Visualizing and Understanding Code Duplication in Large Software Systems

by

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A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Mathematics
in
Computer Science

Waterloo, Ontario, Canada, 2006

Authors Declaration for Electronic Submission of a Thesis

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Code duplication, or code cloning, is a common phenomena in the development of large software systems. Developers have a love-hate relationship with cloning. On one hand, cloning speeds up the development process. On the other hand, clone management is a challenging task as software evolves. Cloning has commonly been considered as undesirable for software maintenance and several research efforts have been devoted to automatically detect clones and eliminate clones aggressively. However, there is little empirical work done to analyze the consequences of cloning with respect to the software quality. Recent studies show that cloning is not necessarily undesirable. Cloning can used to minimize risks and there are cases where cloning is used as a design technique.

In this thesis, three visualization techniques are proposed to aid researchers in analyzing cloning in studying large software systems. All of the visualizations abstract and display cloning information at the subsystem level but with different emphases. At the subsystem level, clones can be classified as external clones and internal clones. External clones refer to code duplicates that reside in the same subsystem, whereas external clones are clones that are spread across different subsystems. Software architecture quality attributes such as cohesion and coupling are introduced to contribute to the study of cloning at the architecture level. The *Clone Cohesion and Coupling (CCC) Graph* and the *Clone System Hierarchy (CSH) Graph* display the cloning information for one single release. In particular, the CCC Graph highlights the amount of internal and external cloning for each subsystems; whereas the CSH Graph focuses more on the details of the spread of cloning. Finally, the *Clone System Evolution (CSE) Graph* shows the evolution of cloning over a period of time.

Acknowledgements

This thesis would not have been possible without the continuous support of my parents who always support me and give me will to succeed.

I would like to thank my supervisor Dr. Richard C. Holt for his support and advice. A special thank you to Dr. Ahmed E. Hassan for his fruitful suggestion and constant motivation throughout my research career both as a undergraduate research assistant and as a graduate student. I also thank him for offering me the opportunity to visit University of Victoria in the summer. That is a very enjoyable experience.

In addition, I appreciate the valuable feedback provided by two of my thesis readers: Dr Michael Godfrey and Dr. Joanne Atlee.

I am very fortunate to work with the amazing members of SWAG. In particular, I would like to thank Cory Kapster, Abram Hindle, LiJie Zou, and Olga Baysal for all their help and encouragement.

Finally, I thank for all my friends who patiently put up with me while I worked away on my thesis.

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Chapter 1

Introduction

Clones are identical or near identical segments of source code. Code clones are usually intentionally created through copying another piece of code. However, in certain cases [35] clones appears unintentionally due to code segments using the same APIs. Code cloning is a common phenomena in the development of large software systems. It is reported that 5-50% of large software systems are clones [8, 39, 7].

This chapter consists of the following parts: Section 1.1 provides a background of code cloning. Section 1.2 gives an overview of the thesis. Section 1.3 briefly discusses the novelties of this thesis. Section 1.4 talks about the organization of the thesis.

1.1 Code Cloning

A clone is a segment of code that has been created through duplication of another piece of code. Clones share similar code structures. However, since the size and the degree of similarities among code segments vary, code cloning is a fairly subjective concept. It depends on the context or human judgement whether it is a code clone or not.

linux-2.6.16.13\drivers\net\ne2.c : 285 - 295

```
#ifndef MODULE
struct net_device * __init ne2_probe(int unit)
{
        struct net_device *dev = alloc_ei_netdev();
        int err;

        if (!dev)
                return ERR_PTR(-ENOMEM);

        sprintf(dev->name, "eth%d", unit);
        netdev_boot_setup_check(dev);

        err = do_ne2_probe(dev);
        if (err)
                goto out;
        return dev;
out:
        free_netdev(dev);
        return ERR_PTR(err);
}
#endif
```

(A)

linux-2.6.16.13\drivers\net\lne390.c: 152 - 162

```
#ifndef MODULE
struct net_device * __init lne390_probe(int unit)
{
        struct net_device *dev = alloc_ei_netdev();
        int err;

        if (!dev)
                return ERR_PTR(-ENOMEM);

        sprintf(dev->name, "eth%d", unit);
        netdev_boot_setup_check(dev);

        err = do_lne390_probe(dev);
        if (err)
                goto out;
        return dev;
out:
        free_netdev(dev);
        return ERR_PTR(err);
}
#endif
```

(B)

linux-2.6.16.13\drivers\net\lance.c: 437 - 447

```
#ifndef MODULE
struct net_device * __init lance_probe(int unit)
{
        struct net_device *dev = alloc_etherdev(0);
        int err;

        if (!dev)
                return ERR_PTR(-ENODEV);

        sprintf(dev->name, "eth%d", unit);
        netdev_boot_setup_check(dev);

        err = do_lance_probe(dev);
        if (err)
                goto out;
        return dev;
out:
        free_netdev(dev);
        return ERR_PTR(err);
}
#endif
```

(C)

Figure 1.1: Clone example taken from Linux Kernel version 2.6.16.13.

Figure 1.1 shows an example of code cloning drawn from the Linux Kernel. The source code is taken from the code responsible for supporting the different network cards in the Linux Kernel version 2.6.16.13. The top row shows the file names and line numbers separated by colons. Areas highlighted in grey indicates the code duplication sections and the red font marks variation points.

When referring to clone relations, we use two terms: clone pairs and clone classes. A clone pair is a pair of code segments which are identical or similar to each other. A clone class is the maximum set of code segments in which any two of the code segments forms a clone pair. For example, A, B, C is a clone class. It implies that we have clone pairs $(A,\ B)$, $(B,\ C)$, and $(C,\ A)$.

Figure 1.2 shows 4 clone pairs. Three red blocks from "File1", "File2" and "File3" form three clone pairs, respectively. Two blue blocks from "File2" and "File3" form another

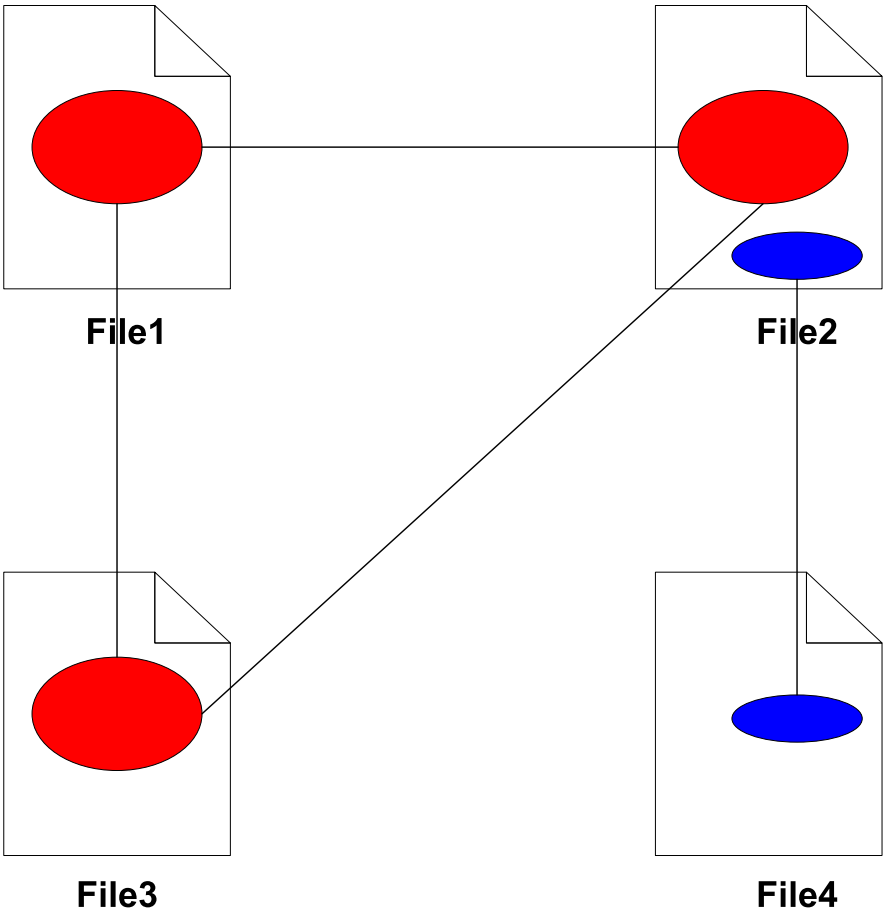


Figure 1.2: An example of clone pairs.

