OpenOffice.org C680_m7        | 1134        | 10.7            | 3.92  |
| SeaMonkey 1.0.6                | 532         | 9.6             | 3.73  |
| Eclipse 3.2.1                 | 1116        | 14.1            | 3.62  |
| NetBeans 5.5                  | 2492        | 7.6             | 4.78  |
| JBoss 5.0.0.Beta1             | 1471        | 7.5             | 4.56  |
| Emacs 21.4                    | 16          | 48.4            | 1.71  |
| XEmacs-Packages 21.4.19       | 120         | 18.8            | 2.61  |

have increased (while depth has correspondingly decreased), as could be expected by the smaller number of directories considered. Values have mostly gone out of the “magic range”, to the point that only three software packages remain inside: two in Java, NetBeans and JBoss, and one in C++: KOffice.

4.5 Complexity per Level

Table 8 shows the depth once the correction for functions (adding one level to every depth) is taken into account. It also summarizes the number of elements per component at levels 0 (LOC per function), 1 (functions per file) and higher than 1 (items per directory); according to the assumptions in subsection 2.5 this number would represent complexity at each level.

LOC count can be approximately recovered based on these measures. To recapitulate: $S$ is the size in LOC, and $c(i)$ is the number of elements at level $i$; $d$ is the total hierarchy depth (number of levels), $a$ the average number of items per directory, and $T$ is the total number of source files. Now $l$ is the exponential depth, so that $d = l + 1$. (Table 8 shows, from left to right: $c(0)$, $c(1)$, $a$ and $d$.) Then starting from equation 1:

$$S = \prod_{i=0}^{d} c(i) = c(0) \times c(1) \times T,$$

and recalling equation 4

$$S = c(0) \times c(1) \times a^{d-1}.$$ 

The count is not exact due to rounding.

4.6 Discussion

In this subsection we will discuss the experimental results, referring to table 8 unless explicitly stated.
Table 8: Complexity at various levels and depth (number of levels) of the component hierarchy. Complexity is computed as number of subcomponents per component; corrected depth is found adding one to exponential depth. Pruning is used.

| package                | level 0 | level 1 | level > 1 | depth |
|------------------------|---------|---------|-----------|-------|
| Linux 2.6.18           | 25.2    | 16.0    | 11.9      | 4.65  |
| OpenSolaris 20061009   | 35.6    | 9.6     | 10.9      | 4.96  |
| GNOME 2.16.1           | 24.1    | 16.4    | 10.3      | 4.95  |
| KDE 20061023           | 12.9    | 15.7    | 10.2      | 5.09  |
| KOffice 20061023       | 16.0    | 14.5    | 8.7       | 3.56  |
| OpenOffice.org C680_m7 | 30.2    | 10.4    | 10.7      | 4.92  |
| SeaMonkey 1.0.6        | 17.1    | 15.2    | 9.6       | 4.73  |
| Eclipse 3.2.1          | 9.5     | 11.2    | 14.1      | 4.62  |
| NetBeans 5.5           | 8.6     | 11.3    | 7.6       | 5.78  |
| JBoss 5.0.0.Beta1      | 8.6     | 5.7     | 7.5       | 5.56  |
| Emacs 21.4             | 24.6    | 25.3    | 48.4      | 1.71  |
| XEmacs-Packages 21.4.19| 24.7    | 17.6    | 18.8      | 3.61  |

Looking just at corrected depth, almost all measured values are well below the “magic range” 7 ± 2, as corresponds their medium size. In fact there are only three values in the range: NetBeans at 5.78, JBoss at 5.56 and KDE with 5.09, with several others grazing the 5. Interestingly, the second deepest hierarchy is found in JBoss, even though it is the smallest package considered.

Taking now a closer look at complexity for level > 1 (i.e. average items per directory): the first thing to note is that before pruning (table 5) most values were inside the “magic range”. After pruning there are only three values inside the range; this time all the rest are above. JBoss holds now the lowest value with 7.5, very close to NetBeans with 7.6; both are near the “nominal” value of the range in table 1 while the rest would appear upon or above the “complex” end. The remaining Java project, Eclipse, has the highest measure of all but both versions of Emacs, with 14.1. This value might be an artifact of pruning (as explained in subsection 3.6); however, all attempts at consolidation yielded the same results, or worse. It appears that Eclipse is not as modular in high levels of componentization as other packages; or that its logical structure is not reflected in its on-disk layout.

Emacs and XEmacs-Packages have far higher measures of complexity for level > 1 than the rest. Even the more modern refactorization has 18.8, while the venerable branch has a staggering value of 48.4. Even if at low levels they behave much better, it appears that they just are not modularized in a modern sense, i.e. in a hierarchical fashion. As to the rest, they are just above the “magic range”, from Linux with 11.9 to KOffice with 8.7. At least for the C/C++ packages there appears to be some correlation between application area and complexity: systems software packages like Linux and OpenSolaris (with 11.9 and 10.9 respectively) rank higher than the desktop environments GNOME and KDE (10.3 and 10.2), in turn higher than the graphical applications SeaMonkey and KOffice (9.6 and 8.7). OpenOffice provides the exception for a graphical application with 10.7, but it is also the only package in the set with roots
in the decade of 1980 [15]. Figure 5 shows a summary of the effect. Incidentally, this correlation has only been made apparent after pruning.

