Maintainability of the Linux Kernel

Stephen R. Schach, Bo Jin, David R. Wright
Department of Electrical Engineering and Computer Science, Vanderbilt University, Nashville, TN, USA
srs@vuse.vanderbilt.edu, {bo.jin, david.r.wright}@vanderbilt.edu

Gillian Z. Heller
Department of Statistics, Macquarie University, Sydney, Australia
gheller@efs.mq.edu.au

and A. Jefferson Offutt
Department of Information and Software Engineering, George Mason University, Fairfax, VA, USA
ofut@ise.gmu.edu

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ABSTRACT

We have examined 365 versions of Linux. For every version, we counted the number of instances of common (global) coupling between each of the 17 kernel modules and all the other modules in that version of Linux. We found that the number of instances of common coupling grows exponentially with version number. This result is significant at the 99.99% level, and no additional variables are needed to explain this increase. On the other hand, the number of lines of code in each kernel modules grows only linearly with version number. We conclude that, unless Linux is restructured with a bare minimum of common coupling, the dependencies induced by common coupling will, at some future date, make Linux exceedingly hard to maintain without inducing regression faults.

KEY WORDS: open-source software, Linux, coupling, dependencies, common coupling, maintenance

1. INTRODUCTION

Numerous articles in newspapers and popular magazines point out the many strengths of Linux, the open-source operating system [1]. Linux is also increasingly featured on television news programs. Typically, such items include an interview with a former user of Microsoft Windows who proudly asserts that Linux fails far less frequently on his or her PC than Windows did. Occasionally a magazine article might mention that it is important for one to install a version of Linux that is appropriate for one's PC or that it is helpful to know a Linux guru, but most media coverage is largely uncritical of Linux.

A cynic might claim that these articles are just a manifestation of a worldwide campaign of "Microsoft bashing." A statistician would surely point out that the articles are anecdotal in nature and can hardly be considered to constitute scientific evidence. Nevertheless, the sheer volume of material praising Linux in the popular press and on television is difficult to ignore.

Turning now to software experts, their adulation of Linux is somewhat more muted. For example, in the May 1999 issue of *IEEE Computer*, Ken Thompson (co-creator of UNIX) wrote: "I don't think [Linux] will be very successful in the long run. I've looked at the source and there are pieces that are good and pieces that are not. A whole bunch of random people have contributed to this source, and the quality varies drastically. My experience and some of my friends' experience is that Linux is quite unreliable. Microsoft is really unreliable but Linux is worse. In a non-PC environment, it just won't hold up. If you're using it on a single box, that's one thing. But if you want to use Linux in firewalls, gateways, embedded systems, and so on, it has a long way to go" [2].

A key phrase in Thompson's remarks is "I've looked into the source." That is, a critical difference between Linux and Windows is that Linux is open-source software—anyone can study the source code and comment on (say) its quality.

It has been claimed that open-source software is superior to proprietary software. One reason given for this assertion is that open-source software can be improved by anyone who has a copy of the program. A second reason frequently put forward is the fact that the name of the author of a module is usually incorporated into the source code; public knowledge of who wrote the software is viewed as an inducement for writing quality code. Finally, in the case of products like Linux, yet another reason given is that most of the code has been written by volunteers working on their own time, as opposed to employees battling against management-imposed deadlines. On the other hand, Thompson's statements that "there are pieces [of Linux] that are good and pieces that are not" and "the quality varies drastically" cannot be disregarded.

Notwithstanding Ken Thompson's stature within the software engineering community, in a certain sense his opinion of the quality of Linux is as anecdotal as the views expressed by Linux users in press interviews. After all, Thompson apparently did not use a metric (such as number of faults detected) to measure quality. Furthermore, it is not clear whether his opinion is based on an exhaustive study of all of Linux, or on a sample of the code.

This paper presents results from an examination of available subversions of versions 1.0 through 2.3 of Linux, a total of 391 subversions. Table I summarizes this data set. In Table I and the throughout this paper, the term "module" refers to a file containing executable C code (that is, a file with the suffix .c, as opposed to, say, header file with suffix .h).

We have examined one aspect of the maintainability of the Linux kernel. Specifically, we have measured the *common coupling* in successive versions of the Linux kernel, and

observed that the common coupling increases exponentially. We conclude that if this trend continues, the maintainability of Linux will degrade in the future.