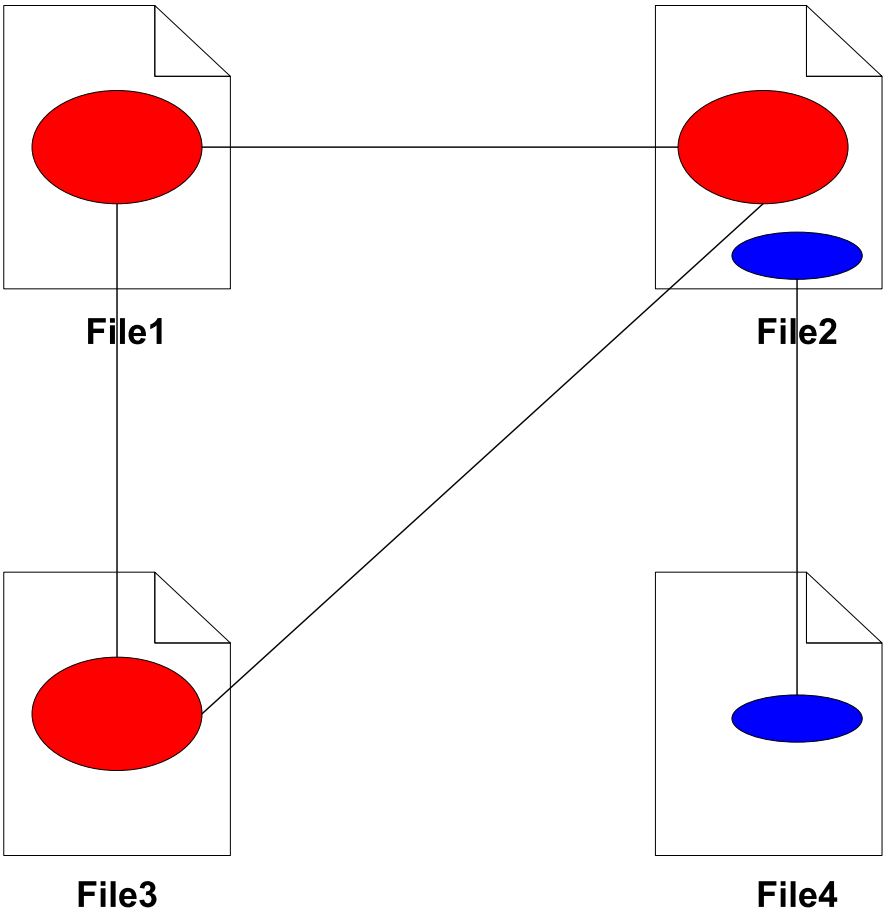


Figure 1.3: An example of clone classes.

clone pair. Figure 1.2 shows the same cloning data by using clone classes relations. It has two clone classes: a pink diamond indicating the clone class connecting three red blocks; and a blue diamond representing another clone class connecting two blue blocks.

The rest of this section is organized as follows. First, we talk about intentions why developers clone source code. Then we discuss reasons why developers should not clone source code. Finally, we present a few challenges of managing code clones.

1.1.1 Why Do People Clone Source Code?

There are a number of reasons why developers clone source code [36, 8, 32]. Here we summarize a few common scenarios.

Code cloning is unavoidable due to language limitations. For example, Standard Template Library(STL) in C++ is considered as a typical example of genericity. However, Basit et. al. [20] showed that there are still code duplications which cannot be eliminated by using generic programming language features such as templates.

Code cloning is used for reusing certain design patterns. For example, Cordy [22] pointed out from his years of experience in dealing with financial software systems that cloning is "the way in which designs are reused in these systems". He observed that there are only a limited number of tasks in the finance field; therefore the data structure and data manipulation operations are quite similar to each other. Consequently, whenever there is a need to write a new module; it is considered common practice to copy from the old code, which is trusted and tested.

Code cloning is adopted to preserve performance. For example, in real-time applications, some common operations are hand-optimized to achieve best performance.

It is required to copy from the existing optimized code whenever the same operations is needed.

Code cloning is used for experimentation purposes. It is discovered that [32] when developers start implementing new features they tend to copy from existing code. As they gain a deeper understanding of the problem and think more about the solution; these clones will be eliminated.

Code cloning is used for templating. For example, drivers are code written to enable operating systems to interact with hardware devices. Driver code is considered as the main source of errors in operating system [2]. What is more, it is fairly mechanic to write drivers. To implement a Linux SCSI driver [3], we need to implement only a few specified functions, and set these functions to point to appropriate fields for one *struct*. Rather than writing driver code from scratch, which is time-consuming and error-prone, it is preferable to copy from an existing driver code and modify it.

Code cloning is used in cross-cutting concerns. Code segments for error-checking or logging are usually scattered across the code base [30]. Developers clone error-checking or logging code to preserve consistency of the coding style.

Code cloning is used for risk minimization. Cordy [22] and Kapster [11] observed that rather than abstracting out the common operations, copying well-tested code reduces the risks of either breaking existing functionality as well as isolating the risks of introducing software defects to a single place.

Academically, there are studies [32, 27, 11] showing that cloning is considered a common practice in the software development process. There are quite a few cases when clone is used as a design pattern and are considered beneficial. For example, the forking patterned

mentioned in [11] can be used to test new features without affecting existing functionality. Therefore, there is a need to develop various kinds of clone maintenance tools [11].

1.1.2 Why Should People Not Clone Source Code?

Many researchers believe that cloning is a "bad smell" for code quality as it brings up challenges for software maintenance.

- Code cloning leads to a bloated code base. This leads to a large binary executables and requires more storage spaces. In devices that have limited storage spaces such as cell-phones, the amount of cloning has to be minimized.
- Code cloning causes additional effort for developers. As clone instances are similar to each other, developers need to careful examine the two pieces of code in order to tell the differences among clone instances.
- Code cloning brings challenges to software maintenance. When developers modify one clone piece apart(usually for bug fixes), it is very likely that they need to apply the same changes to its cloning instances. Therefore,
  - developers need to check all its cloning instances to decide whether similar changes need to be applied on them, and
  - uncover cloning information is hard, since cloning knowledge is usually left as undocumented and only exists in developers' head as short term memory.

Based on this brief, tools have been developed to automatically detect clones [25, 28, 8] and techniques have been proposed to automatically eliminate clones [16, 34].

1.1.3 Challenge of Dealing with Clones

Code cloning is a common practice in the software development, yet the long term effects are not well-understood. As we have shown in Sections 1.1.1 and 1.1.2, there are two opposing views towards code cloning. These two views examine clones from different perspectives and are both tenable. Unfortunately, to date there has been only one empirical study done to study the consequence of cloning [4].

A major problem of conducting clone studies in a large software system is how do handle large volume of data. Code clones are quite common in large software systems. Software systems such as Linux Kernel, which has several million lines of source code, may contain thousands of lines of clones.

The goal of this thesis is to develop tools and techniques to aid researchers to analyze code cloning in large software systems.

Our approach uses scaling and visualizing. We scale the huge volume of cloning data by three techniques: merging clone classes into bigger clone classes, lifting cloning relations from code segment level to file level or subsystem level, and pruning irrelevant cloning relations. Then we visualize our data along three dimensions: amount, spread, and time. The overview of the thesis is presented in Section 1.2.

1.2 Overview of Thesis

In this thesis, we propose tools and techniques to help researchers to understand code cloning in large software systems. We accomplish this by providing visualizations which support large data set.

We scale down the cloning data by providing various levels of abstractions and then provide three visualization techniques to highlight cloning along three different dimensions.

1.2.1 Scaling

We achieve scaling by three techniques: merging, lifting and filtering. We detail the scaling process as follows:

Merging: Each clone class obtained from the clone detection tools contains the line interval which are duplicates. Different clone classes can have the same files but with different line intervals. If two clone classes contain exactly the same files or subsystems, then we merge these clone classes into one bigger clone class.

We are going to illustrate this by means of an example. Figure 1.4 shows the clone classes before merging. We have three clone classes: the red, the blue and the yellow clone classes. Both the red clone class and the blue clone class contain three files; whereas the yellow clone class only contains 2 files. Figure 1.5 shows the clone classes after merging. We have two clone classes: the grey clone class, which is the result of merging the red and the blue clone classes; and the yellow clone class stays the same since it only contains 2 files and cannot be merge with the other two clone classes which both contain three files.

Lifting: The lifting step elevates cloning relations from the code segment level to the file level or up to the subsystem level.

We will illustrate the lifting process by means of an example. Figure 1.6 shows the cloning relations before lifting. We have three directories: “dirA”, “dirB” and “dirC”. Under “dirA”, we have three files: “File1”, “File2” and “File3”; under “dirB”, we have 1 file: “File4”; and under “dirC”, we have 1 file: “File5”. We have 2 clone classes: one clone classes contains code segments shown in red and one clone classes contains code segments shown in blue. Figure 1.7 shows the result after lifting. Since “File1” and “File2” are both under “dirA”, therefore the red clone class gets lifted to

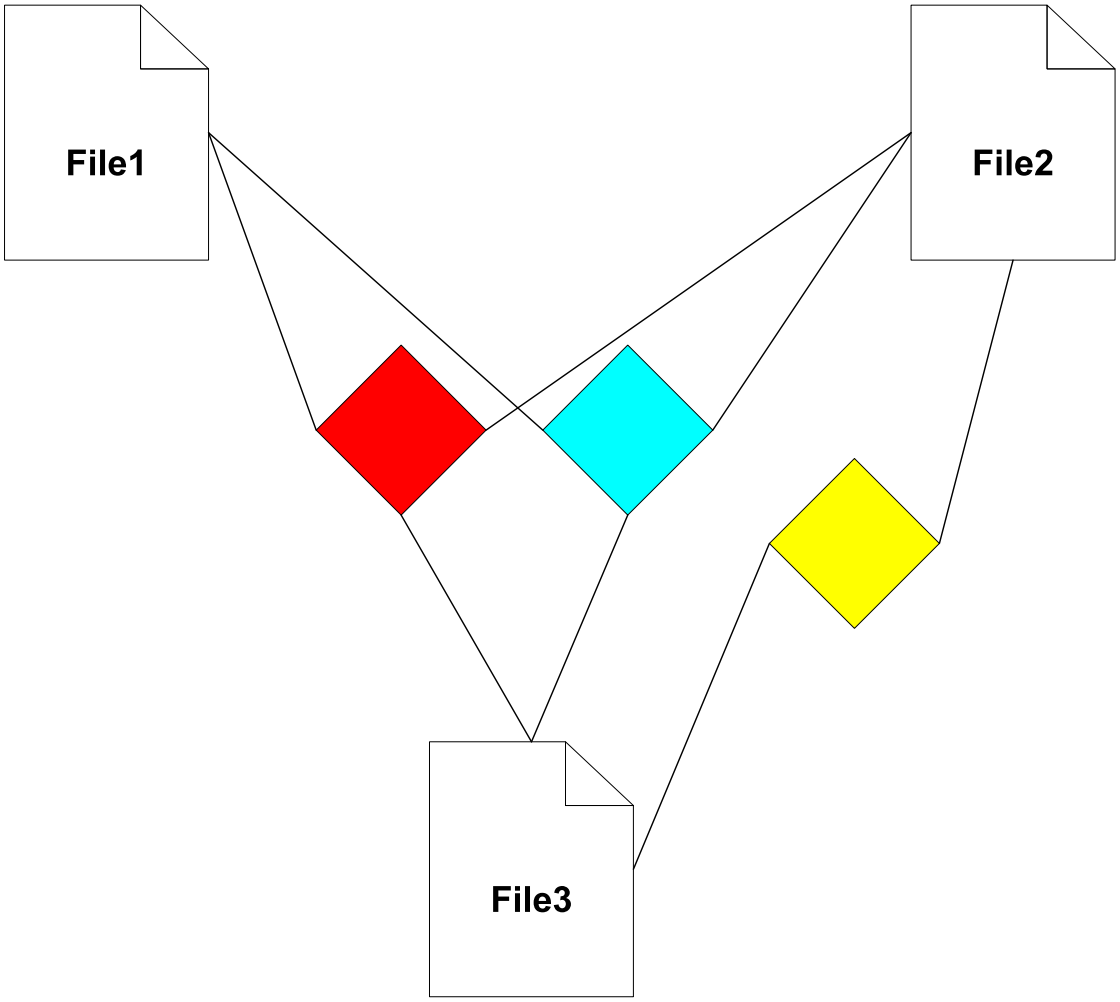


Figure 1.4: Clone classes before merging.