![Diagram showing complexity per application area](image)

Figure 5: Complexity per application area. As should be expected, systems software is more complex than graphical environments, which in turn are more complex than graphical applications. The exception is OpenOffice, a software package with roots in the eighties.

On the other end, level 0 complexity or LOC per function obviously do not behave as subcomponents in a component: the value is out of the “magic range” for almost all software packages. Java packages show the lowest count for LOC per function with 8.6, 8.6 and 9.5; but the highest count is for OpenSolaris with 35.6, which otherwise shows good modularity. It appears that having far more than $7 \pm 2$ LOC per function is not a problem for package modularity.

More surprising is to find that level 1 complexity (functions per file) is out of range too in almost all instances, except for JBoss. For C software results are 9.6, 16.0 and 16.4, very similar to C++ where we find 10.4, 14.5, 15.2 and 15.7. These results are typical of the values that have been observed in other software packages: a range of $[2, 20]$ would capture most C and C++ software. Sometimes an effort is done to modularize code at this level, as can be seen in OpenSolaris and OpenOffice. Java software seems to be closer to this goal: results for methods per file are now 5.7, 11.2 and 11.3, mostly still out of range but close enough. In wider field tests a range of $[2, 12]$ would capture most Java software. The remaining software in Lisp meanwhile does a little worse with 17.6 and 25.3 functions per file; some efforts seem to have been given in this front, but the amount of the reduction from Emacs to XEmacs-Packages is not too significant (and is even less evident in XEmacs proper, not included in this study).

A possible explanation for this discrepancy at level 1 is that only exported functionality should be counted; when considering a component from the outside a developer
only needs to be concerned with visible functions (i.e., public functions in C++, or public methods in Java). The problem remains for internal consideration of components, which is precisely where the “magic range” can have the biggest effect. Another explanation is that only in object-oriented languages there is a sensibility for modularity within source files, and it appears to be the case at least for Java. In the next subsection some explanations are explored for C++.

It appears that many popular free software packages tend to be organized as one would expect from purely theoretical grounds; after measuring more than 25 million lines of code it has been found that several popular free software packages tend to comply with the theoretical framework about a hierarchy of components, at least as far as file layout is concerned. Other software packages that were conceived using less modern practices, like Emacs, do not follow this organization. Whether this structure indeed corresponds to modularization is a different question, difficult to answer without intimate knowledge of their internal structure; more research is required to give definitive responses.

4.7 Classes and Files in C++

C++ offers the possibility to arrange several classes in a file; according to the theoretical study presented in subsection 2.3, this organization should result in another level of articulation within files. It is however good coding advice to put only one module unit per file [16]; in C++ this translates into placing each class in a separate file. If this convention is followed the number of functions per file might be expected to follow the magic range. In Java, where the limitation of declaring one class per file is enforced by the language, the results are indeed near the expectation with 5.7, 11.2 and 11.3. However, C++ results (10.4, 14.5, 15.2 and 15.7) are similar to those for C; again, a typical range seems to be [7, 20]. On the other hand, if each file contained two levels of articulation (functions and classes) the number of functions per file that could be expected would rather be \((7 \pm 2)^2\) = [25, 81]. It is clear that in C++ there is nothing near this interval either. This deviation deserves a deeper exploration. In this subsection four possible explanations will be advanced.

The C++ convention is to have one public class per file; there can be some private classes within the same source file. One private class per public class (or two classes per file) would yield an interval twice the “magic range”, or [10, 18], consistent with observations. Alternatively, the range might apply only to public functions and not to those private to the class, but this explanation was discarded in the previous subsection since external consideration is not where the number of elements would have the most effect.

Some software packages may disregard the “one public class per file” convention altogether or in parts; sometimes it is possible to find multi-class files in otherwise compliant software packages, yielding more than one level of articulation between files and functions. For example, an average of 1.3 levels would yield an interval of \((7 \pm 2)^{1.3} \approx [8, 17]\), also congruent with observations. It can be noted that mean depth for C packages is 4.85, and 5.32 for Java; but for C++ it is lower with an average of only 4.57. The difference may be suggestive that C++ may have a partial “hidden articulation level” in classes per file, and even grossly coincides with the conjectured
1.3 levels, but it is not statistically significant. Note also that KOffice is quite smaller than most packages.

C++ also tends to require a large number of supporting code for each class implemented. It is not uncommon to find an explicit constructor, a destructor, an assignment operator and a copy constructor declared for each class [17]. With four additional functions per file, the interval would become [9, 13]; if half the functions were supporting code, we would again get a range of [10, 18].

The last explanation is psychological, and can be the underlying cause for all the previous hypotheses. It seems that C++ developers don’t see a problem with having as many as 20 functions per file; in fact going below 10 may look very difficult when writing C++ code. For example, Kalev writes [18]:

As a rule, a class that exceeds a 20-30 member function count is suspicious.