Section 2 describes dependencies, and common coupling and its effect on maintainability. We discuss successive versions in Section 3. Section 4 describes how we counted instances of common coupling, and our results are presented in Section 5. Our conclusions appear in Section 6.

2. DEPENDENCIES

The *coupling* between two units of a software product is a measure of the degree of interaction between those units [3] and, hence, of the dependency between the units. In their 1974 paper, Stevens, Myers, and Constantine outlined six levels of coupling. These were presented as an ordered list by Page-Jones [4], who gave three principal reasons why reducing the number of instances of coupling between modules is desirable: (1) fewer interconnections between modules reduce the chance that a fault in one module will cause a failure in other modules; (2) fewer interconnections between modules reduce the chance that changes in one module cause problems in other modules, which enhances reusability; and (3) fewer interconnections between modules reduce programmer time in understanding the details of other modules. Various modifications and extensions to these levels of coupling have been proposed over the past 25 years [4–6]. Although all types of coupling are sometimes useful in design, it has been demonstrated that some types have greater potential for introducing faults into software [7–10]. Because some types of coupling are more likely to lead to faults than others, it is widely accepted that some coupling types should be limited in use.

In the 11-level categorization of [5], the two lowest levels of coupling are call coupling and scalar data coupling. There is *call coupling* between modules P and Q if P calls Q or Q

calls P, but there are no parameters, common variable references, or common references to external media between P and Q. There is *scalar data coupling* if a scalar variable in P is passed as an actual parameter to Q and it is used for computation purposes ("C-use"), but not for control purposes ("P-use") or indirect purposes ("I-use"). This paper considers the classical coupling category *common coupling,* which corresponds to level 10, *global coupling,* in the categorization of Offutt et al. [5]. Modules P and Q are global coupled if P and Q share references to the same global variable.

If there were no coupling at all in a software product then that product would consist of one large module, so some amount of coupling clearly is needed. That is, coupling is a necessary consequence of modularization. However, where there is coupling between two modules, there is some degree of dependence between those modules. The resulting degree of dependence between two modules may be high ("*strong coupling*") or low ("*weak coupling*"). A well-designed software product makes considerable use of weak coupling and avoids, as far as possible, strong coupling. For example, a well-designed product utilizes coupling categories such as call coupling and scalar data coupling, and eschews common coupling as much as is feasible [3, 11].

It has been shown [12] that coupling is related to fault-proneness. Coupling has not yet been explicitly shown to be related to maintainability. On the other hand, we do not yet have a precise definition of maintainability, and therefore there are no generally accepted metrics for maintainability. Nevertheless, if a module is fault-prone then it will have to undergo repeated maintenance, and these frequent changes are likely to compromise its maintainability. Furthermore, these frequent changes will not always be restricted to the fault-prone module itself; it is not uncommon to have to modify more than one module to fix a single fault. Thus,

the fault-proneness of one module can adversely affect the maintainability of a number of other modules. In other words, it is easy to believe that strong coupling can have a deleterious effect on maintainability.

As previously mentioned, in this paper we consider *common coupling*. There are three reasons why we did this. First, it was shown in a case study on the maintainability of multiversion real-time software that the overwhelming preponderance of strong coupling introduced during the maintenance phase was common coupling [13]. Second, there is considerable controversy regarding what precisely constitutes weak or strong coupling, let alone which categorization of coupling should be followed. However, all categorizations we have seen include a form of coupling that corresponds to classical common coupling, and there seems to be unanimity that common coupling is undesirable.

The third reason why we concentrated on common coupling is that common coupling possesses the unfortunate property that the number of instances of common coupling between module M and the other modules can change drastically, even if module M itself never changes; this is termed *clandestine common coupling* [14]. For example, if modules M and N both reference global variable gv, then there is one instance of common coupling between module M and the other modules. But if 10 new modules are written, all of which reference global variable gv, then the number of instances of common coupling between module M and the other modules increases to 11, even though module M itself is unchanged. Bearing in mind that the size of Linux has increased nearly 1000% since version 1.0 (see Table I), we suspected that common coupling between a module in the kernel and the rest of the modules might increase dramatically, even though the kernel module itself did not change hugely.