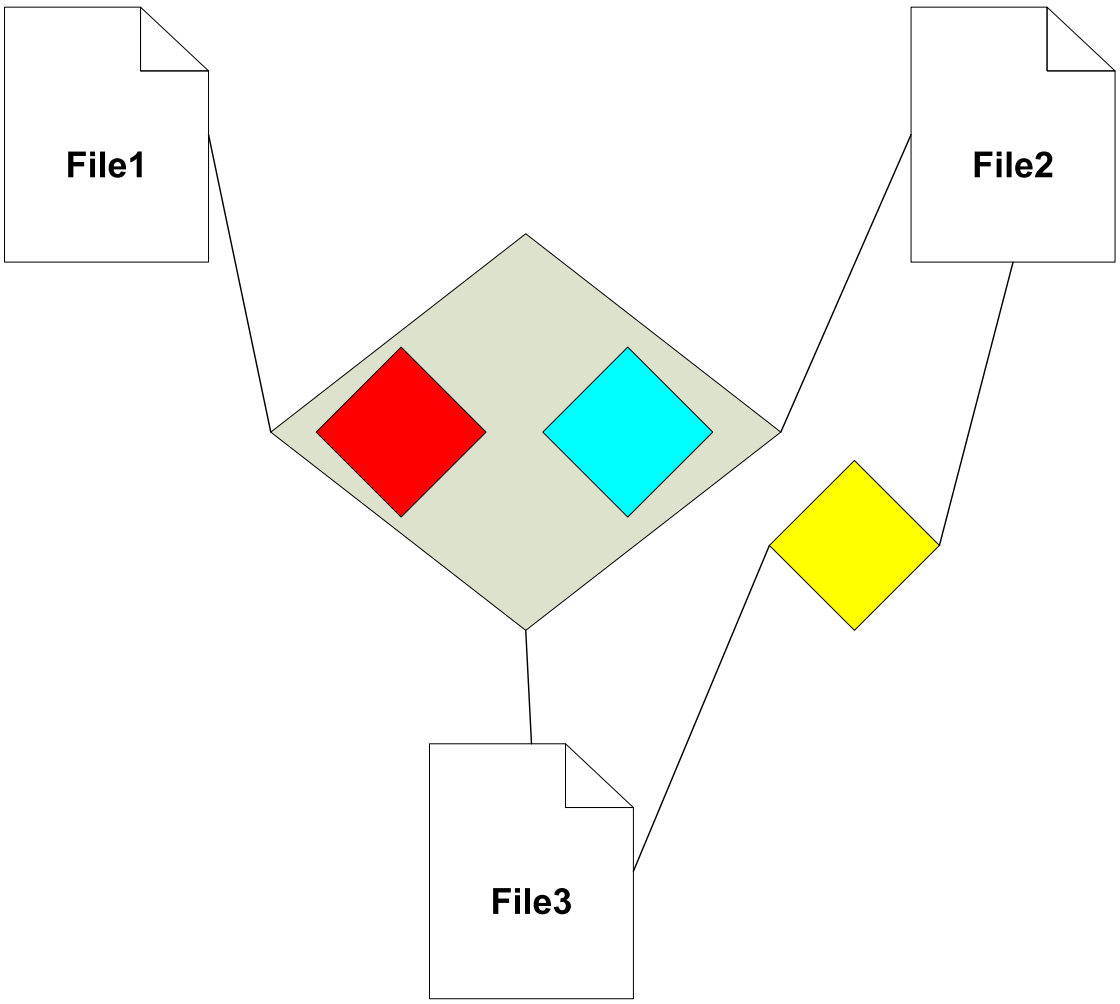


Figure 1.5: Clone classes after merging.

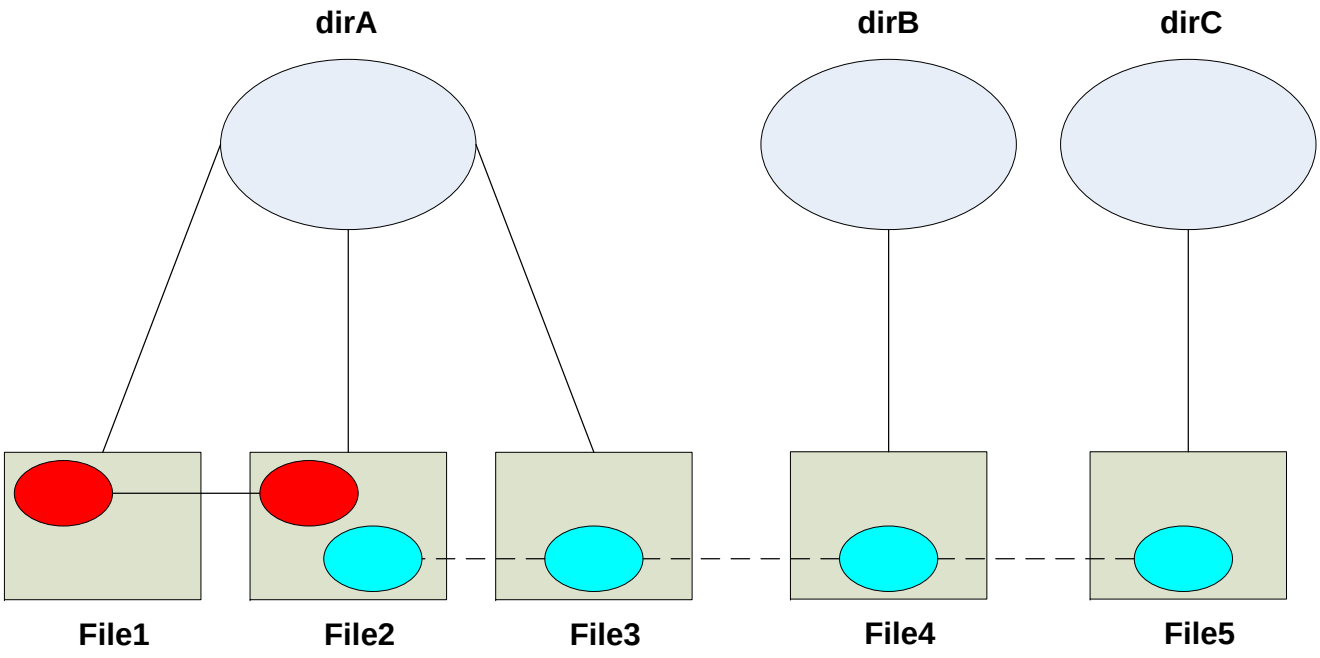


Figure 1.6: Clone classes before lifting.

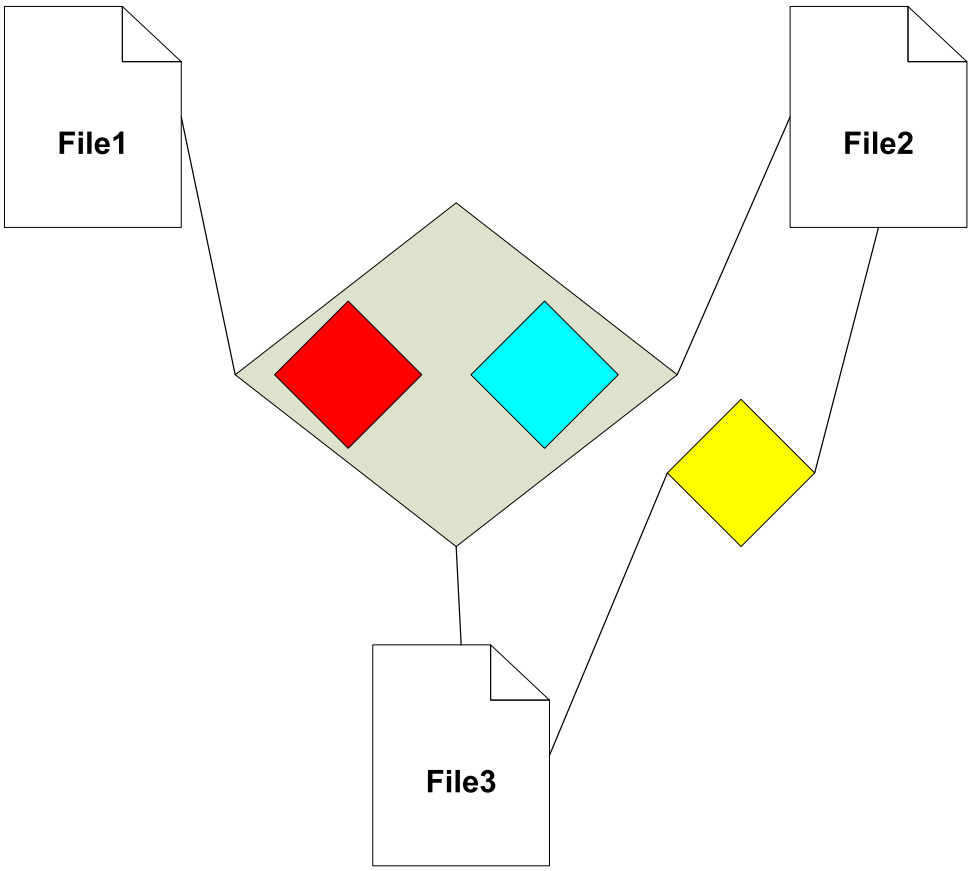


Figure 1.7: Clone classes after lifting.