Such a number would raise the hairs on the back of the neck for experienced Java developers. Whether this concern is valid or it is just an idiomatic difference shall remain an open question until further research can validate the alternatives.

5 Conclusion

The theoretical framework presented in this study should allow developers to view really large systems in a new light; the experimental results show that complexity in a hierarchy of components can be dealt with and measured. Until now most of these dealings have been made intuitively; hopefully the metrics developed in this paper can help developers think about how to structure their software, and they can be used for complexity analysis by third parties.

As a first proof of their usefulness, several object oriented software packages have been shown to have a bigger sensibility to modularization than those written in procedural languages, and these in turn higher than functional language software. These concerns may explain their relative popularity better than language-specific features. Application area also seems to play a role, as does age of the project. Apparently the set of metrics reflect, if not the exact hierarchy of logical components, at least general modularity concerns.

5.1 Metrics in the Real World

Metrics can be highly enlightening, but if they cannot be computed automatically they are less likely to be used in practice. Function points are very interesting but hard to compute, and therefore they have not yet reached their potential as a universal size measure [19].

The metrics presented here are very easy to compute; a few regular expressions and some commands should be enough to get full results. A software package which analyzes source code automatically and produces a report should be very easy to develop; extending existing packages should be even easier.
Despite the automatic nature of the metrics, a certain amount of manual inspection of the intermediate results must always be performed in order to assess if directory structure reflects software modularity. This is usually the case with source code, so inspections are a good idea in any case.

5.2 Further Work

This study has focused on well-known free software packages with sizes within an order of magnitude (500kLOC to 5000kLOC). Extending the study to a big range of projects (with hard data for maintainability) would add reliability to the metrics proposed. Future research will try to identify complex areas in otherwise modular programs. An interesting line of research would be to model the software not as an exponential tree, but as a more organic structure with outgrowths, stubs and tufts; this approach might help locate problematic areas.

The set of metrics presented is only a first approximation to measures of complexity. Until these metrics are validated by wider studies they should not be applied to mission-critical projects or used to make business decisions. On the other hand, making hierarchical complexity measurable is an important step that should lead to more comprehensive but hopefully just as simple metrics.

A goal that can immediately be applied to current development is to make explicit and to document the hierarchical component organization. The process of sorting out and naming levels of components following a conscious and rational scheme will probably lead to better modularization; in the end it is expected that more maintainable software will be attained.

5.3 Acknowledgments

The author would like to thank Rodrigo Lumbreras for his insights on professional C++ development, and Carlos Santisteban for his sharp corrections.

References

[1] L M Laird, M C Brennan: “Software Measurement and Estimation”, ed John Wiley & Sons, 2006, p 58.

[2] Y K Malaiya, J Denton: “Module Size Distribution and Defect Density”, in Proceedings of ISSRE ’00, 2000.

[3] C Jones: “Applied Software Measurement”, ed Mcgraw-Hill, 1991, pp 237-241.

[4] M Blume, A W Appel: “Hierarchical Modularity”, in ACM Transactions on Programming Languages and Systems, vol 21, n 4, July 1999.

[5] S McConnell: “Code Complete”, ed Microsoft Press, 1993, p 775.

[6] H Washizaki et al: “A Metrics Suite for Measuring Reusability of Software Components”, in Proceedings of METRICS’03, 2003.
[7] Alice T. Lee et al: “Software Analysis Handbook: Software Complexity Analysis…”, ed NASA Johnson Space Center, August 1994.

[8] M Agrawal, K Chari: “Software Effort, Quality, and Cycle Time: A Study of CMM Level 5 Projects”, in IEEE Transactions on Software Engineering, vol 33, n 3, March 2007.

[9] C Jones: “Applied Software Measurement”, ed Mcgraw-Hill, 1991, p 9.

[10] S W Ambler: “The Elements of UML 2.0 Style”, ed Cambridge University Press, 2005, p 10.

[11] C Jones: “Applied Software Measurement”, ed Mcgraw-Hill, 1991, p 240.

[12] G A Miller: “The Magical Number Seven, Plus or Minus Two: Some Limits on Our Capacity for Processing Information” en The Psychological Review, 1956, vol 63, pp 81-97.

[13] GNOME Project: “GARNOME Documentation”, accessed February 2007. [http://www.gnome.org/projects/garnome/docs.html](http://www.gnome.org/projects/garnome/docs.html)

[14] Sun Microsystems: “Code Conventions for the JavaTM Programming Language”, revised April 20, 1999, ch 9.

[15] C Euler: “File transformation with OpenOffice and its use for E-Learning”, in Future Trends in E-Learning Technologies, 2005.

[16] S McConnell: “Code Complete”, ed Microsoft Press, 1993, p 445.

[17] D Kalev: “ANSI/ISO C++ Professional Programmer’s Handbook”, ed Que, 1999, chapter 4.

[18] D Kalev: “ANSI/ISO C++ Professional Programmer’s Handbook”, ed Que, 1999, chapter 5.

[19] L M Laird, M C Brennan: “Software Measurement and Estimation”, ed John Wiley & Sons, 2006, p 50.