There were two reasons why we decided to concentrate our efforts on the Linux kernel. First, there are only 17 kernel modules and 6,506 versions of those modules; in contrast, the current version of Linux has nearly 2,000 modules, and there are up to 390 previous versions of each of those modules. In other words, the research project was manageable because we restricted our efforts to analyzing "only" 6,506 modules. Second, in the case study on repeated maintenance we previously referenced [13], the major discriminating factor was differences in individual programmer abilities. In the case of Linux, the original versions of all the kernel modules were written by Linus Torvalds, and he has either maintained them himself or in conjunction with one or two other programmers. There is therefore no need to correct for individual programmer skills.

3. SUCCESSIVE VERSIONS

We measured the change in the number of lines of code and in the common coupling between successive versions of Linux kernel modules. The term "successive versions" needed to be clearly defined, because some software products undergo parallel development, that is, the baseline version of the software is extended in more than one direction at the same time. Sometimes, one or more of these branches later coalesce, whereas other branches are terminated.

In the case of Linux, an additional complication is that, in some sense, there are two sets of versions of Linux kernel modules. Kernel modules that have a version number whose second, or *minor*, digit is *even* (for example, the '2' is even in version 1.2.9) are considered stable, and those whose minor number is *odd* (for example, version 2.1.132) are considered developmental. When the developmental version appears to be mature, it becomes part of the stable tree with the minor number incremented (for example, with only a few small changes, version 2.1.132 became version 2.2.0).

In order to handle the issue of parallel development, we decided to discard all versions with a date stamp later than a version with a higher version number. The remaining versions with successive version numbers were then defined to be "successive versions."

After we had downloaded all 391 versions of Linux available on the Web [1], we discovered that versions 2.0.30 through 2.0.39 had date stamps later than the date stamp on version 2.1.0, so we discarded those 10 versions. Similarly, versions 2.2.2 through 2.2.17 had date stamps later than the date stamp on version 2.3, so we ignored those 16 versions, too. That left 365 versions of Linux to investigate.

We comment on implications of our definition of successive versions in Section 5.2.

4. COUNTING INSTANCES OF COMMON COUPLING

As stated in Section 2, modules P and Q are common (global) coupled if P and Q share references to the same global variable. We downloaded all the modules of each version of Linux. For each of the 17 modules that constitute the kernel, we manually determined which variables are global. We then determined in how many modules each global variable in a kernel module is referenced. The counting was done at the module level, so multiple references to the same common variable within a given module were ignored. We also ignored common coupling of constants.

We then determined whether the code had been modified from the previous version and, if so, we noted the number of lines of code in that new version of that kernel module and when it was released.

Data for the 365 versions of Linux we investigated are shown in Table II. A blank in the LOC or date column denotes that the code has not changed between successive versions. Thus, for example, version 2.1.104 of kernel module Panic.c was released on May 21, 1998. That

version had 79 lines of code, and there were 914 instances of common coupling between module Panic.c and all the other modules in version 2.1.104 of Linux. The number of instances of common coupling steadily increased to 946 in version 2.1.109, even though the code for Panic.c did not change at all, an example of clandestine common coupling [14].

Finally, for simplicity in the statistical analysis, we renumbered the versions as consecutive integers between 1 and 365. Thus, version 2.1.104 above became version number 196, as shown in Table II, and similarly for the other versions.

5. RESULTS

We present models for the relationship between LOC and version number; and between instances of common coupling and version number. A fundamental assumption of normal regression models is independence of observations; our observations are by their nature sequential and hence have a temporal dependency. The appropriate statistical tool is therefore a *growth curve* [15]. A separate growth curve is needed for each module because the changes in LOC and in instances of common coupling are module-specific. We found, however, that normal regression models produce very similar results to the growth curves, and have the advantage that all modules can be accommodated in a single model. For ease of presentation, therefore, we present in this paper the results of normal regression models [16].

5.1 Lines of Code

We first considered the change in lines of code (LOC) through versions. A linear regression of LOC versus version number was fitted, allowing different intercepts and slopes for each of the 17 different modules. Version number, module, and a version number–module interaction were all significant ($p < 0.0001$), as shown in the analysis of variance (ANOVA) of Table III.