"dirA", one blue block in "dirA" is from "File3". Similary, all the cloning relations from "File4" and "File5" are lifted to "dirB" and "dirC", respectively.

Pruning: Depending on the study we focus on, irreverent cloning data can be selectively removed. For example, if we are only interested in cloning related to "drivers" subsystem; then we can remove all the clone classes which do not contain files in "drivers". If we are only interested in cloning relations among subsystems, then we can remove all the file level cloning relations.

We name the resulting clone classes after merging and lifting steps as **Super Clone Classes**.

Note that merging and lifting steps can be used at any levels of system abstraction. In addition, the ordering of executing merging and lifting actions does not really matter.

For example, if we want the data to be scaled at the file level, we can first lift the clone classes at the code segment level first to the subsystem level and then merge the lifted clone classes. Alternatively, at the code segment level we can choose to merge clone classes that contain exactly the same set of files, then we lift them to the file level. The results will be the same.

Similarly, if we want the data to be scaled at the lowest subsystem level, we can first merge clone classes which associate with exactly the same lowest level subsystems, then we lift the clone classes into the lowest subsystem level, or the other way around.

1.2.2 Visualization

Three visualization techniques are proposed in this thesis. Each of them emphasizes cloning along different dimensions: quantity, spread and time, respectively. Quantity refers to how much duplications within one subsystem (internal cloning) and between subsystems

(external cloning). Spread refers to the details of cloning relations; that is how many subsystems or files it cross-cut. Time refers to how clones evolve over time in different parts of the subsystem.

Quantity: The *Clone Cohesion and Coupling* (CCC) Graph displays the amount of cloning that exists within one subsystem (internal cloning) as well as the the amount of cloning that exists between subsystems (external cloning).

It highlights the amount of code duplication between subsystems.

Spread: The *Clone System Hierarchical* (CSH) Graph lays out the cloning data in the system hierarchical structure.

It highlights cloning relations for individual files and directories by mouse movements. It emphasize the spread of cloning.

Time: The *Clone System Evolution* (CSH) Graph visualizes the evolvement of clones over time.

It highlights the most recent changes of code cloning.

1.3 Major Thesis Contributions

In this thesis, we introduce the concept of "Architecture of Clones" to help researchers to understand large set of cloning data. The concepts of cohesion and coupling are applied in the context of cloning to evaluate the quality of the software systems.

Three visualization techniques are proposed to help researchers to better understand large set of cloning data.

- The CCC graph is the first attempt to use energy-based graph layout to visualize the strength of external cloning among subsystems. Super clones scale the studies; what is more, visualization clone classes rather than pairs reduces the cross-cutting edges.
- The CSH graph lays out clone information in the hierarchy containment structure highlighting the spread of cloning. It also provides mechanisms to allow researchers to interactively query clone relations for each subsystem.
- The CSE graph shows the evolution of architecture of clones over time.
- For each of the three of the visualizations proposed in this thesis, we provide a guideline that summarizes how to reconstruct our visualizations. This is useful for researchers who are interested in using our tools to analyze cloning for other software systems.
- All three graphs covey the information of clone cohesion and coupling in the large software systems. They can also be applied to other areas of research like co-change.

In addition, two data filtering techniques are introduced and compared to remove false clones.

Finally, the metric *uloc* is a new metric to study the growth rate of the software systems.

1.4 Thesis Organization

The rest of this thesis is organized as follows: Chapter 2 shows how we obtain the cloning data set. Chapter 3 presents related research. Chapter 4 presents the first of our three clone visualizations: the *Clone Cohesion and Coupling(CCC)* graph. Chapter 5 explains the second visualization technique: the *Clone System Hierarchical (CSH)* graph. Chapter 6

introduces the concept of *uloc* and the third visualization: *Clone System Evolution (CSE)* graph. Finally, Chapter 7 summarizes our work and presents some future work.

Chapter 2

Clone Data Extraction

This chapter explains the steps used to extract the cloning data from a large software system. It is organized as follows: Section 2.1 explains the current existing clone detection techniques. Section 2.2 explains our choice of clone detection tool and techniques to remove inappropriate clones.

2.1 Summary of Clone Detection Techniques

There are four general techniques to detect clones:

Metrics Analysis: Metric-based clone detection techniques [28] collect various metrics such as: McCabe's Cyclomatic complexity, number of passed parameters, number of used/defined local/global variables, etc. Depending on how similar these metrics are, various code segments may be marked as clones. This approach is fast to compute, but it lacks precision. It is recommended to be used for pre-processing step to narrow down the selection of files that are going to be processed for more finely grained clone detection.

Simple Text Comparison: Simple text comparison techniques locate exact matches of code segments. The *Exact Match Clone Detection* algorithm described in [14] is an example of such a technique. The algorithm normalizes the code by removing comments and suppressing white spaces. It then tries to find all matched lines for each line. The algorithm uses a pattern matching algorithm to generate a list of maximal number of consecutive lines of cloned code for each code segment. Finally, cloning results are generated by filtering out smaller code segments. For the example shown in Figure 1.1, a simple text comparison technique would not recognize the variation points (in red). Instead of identifying a single large clone code segment, the algorithm would identify several smaller code segments as clones.

Lexical Analysis: Lexical analysis techniques tokenize the code and concatenate tokens into token sequences. Then they create abstract token strings to mark identifers and code constructs. The abstract token strings are used to locate maximal substring matches. An example of a tool that uses such a technique is the CCFinder tool [25]. The example shown in Figure 1.1 was identified by CCFinder.

AST Analysis: Abstract Syntax Tree (AST) Analysis techniques parse the code and create an abstract syntax tree. The techniques then compare AST subtrees. Clones are detected if two subtrees are identical to each other. An example of such a technique is presented in [5]. The example shown in Figure 1.1 would be identified by such techinques.

2.2 Data Generation and Pre-Processing

This section describes how we pre-process the data used for our visualizations. It consists of two steps: automatic detecting clone data and removing false clones.

2.2.1 Automatic Clone Data Detection

We use the CCFinder [25] as our clone detection tool. CCFinder is a lexical-analysis-type clone detection tool. It uses"Parameterized String Matching" algorithm to extract clone pairs and is reported to have a high recall rate compared to other tools [9].

In order to reduce the reporting of rather small trivial clones, CCFinder must be configured with a minimum clone size. We chose 30 tokens as the minimum clone size, since previous studies [27, 26] show that the output of CCFinder is of reasonable accuracy at this token level. We also turn off the option to locate clones within the same file, since we are more interested in detecting similarities across source code files and subsystems at the architecture level. Different options can be configured and other clone detection tools can be used if needed.

CCFinder output the clone detection results both in the form of clone pairs and clone classes.

2.2.2 Clone Data Filtering

Through a manual analysis of the CCFinder output, we discovered that CCFinder occasionally produces inappropriate cloning relations.

For example, it treats blocks of code that contain variable declarations and function prototypes as clones. The following function prototype declarations taken from $linux-2.6.16.13/drivers/scsi/aha152x.c$ and $linux-2.6.16.13/drivers/scsi/esp.c$ are considered as clones by CCFinder:

```
linux-2.6.16.13/drivers/scsi/aha152x.c:

static void datai_init(struct Scsi_Host *shpnt);
static void datai_run(struct Scsi_Host *shpnt);
static void datai_end(struct Scsi_Host *shpnt);
static void datao_init(struct Scsi_Host *shpnt);
static void datao_run(struct Scsi_Host *shpnt);
```

```
linux-2.6.16.13/drivers/scsi/esp.c:

static int esp_do_phase_determine(struct esp *esp);
static int esp_do_data_finale(struct esp *esp);
static int esp_select_complete(struct esp *esp);
static int esp_do_status(struct esp *esp);
static int esp_do_msgin(struct esp *esp);
```

To remove the inappropriate clone relations reported by CCFinder, we have developed two filtering techniques: *Structural Filtering* and *Textual Filtering*.

- **Structural Filtering**

  We call cloned code segments that are not inside a function "non-functional clones". In the above example, the reported cloned segments are inside the variable declaration block and these false positives are due to similar structures in variable declarations. Therefore, we choose to remove non-functional clones to eliminate inappropriate clone relations caused by variable declarations.

  The filtering is accomplished by a Perl script. The script invokes a source code tagging tool, called ctags [13] then parses the file to determine the beginning and ending lines of all defined code entities such as functions, variables, macros, and prototypes. The script then removes all identified CCFinder clone pairs which are non-functional clones.

- **Textural Filtering**

  Although structural filtering allows us to remove the non-functional clones caused by variable declarations, it cannot filter out false positives caused by similarities in program constructs.