The "Degrees of freedom" column gives the number of parameters to be estimated for each effect in the model. The effect "Version number × Module" consists of the version number–module interaction terms. These terms allow for differing gradients of the LOC–Version number regression line for each module. The parameters for the interaction terms are the differences between the gradient of one of the modules (we arbitrarily chose Printk.c) and each of the other modules. Consequently, the number of parameters to be estimated is 16, the number given in the "Degrees of freedom" column. The effect "Version number" has one parameter, the gradient of the Printk.c module LOC–Version number regression line, and the effect "Module" has 16 parameters, each of these being the difference between the intercept of the LOC–Version number regression line for each module, and the intercept for the Printk.c module regression line. The F statistics are the ratios of the variation explained by each effect, to residual variation or noise. If this statistic is sufficiently large, we conclude that the effect is statistically significant. We judge the size of the F ratio for each effect by comparing it against the distribution we would expect it to have if the effect were in fact not present, namely, the F distribution. If the F ratio falls in the upper tail of the F distribution, we conclude that the effect is present, or statistically significant.

The model explains 95.1% of the variation in LOC. That is, the two variables and their interaction account for 95.1% of the observed behavior of LOC. This result is deduced from the value of R^2 in Table III, which is the ratio $\frac{\text{variation explained by model}}{\text{total variation}}$, that is, the proportion of total variation in LOC explained by the model.

5.2 Common Coupling

Figure 1 shows how common coupling varies with version number. Four of the Linux kernel modules appear in the first, second and third graphs, and five in the fourth. All four graphs show both the measured value of the common coupling and the values predicted by our model. Figure 1 reveals an extremely clear exponential trend, which is again module-specific. In passing, we note that the smoothness of the graphs of Figure 1 supports the definition of "successive modules" we gave in Section 3. Similar observations also hold for the graphs showing lines of code against version number (not shown here for reasons of space).

Because of the exponential nature of the relationship, a linear model was used, with the natural logarithm of the number of instances of common coupling as the response variable. (The constant 0.1 was added before taking logarithms, because eight of the common coupling values were zero.) Because of the strong linear dependency between LOC and version number, the inclusion of LOC in this model would have resulted in severe numerical instability, and LOC was therefore not included in this model. Version number, module, and version number–module interaction were all found to be significant. The analysis of variance table is given in Table IV.

The model has $R^2 = 0.946$, meaning that 94.6% of the variation in the number of instances of common coupling can be explained by the two variables and their interaction.

6. CONCLUSIONS AND FUTURE WORK

As described in Section 3, we downloaded 365 versions of Linux. For each version in turn, we looked at the 17 kernel modules and counted the number of lines of code in each module. Then we counted the number of instances of common (global) coupling between each of the kernel modules and all the other modules in that version of Linux. We also recorded the version number as an integer between 1 and 365. We obtained two primary results.

First, we found a module-specific linear dependency between lines of code and version number that is significant at the 99.99% level; 95.1% of that dependency can be explained by the three effects: version number, module, and their interaction. In other words, the number of lines of code in each kernel module increases linearly with version number, and no additional variables are needed to explain this increase; it is an inherent feature of successive versions of Linux. This result is not surprising. After all, successive versions of Linux provide additional functionality. One would expect this increase of functionality to be achieved by both inserting additional code into existing modules and adding new modules. The fact that the size of the kernel grows only linearly could be an indication that the kernel modules are well designed; only a small amount of additional code needs to be inserted to interface the kernel with modified existing modules and new modules that provide the additional functionality.

Second, we found that the number of instances of common coupling grows exponentially with version number. This result, too, is significant at the 99.99% level. In this case, 94.6% of the observed growth can be explained by the three effects: version number, module, and their interaction. That is, the exponential growth in common coupling is again an inherent feature of successive versions of Linux.

In Section 2, we related common coupling to fault-proneness. Consequently, combining our two results reveals a disturbing trend. Even though the number of lines of code in the kernel grows only linearly, the number of instances of common coupling between each kernel module and all the other Linux modules grows exponentially. Suppose that every statement added to a kernel module were a call to another module. Because the number of lines of code grows only linearly, the number of new instances of coupling induced by these calls even in this extreme case can grow only linearly. However, as explained in Section 2, common coupling can increase

even when a module does not change. That is how the common coupling increases exponentially even though the number of lines of code increases only linearly.

Common coupling was introduced into Linux from the very beginning, and the nature of common coupling led to an exponential growth in the number of instances in successive versions of Linux. There is no reason to suppose that this growth will be slowed in the future unless Linux is completely restructured with a bare minimum of common coupling. It could be argued that this restructuring of a huge product will mean that the development of Linux will have to be put on hold for many months until the restructuring is complete. On the other hand, if this restructuring is not performed, it seems inevitable that, at some future date, the dependencies between modules induced by common coupling will render Linux extremely hard to maintain. It will then be exceedingly hard to change one part of Linux without inducing a regression fault (an apparently unrelated fault) elsewhere in the product. The only alternative will then be to restructure what by that time will be an even larger software product.

In conclusion, our analysis of the growth of common coupling within successive versions of Linux tends to support Ken Thompson's remark quoted in Section 1: "I don't think [Linux] will be very successful in the long run" [2]. However, the future problems we have identified can be averted if Linux is restructured with common coupling reduced to a bare minimum, and if a careful watch is kept to ensure that virtually no additional instances are introduced after the restructuring has been performed.

If general open-source software suffers from a heavy reliance on common coupling, this would be a problem for the future adoption of open source software. However, we have no data or intuition to support such a conclusion. We are currently building a CASE tool to automate the process described in this paper. We will use this CASE tool to measure the growth of common

coupling between successive versions of other open-source software to determine whether the potential maintenance problem we have identified in Linux is also present in other open-source software.

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Table I. Summary of Linux versions and subversions.

Version Number	Number of Subversions	LOC (Modules)	Number of Modules	Total Number of Files
Ver. 1.0	1	141,255	282	572
Ver. 1.1	36	141,068	282	561
Ver. 1.2	14	234,704	400	909
Ver. 1.3	100	258,621	431	991
Ver. 2.0	40	563,104	779	2,018
Ver. 2.1	130	580,698	785	2,059
Ver. 2.2	18	1,310,807	1,891	4,599
Ver. 2.3	52	1,385,026	1,946	4,721
Total	391			

Table II. Data for six successive versions of three kernel modules.

Version Number	Panic.c			Module.c			Ksyms.c		
	CC	LOC	Date	CC	LOC	Date	CC	LOC	Date
2.1.104 (or 196)	914	79	05/21/98	963	1018	05/21/98	359	397	06/04/98
2.1.105 (or 197)	921			974	1019	06/07/98	360		
2.1.106 (or 198)	933			989			368	398	06/13/98
2.1.107 (or 199)	935			992			369		
2.1.108 (or 200)	942			992			369		
2.1.109 (or 201)	946			999			373		

Table III. Data for lines of code.

Effect	Degrees of freedom	F	p
Version number	1	4517.3	< 0.0001
Module	16	901.9	< 0.0001
Version number × Module	16	511.2	< 0.0001
$R^2 = 0.951$			

Table IV. Data for common coupling.

Effect	Degrees of freedom	F	p
Version number	1	2.1E+04	< 0.0001
Module	16	824.44	< 0.0001
Version number × Module	16	163.50	< 0.0001
$R^2 = 0.946$			

LIST OF CAPTIONS

Figure 1. Graphs of measured and predicted common coupling versus version number. The measured common coupling is represented by discrete points, the predicted common coupling by a line.

(Note: This figure is in four parts.)