  For example, the format for case switch statement is usually one case statement followed by one line of method invocation and then the break statement. The two

code segments shown are reported as clones to each other by CCFinder, since they both use case switch statements. However, we do not consider them as appropriate cloning relations since they do not share similar semantic meanings.

```
linux-2.6.16.13\drivers\scsi\ips.c: 2383-2398

case IPS_SUBDEVICEID_4M:
            ha->ad_type = IPS_ADTYPE_SERVERAID4M;
            break;

        case IPS_SUBDEVICEID_4MX:
            ha->ad_type = IPS_ADTYPE_SERVERAID4MX;
            break;

        case IPS_SUBDEVICEID_4LX:
            ha->ad_type = IPS_ADTYPE_SERVERAID4LX;
            break;

        case IPS_SUBDEVICEID_5I2:
            ha->ad_type = IPS_ADTYPE_SERVERAID5I2;
            break;
```

```
linux-2.6.16.13\drivers\scsi\iscsi_tcp.c: 3466-3477

    case ISCSI_PARAM_IMM_DATA_EN:
        session->imm_data_en = value;
        break;
    case ISCSI_PARAM_FIRST_BURST:
        session->first_burst = value;
        break;
    case ISCSI_PARAM_MAX_BURST:
        session->max_burst = value;
        break;
    case ISCSI_PARAM_PDU_INORDER_EN:
        session->pdu_inorder_en = value;
        break;
```

In order to focus on the code segments which have not only similar code structures but also similar semantics, we adopt the *Textural Filtering* technique. We write another Perl script to accomplish this task. We take the clone relations generated from clone detection tools and then for each clone pairs we do a textural diff between two code segments. If the percentage in common between these two code segments falls below certain threshold we set, we filter them out. To determine a reasonable

value of the threshold, we sample a few clone pairs and see whether there are similar in semantics. If they are common in code structure only, we set the threshold to be high enough to filter it. We repeat this process until it filters out all the "structural similar only" clones in the sample.

In addition, textual filtering require a lot of I/O operations as for each clone pair we need to compare the differences between the code segments. The amount of clone pairs produced by CCFinder is massive, thus it will take a long time to do the comparison. Our experiment shows that it takes more than 2 months to do the filtering tasks on a server for one release of Linux 2.6 series! To resolve this, we need to minimize the I/O overhead as much as possible. We group clone pairs by the files. So for comparing different code segments from the same pairs of files, we do not need to read the same files multiple times. Then we use the Perl's diff package rather than the Unix diff. This enables us to do the textual comparison in-memory rather than writing the code segments into files and invoke the Unix "diff" command. These ehancements dramatically improve the filtering performance, as it only takes hours to complete filtering on one version of Linux 2.6 series!

Textual filtering technique removes more cloning relations than structural filtering, since it removes non-functional clones as well. Take the inappropriate cloning relations due to similar code constructs in variable declarations for example. If we do a line-by-line textual comparison, the two code segments resembles nothing in similar. Therefore, they will be removed by our textual filtering technique.

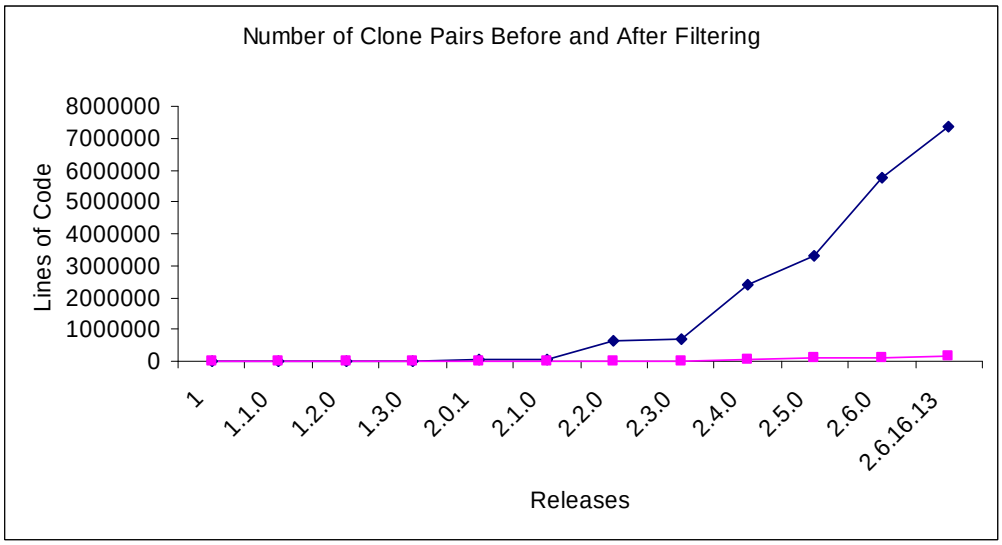
Table 2.1 shows the filtering result using *Textural Filtering* technique. We apply the filtering technique on the CCFinder's reported clones on 12 versions of Linux Kernel. The numbers of clone pairs both before and after filtering are shown.

releases	before(pair)	after(pair)
1.0	2486	1296
1.1.0	2488	1105
1.2.0	5766	1672
1.3.0	6745	1828
2.0.1	37154	4583
2.1.0	40000	5745
2.2.0	633522	22362
2.3.0	687555	23671
2.4.0	2403684	73299
2.5.0	3303538	95202
2.6.0	5773032	124301
2.6.16.13	7369040	160707

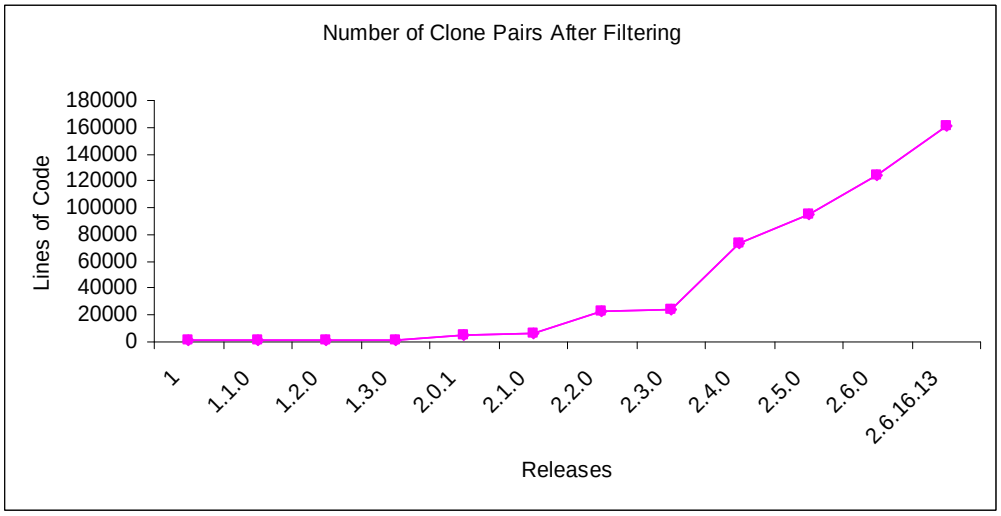
Table 2.1: Number of Clone Pairs Before and After Filtering for Linux Kernel.

Figure 2.1 shows the number of clone pairs before and after our structural filtering. As shown in Figure 2.1(A), our filtering technique eliminates a lot of false clones. The number of clone pairs before filtering and is much bigger than the number of clone pairs after filtering. The difference between the two is so big that the the number of clone pairs after filtering almost shapes like a flat line along the horizontal axis. Figure 2.1(B) only displays the number of clone pairs after the filtering. Interesting enough, the trend of number of clone pairs across releases stay the same before filtering and after filtering.

The filtering step takes detected clone pairs and perform textural diff between two pieces of code; therefore, the result of the filtering is also in clone pair format. Most



(A)



(B)

Figure 2.1: Structural Filtering

of our study uses clone classes. We write a Perl script to transform the data format from clone pairs to clone classes.

In summary, this chapter describes the steps to obtain cloning data in this thesis. The data is initially extracted from a clone detection tool, CCFinder. Then textual filtering is applied to remove the inappropriate clone relations.

Chapter 3

Related Work

In this chapter, we present two areas of related work: clone visualization and clone evolution.

3.1 Clone Visualization

For large software systems, clone detection tools usually report a large number (thousands) of clone pairs and clone classes. In order to help software maintainers in examining the output of clone detection tools, several clone visualization approaches and tools have be proposed in literature.

We break down previous clone visualization approaches along two dimensions:

1. **Visualized Source Entities**: Are clones shown at the code segment level, lifted to the file level, or lifted to the subsystem level? Higher abstractions (such as subsystems) permit the study of large software systems since they reduce the amount of clutter shown in the generated visualization.

2. **Visualized Clone Relations:** Are clones shown as clone pairs, grouped as clone classes, or grouped as super clone classes? By grouping clone code segments between common files or subsystems, then practitioners can concentrate on suspicious (large amounts of) cloning between two source entities instead of being overwhelmed by many smaller clone pairs.

Table 3.1 summarizes current clone visualization research along these two dimensions. The table also compares our presented visualizations to prior work. It categorizes each visualization along two dimensions: the source entities the tool visualizes (such as code segment level, file level or subsystem level) and the clone relations the tool visualizes (such as clone pairs, clone classes or super clone classes).

In addition, our Clone Cohesion and Coupling (CCC) graphs visualize the cloning relations by clone classes rather than clone pairs. Kapster et al. [26] show cloning relations in boxes-and-arrows like architectural diagrams. They visualize cloning pairs between subsystems. Figure 3.1 compares two different approaches (visualizing files using clone pairs and clone classes). The square nodes are files; the circle nodes are clone classes. Edges indicating cloning relationship. Both views visualize the same cloning data. The left view shows clone pairs, whereas the right view groups clones into clone classes. The left view contains more crossing edges than the right view. These edges make the visualization much harder to view in particular for large software systems. Moreover, the use of clone pairs in the visualization causes the loss of other relevant information. For example, it is not clear that the cloning relationship AB_1 is only between files A and B (clone class 2) or if it is among files A, B, C and D (clone class 1). Both of these problems are exaggerated for large software systems.

To further reduce the clutter for large software systems, we propose the creation of super clone classes. Super clone classes group multiple clone classes between the same

Name	**Source Entity**	**Clone Relation**
Scatter Plot [21, 38, 43]	Code Segments	Clone Pair
Metric Graph [43]	Code Segments	Clone Class
File Similarity Graph [43]	File	
Hass Diagram [23]	File	Clone Class
Hyper-linked Web [24]	File	Clone Class
Link Editing [42]	Code Segment	Clone Class
Dependency Graphs [26]	Subsystem	Clone Pair
Duplication Web [38]	File	Clone Pair
Duplication Aggregation Tree Map [38]	Subsystem	Clone Class
System Model View [38]	File, Subsystem	Clone Pair
Clone Class Family Enumeration [38]	File	Clone Class
Clone Cohesion and Coupling (CCC) Graph	Subsystem	Super Clone Class
Clone System Hierarchy (CSH) Graph	Files and Directories	Lifted Clone Classes
Clone System Evolution (CSE) Graph	Files and Directories	Lifted Clone Classes

Table 3.1: Summary of Clone Visualization Tools

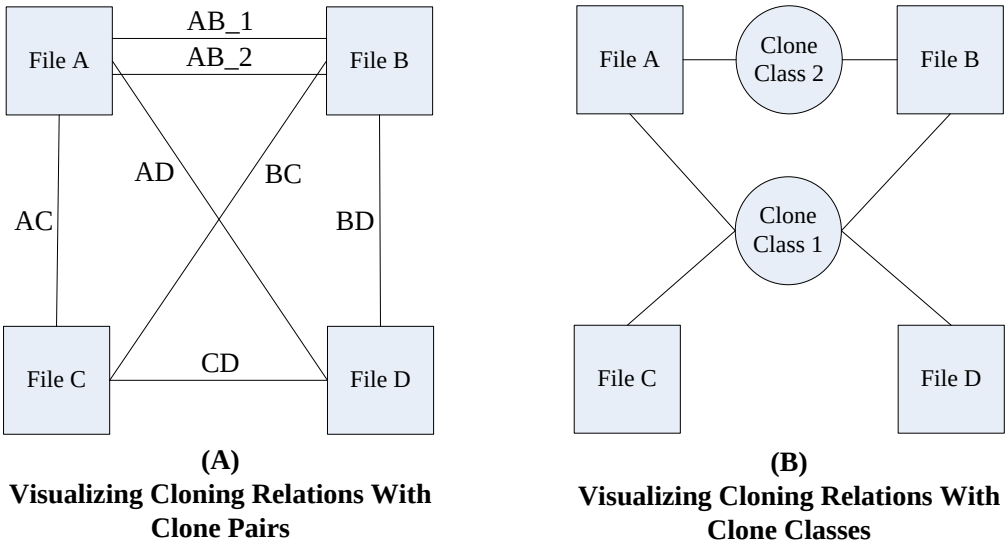


Figure 3.1: Comparison between two approaches

source entities. These super clone classes aggregate many small clone classes into one large super clone. These super clone classes help us deal with the limitation of simple text comparison techniques and other clone techniques which may not recognize variation points and may instead report them as separate clones. These super clone classes help highlight and summarize to developers the magnitude of cloning between two source code entities.

The Clone System Hierarchy (CSH) graph and the System Model View [38] display the cloning information in a directory structure. They both use the node size and edge width to indicate the amount of internal and external cloning. However, the System Model View shows the cloning relations between files whereas CSH can display cloning relations for any subsystems or files. In addition, CSH highlights the cloning relations by mouse movement rather showing all the edges in the graph. Therefore, CSH has less cross-cutting edges and contains more detailed cloning information than System Model View.

No previous techniques, to the author's knowledge, has been proposed to visualize the evolution of code clones. Clone System Evolution(CSE) graph is the first attempt to display the change of code cloning over time.

3.2 Clone Evolution

Lague et al. [4] studies the clone evolution on six subsequent versions of a large telecommunication projects over a period of three years. They incorporate the metric based clone detection technique and found out that even though old clones have been removed and but the overall number of clones keep increasing since new clones have been added in at a faster pace. They classify clone changes as new clones, deleted clones and modified clones.

Merlo et al. [15] analyzes 365 releases(from 1994 to 2001) of Linux kernel are analyzed. They uses the metric approach as their clone detection technique and found out that as system evolves over time, the quality of the code base does not degenerate because of cloning. As the addition of similar subsystem is accomplished through code reuse rather than code cloning.

Kim et al. [27] proposed a clone genealogy extractor which tracks individual clone instances over multiple releases. They present a more fine grained clone change patterns: same, add, subtract, consistent change, inconsistent change and finally shift. Their case study using the genealogy extractor shows that many clones are short lived and long lived clones usually change consistently over time and are not easily refactorable.

In summary, this chapter cover the previous work related to this thesis, namely the related work in the area of clone visualization and clone evolution.

Chapter 4

Clone Cohesion and Coupling (CCC) Graph

This chapter introduces *Clone Cohesion and Coupling (CCC)* graph, which visualizes the amount of internal cloning and external cloning for subsystems.

Coupling and cohesion between subsystems are commonly studied metrics when analyzing the architecture of large software systems. It is usually desirable for subsystems to have high cohesion within the subsystem and to have low coupling to other subsystems. In this chapter, we extend the ideas of coupling and cohesion to code cloning. As it has been previously explained, a code clone is a segment of code that has been created through duplication of another piece of code. Previous research has shown that in some instances code cloning is desirable, whereas in other cases it is not. This thesis takes the position that it is justifiable to have code cloning within subsystems (high cohesion), whereas it is not justifiable and likely not desirable to have it across subsystems (high coupling).

We present an approach, which consists of a framework that generates cloning data and a visualization technique for visualizing clone cohesion and coupling. Our approach can be

used by developers to locate undesirable cloning in their software system. We demonstrate our approach through a case study on the code responsible for SCSI drivers in the Linux kernel.

The rest of this chapter is organized as follows. Section 4.1 discusses the concept of the architecture of clones as well as the concept of clone cohesion and clone coupling. Section 4.2 presents our clone architecture recovery framework and discusses the data schema used in our framework. We present our visualizations and showcase their main benefits and features. Section 4.3 demonstrates our visualizations using a case study from the Linux Kernel (in particular its SCSI drivers). Finally, section 4.4 shows a brief usage guideline for researchers who are interested in using our visualization.

4.1 Architecture of Clones

Software architecture [17] provides a high-level understanding of large software systems. By analogy, we introduce the concept of **Architecture of Clones** [1] in the hope of abstracting a large volume of cloning information. The architecture of clones and software architecture both consist of two parts: components and connectors. Table 4.1 compares these two kinds of architectures. Components in both architectures refer to a collection of computation units, referred as *subsystems*. Connectors in software architecture refer to the description of interaction among components, such as data flow, call dependencies and so on, whereas in the context of architecture of clones, they mean cloning relations.

The terms cohesion and coupling are commonly used in studying the design or architecture of a software system. These terms measure the structure of dependencies within each subsystem and between subsystems (a subsystem contains files or other subsystems),

[1] We decide not to name it as "Clone Architecture" as to avoid the confusion of copying an architecture.

Category	Software Architecture	Architecture of Clones
Components	Subsystems	Subsystems
Connectors	Data/Dependency	Cloning
Cohesion and Coupling	Dependency	Internal and External Cloning
Examples	Pipe and Filters, Client and Server	Forking, Templating

Table 4.1: Comparison Between Software Architecture and Architecture of Clones

respectively. Coupling is concerned with dependencies between subsystems; while cohesion refers to the dependencies within the subsystem. It is commonly desirable for a software architecture to have low coupling and high cohesion. For example, a subsystem with a large number of functions that are dependant on each other (high cohesion) is more desirable than a subsystem where functions depend heavily on functions in other subsystems (high coupling). This intuition forms the basis of many modern software clustering techniques [33].

Highly cohesive subsystems are desirable since they imply that subsystems represent closely related concerns. Low coupling is also desirable since it implies that the subsystems are relatively easy to modify and evolve. Developers changing software systems with low coupling can have their changes focused to a limited number of subsystems instead of needing to propagate their changes to a large number of subsystems.

In this thesis, we extend the concepts of coupling and cohesion to code cloning. This thesis takes the position that it is justifiable to have some cloning within a subsystem (clone cohesion); whereas it is not desirable to have cloning across subsystems (clone coupling). Cloning within a subsystem is "justifiable" since it is likely due to the similarity between

functions and files within a subsystem. Large amount of cloning across subsystems is not "justifiable" since it is expected that subsystems represent different concerns that are not similar and therefore should not share a large amount of code cloning. This intuition is analogous to coupling for code dependencies, where it is not desirable to have coupling between different subsystems. In summary, we consider that low code coupling and high code cohesion are desirable, and low clone coupling and high clone cohesion are justifiable.

We use the term justifiable for clone coupling and cohesion since as we mentioned earlier that may be good reasons to clone code and there are no definitive research results that rule out the shortcomings or advocate the benefits of clones [27]. Determining whether a clone is desired or not should be done on a project by project basis by system experts. In this chapter, we present an approach to assist system experts to study cloning in their software system. The approach presents a visualization that a system expert use to gain an overview of the amount of clone cohesion and coupling in their software system. Using the same visualization, the system expert can investigate specific code clones to determine if they are justifiable or not. If they are not justifiable, then the system expert can schedule their removal as part of future code refactoring activities. The visualization as well permits the system expert to perform "What-if" analysis to determine the impact of removing particular clones and to determine the amount of effort needed to remove clones between subsystems in large software systems.