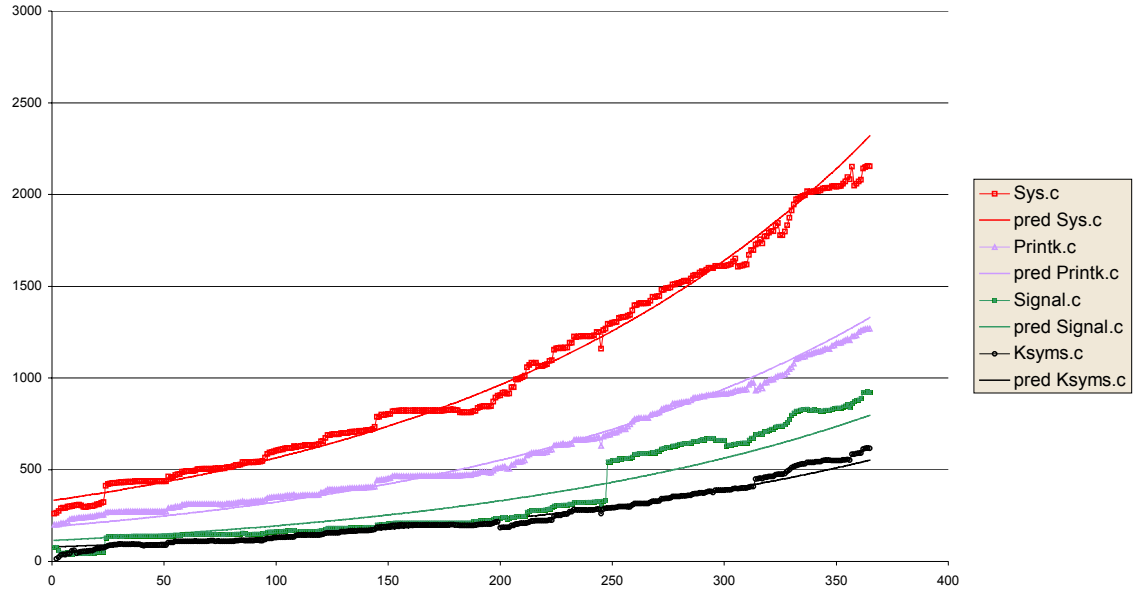

Figure 1 (Part 1 of 4)

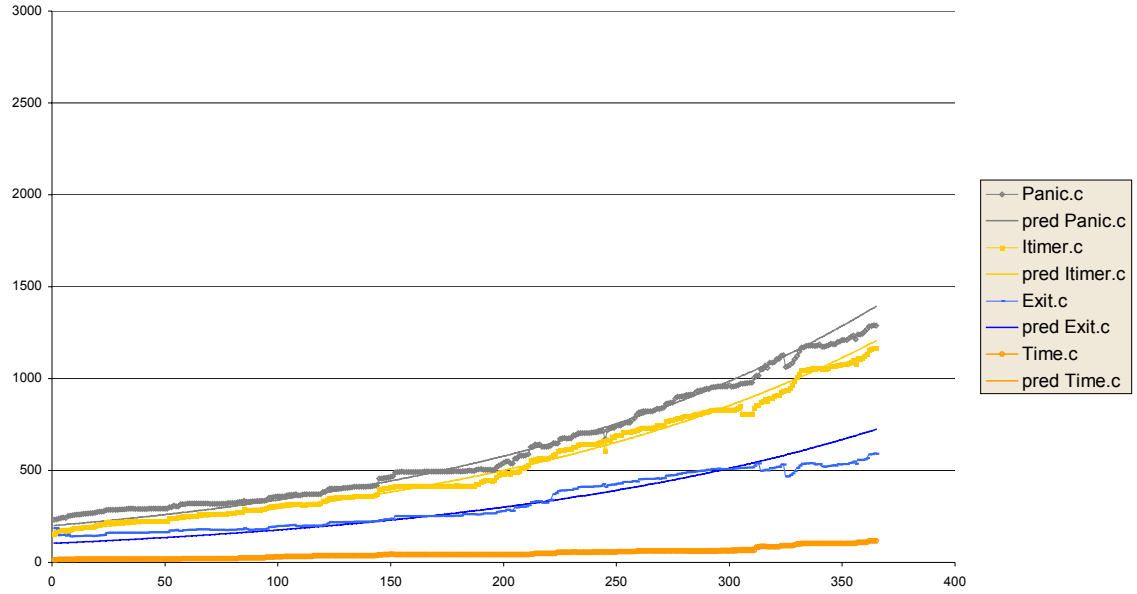

Figure 1 (Part 2 of 4)