4.2 Our Approach

The main motivation for our visualization is to assist practitioners in coping with the large amount of results displayed by clone detection tools. The main purpose of the generated visualization is to highlight to developers cloning within each subsystem and across sub-

systems. Developers can then investigate whether the cloning is undesirable or not. For example, if a developer examining our visualization notices that there is a large amount of cloning between the memory manager and the network drivers in Linux, then he or she may be alarmed since there is no clear justifiable reason for such cloning to occur. On the other hand if our visualization highlighted that two similar driver families using the same hardware chipset have a large amount of common code then the developer may consider such cloning justifiable. The developer may later consult other senior developers to determine whether such cloning is desirable. In short, our produced visualization highlights potentially troublesome clones and we permit developers to study them closely instead of displaying all clones between all code segments in large software systems.

We now detail the main two components of our approach: a clone recovery framework and clone visualization.

4.2.1 Clone Architecture Recovery Framework

In order to visualize clones we must first recover them by running a clone detection tool. The results of the clone detection tool are then post-processed in order to remove false positives. Using the filtered cloning information and the domain knowledge (gathered by a system expert or through reading system documentation), we can produce our visualizations.

Figure 4.1 gives an overview of our framework. In order to communicate between the different tools and steps in our framework we used a set of data schemas. Each step in our framework expects data in the appropriate schema. The schemas are shown in Figure 4.2. The schemas are at decreasing level of detail: Clone-Class-Code-Segment Level, Clone-Class-Subsystem Level, and Super-Clone-Subsystem Level. The steps in our framework lift the cloning data from **Clone-Class-Code-Segment Level schema**, to

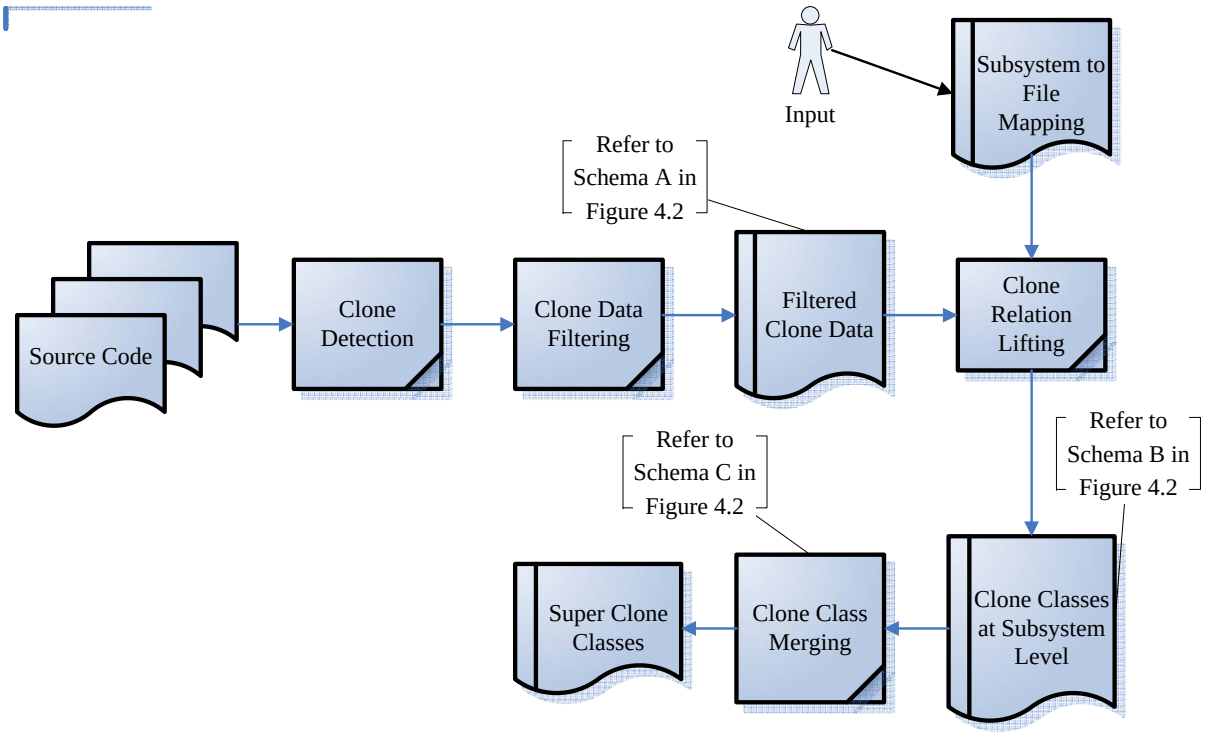


Figure 4.1: Our Clone Architecture Recovery Framework.

Clone-Class-Subsystem Level schema; and then merge clone classes to get **Super-Clone-Subsystem Level** cloning relation. We present below the steps in our framework

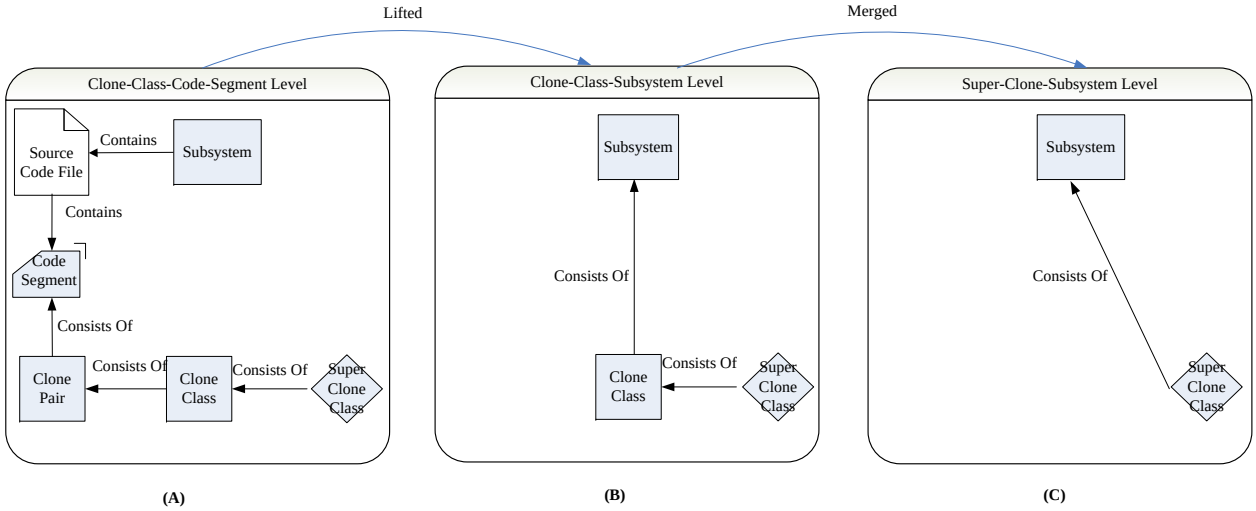


Figure 4.2: Schemas Used in Our Framework.

Data Pre-Processing The first two steps (Clone Detection, and Clone Data Filtering) in the framework are the data pre-processing step. We choose CCFinder as our clone detection tools and set 30 as the minimum number of common tokens to qualify as clones when comparing two segments of code. Then we use textural filtering to remove the false clones. Details are presented in Section 2.2.

Figure 4.2(A) shows the Clone-Class-Code-Segment Level schema after the clone detection and filtering steps. The schema contains four types of entities: source code segments, files, clone pairs and clone classes. A file contains one or more source code segments; each clone pair consists of two code segments; and each clone classes consists of at least one clone pair.

Clone Relation Lifting At this stage, each clone class contains a set of code segments from different files. We use two lifting operations here. First, we lift information to the file level (i.e. we lift our cloning data from Clone-Class-Code-Segment level to Clone-Class-File level). For example, if clone class A contains lines $110 - 130$ in $file1.c$, lines $210 - 230$ in $file2.c$ and lines $10 - 30$ in $file3.c$, then the lifting will results in clone class A containing 20 lines of cloned code, which reside in files $file1.c$, $file2.c$, and $file3.c$, respectively.

Since we plan to visualize relations between subsystems, we need to lift our cloning data to the Super-Clone-Class-Subsystem level. Several clone classes might contain the same set of subsystems or some of them might only contain one subsystem as all the duplicates are within the same subsystems.

To perform the lifting to the subsystem level, we need a mapping from files to subsystems. Ideally, such a mapping would be provided by a system expert. However, if we don't have an expert, as suggested in [6], we have to create this mapping by a few heuristics: such as consulting the documentation, grouping files based on directory structure and naming conventions or manually examining the source code. Continuing the above example, if $file1.c$ is in subsystem $S1$, $file2.c$ in subsystem $S2$, and $file3.c$ in subsystem $S3$; then the lifting result will create clone class A which contains consists of subsystems $S1$, $S2$ and $S3$ which contain 20 duplicated lines, respectively.

Note that, subsystems can contain smaller subsystems. Therefore, depending on the level of system abstractions desired, repeated lifting process should be performed, accordingly. Figure 4.2(B) shows the Clone-Class-Subsystem Level schema after the lifting step. The data at this level contains two types of entities: clone classes and subsystems. Each clone classes consists of at least one subsystem.

Merging of Clone Classes

In this final step, we aggregate the clone classes which contain the same set of subsystem(s) to simplify the cloning relationship. For example, suppose clone classes 128 and 233 both contains subsystems $S1$, $S2$ and $S3$ and no more. We can merge these two clone classes into one super clone class node. Super clone class nodes are named after the names of the subsystems in which the super clone classes contain. If they cross multiple subsystems, then each subsystem is separated by a "#" sign. In the above example, the super clone class is named as $S1\#S2\#S3$ to indicate that they all exactly contain subsystems $S1$, $S2$ and $S3$. We found that this naming convention helps easily identify the degree of cloning in a super clone in our visualization instead of having users follow a large number of edges.

Figure 4.2(C) shows the Super-Clone-Class-Subsystem schema. There are two types of entities here: Super Clone Classes and subsystems. Each super clone class contains one or more subsystems.