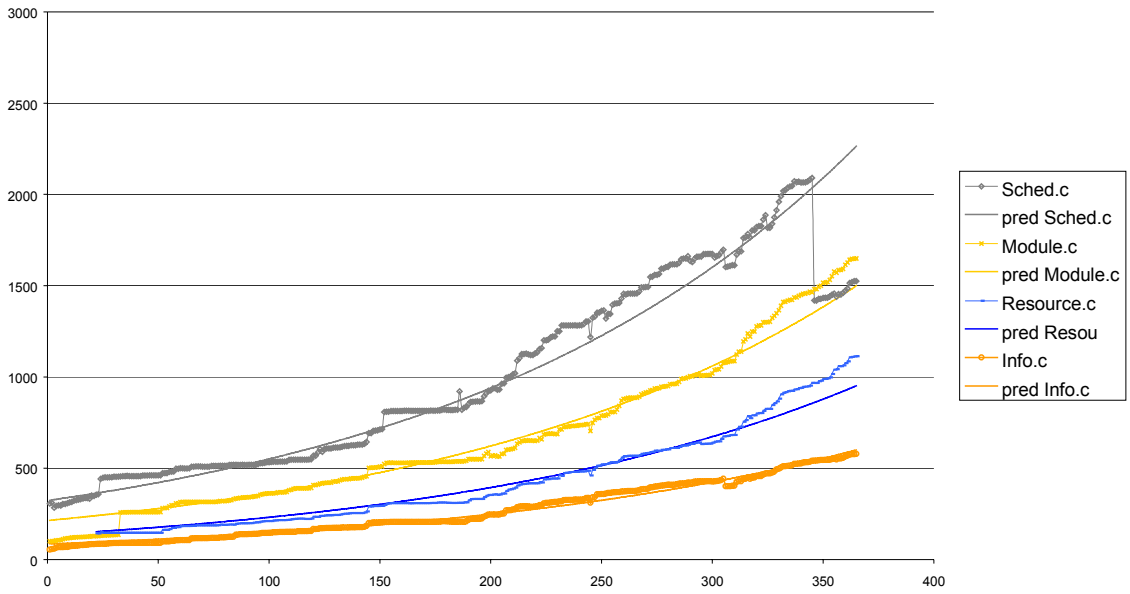

Figure 1 (Part 3 of 4)

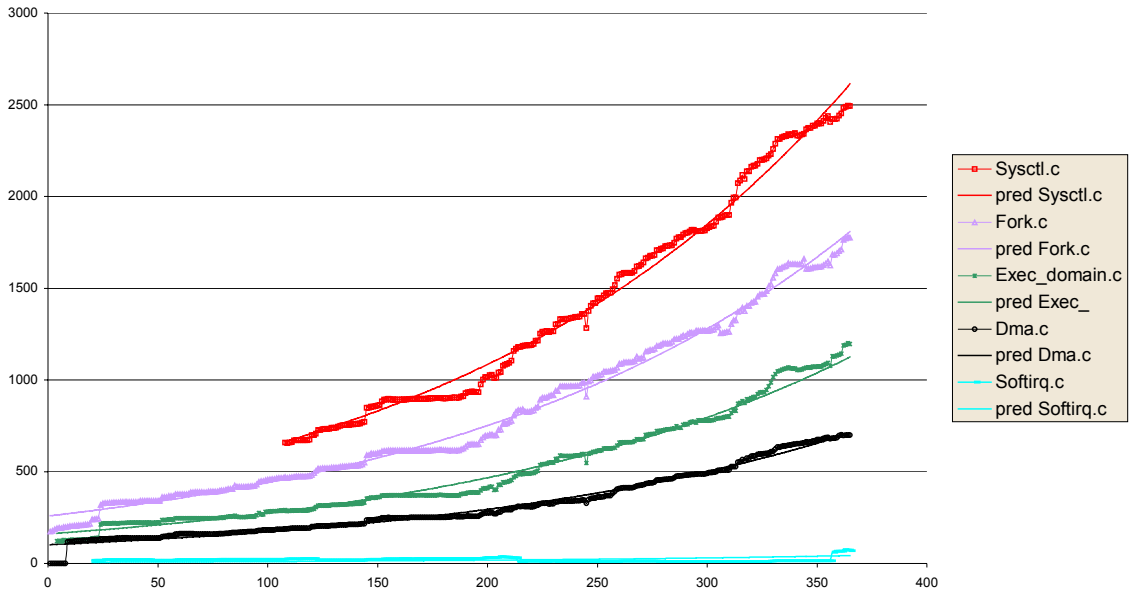

Figure 1 (Part 4 of 4)