4.2.2 Clone Cohesion and Coupling (CCC) Graph

The main goal of our Clone Cohesion and Coupling (CCC) graph visualization is to highlight cloning within each subsystem (cohesion) and across subsystems (coupling). To help to direct practitioners to the most troublesome spots, we define "cloning hotspots" that are brightly colored large nodes that would capture the attention of the viewer.

A secondary goal of our visualization is to show how different subsystems are interrelated according to cloning. Our cloning visualization shows close together subsystems that have a large amount of common code due to cloning, and shows far apart subsystems that have little cloning between each other.

We now discuss the different entities in our visualization. See Figure 4.4 for an example of this visualization. The graph consists of two types of entities: nodes and edges. There are two types of nodes in our graphs: rectangle nodes (subsystems) and diamond nodes (super clones). An edge between a rectangle and a diamond represents a cloning relationship.

We now explain the semantics of our visualization by showing how we satisfy our aforementioned goals.

Goal 1: Cohesion, Coupling and Hot Spots

Node Type	**Width**	**Height**
Subsystem (box)	Number of Lines Cloned Within the Subsystems	Number of Clone Classes Involved Within the Subsystems
Super Clone (diamond)	Number of Lines Cloned With Its Associated Subsystems	Number of Clone Classes Involved With Its Associated Subsystems

Table 4.2: Description of the Dimensions of Nodes

To highlight cohesion and coupling, we define the dimensions of the nodes representing them according to Table 4.2. Using these dimensions, large boxes imply that there is a large amount of cloning within a subsystem (high cohesion) and large diamonds indicate that there there is a large amount of cloning across subsystems (high coupling).

In addition to varying the sizes of the nodes to highlight the amount of cloning, we vary the color of the nodes. In particular, we vary the color of the diamond nodes

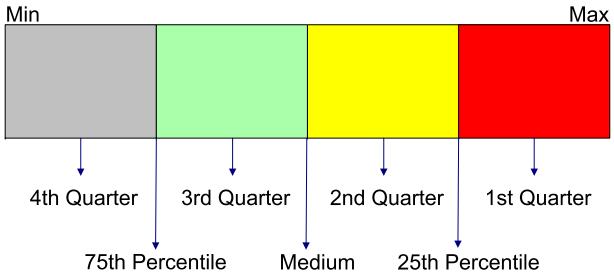


Figure 4.3: Heat Coloring.

since we believe that cross subsystem coupling (i.e. high coupling) is troublesome and should be investigated. We consider large diamonds as "cloning hot-spots". We "heat color" super clones using a quartile based coloring technique. The color of a diamond is based on the total number of lines cloned across subsystems in that super clone node. We choose the total lines of cloned code rather than the total number of cross family clones since we feel that total lines of cloned code is a better indicator of how much effort will be required to examine and refactor a particular super clone node.

The "Heat Coloring" works by calculating the median and the quartiles (the lower quartile is the 25th percentile and the upper quartile is the 75th percentile), the value range of the studied metric is divided into four quarters, which are associated with four different colors respectively. In our case studies, we have chosen red, yellow, light-green, and light-grey as shown in Figure 4.3.

Goal 2: Overall System Cloning View

In order to demonstrate the interrelations between different subsystems according to cloning, we apply a force-based graph layout [41] in our visualization to arrange the

relative position of subsystems. Weights have been exerted to the edges to represent the number of cloned lines from the subsystems to the super clone nodes. Subsystems which have more duplications with each other will be placed closer to the super clone classes; conversely, subsystems which have less cross-family cloning will be pushed further away from the super clone nodes. Overall, subsystems which have a large amount of code cloning with other subsystems will be placed closer to these subsystems than other subsystems.

A Simple Visualization Example

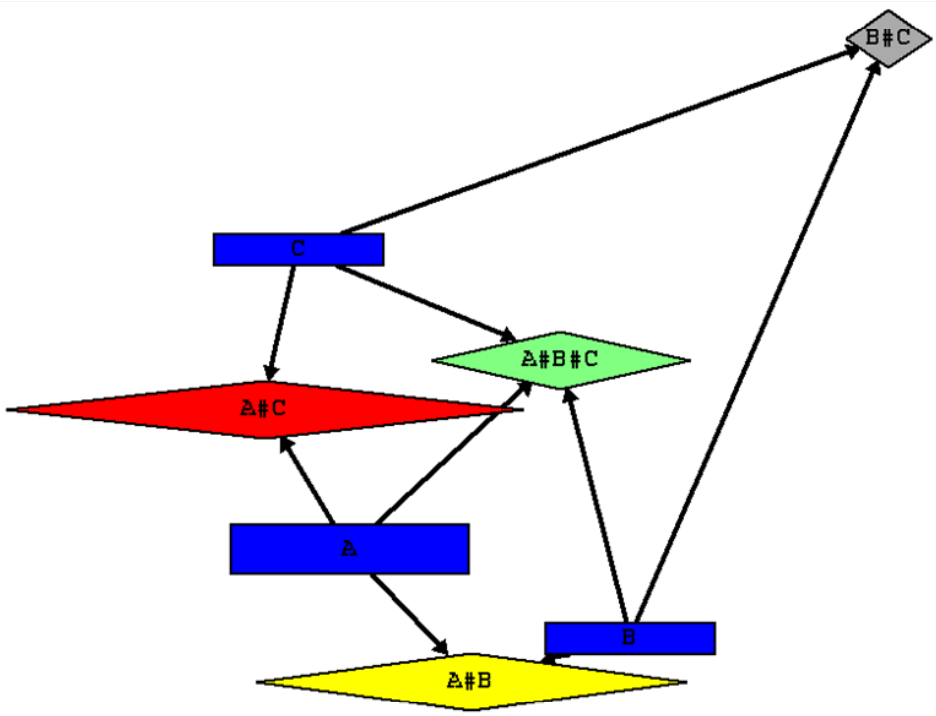


Figure 4.4: An Example of the Clone Cohesion and Coupling (CCC) graph.

Figure 4.4 shows an example visualized using our technique. It consists of three

subsystems: A, B, and C; and four super clone nodes: $A\#B\#C$, $A\#B$, $B\#C$, and $A\#C$. As indicated by the color: $A\#C$ has the biggest cross-subsystem cloning, subsystems A and C are pulled towards that super clone. The second largest super clone node is $A\#B$, followed by $A\#B\#C$, and finally $B\#C$. Since $B\#C$ is the smallest clones, subsystems B and C are pushed away from that super clone node. Subsystem A is taller and wider, since it contains more internal cloning than other subsystems. All super clone nodes are colored using the heat based coloring techniques.

4.3 Case Study: The Clone Architecture of SCSI Subsystem

To demonstrate our framework, we present a study of cloning in the code responsible for *SCSI* drivers in the Linux kernel. *SCSI* stands for "Small Computer System Interface". We believe studying *SCSI* drivers is a good case study to demonstrate clone cohesion and coupling.

Device drivers are programs for interacting with hardware devices. Studies show that writing device drivers is error-prone and is considered as a major source of errors in operating systems [10]. Around 30% of the source code files in the Linux Kernel are devoted for implementing various device drivers. Due to the similarity between hardware devices in the same family (i.e. from the same vendor or that use the same hardware chipset), developers are more likely to clone code between drivers in the same family in order to speed up development and reduce the likelihood of errors. Therefore, we believe that it is justifiable and probably desirable to have cloning within a driver family. However, it may not be justifiable nor desirable to have cloning across different driver families; since drivers from different families resemble little similarities thus these types of cloning might

be questionable. Developers have to be aware of such cross family cloning and may need to propagate changes across driver families. Such change propagation are likely to introduce errors over time as developer forget such unexpected dependencies.

4.3.1 Results of Our Clone Extraction Framework

All code in the SCSI related directories in Linux consists of 858, 727 tokens, 476, 612 lines, and 381 files. CCFinder (with 30 tokens as the minimum clone size) reported that this code has 54, 195 clone pairs and 2, 034 clone classes. After filtering the non-function clones, we have 305 clone classes left. We have 119 clone classes which cross cut two or more subsystems. We have obtained 33 super clone nodes after the merging process, about 67% of them cross cut two or three subsystems.

4.3.2 Subsystem Mapping

An important input needed for our framework is the mappings from files to subsystems. Ideally, a system expert would provide such a mapping. Unfortunately, we don't have one. By reading documentation, analyzing source code and examining files, we created a subsystem mapping. Our subsystem mapping groups files belonging to the same driver family (similar vendor or similar driver chip in the same family) in the same subsystem. We now explain how we built our mapping.

There are 425 files that are in the directories that implement the SCSI drivers in the Linux Kernel version 2.6.16.13. Nevertheless, many of these files do not implement drivers but rather they are testing or libraries files. For our study we decided to only focus on files that implement specific SCSI drivers. To uncover such files, we started by parsing the Makefiles responsible for building the SCSI drivers in the Linux Kernel. We show below an excerpt of a Makefile for SCSI.

```
obj-$(CONFIG_SCSI_SATA_PROMISE) += libata.o sata_promise.o
obj-$(CONFIG_SCSI_SATA_QSTOR)   += libata.o sata_qstor.o
obj-$(CONFIG_SCSI_SATA_SIL) += libata.o sata_sil.o
obj-$(CONFIG_SCSI_SATA_SIL24)   += libata.o sata_sil24.o ...
obj-$(CONFIG_SCSI_IN2000)   += in2000.o
```

In the above example, *libata.o* corresponds to a library; and files like *sata_promise.o* and *sata_sil.o* refer to driver files *sata_promise.c* and *sata_sil.c*, respectively. In addition, *sata_promise.c* and *sata_sil.c* are part of the same family (i.e subsystem). In order to automate the subsystem mapping process, we followed the following steps:

- Object files (e.g. *libata.o*) which appear multiple times are considered as library files and are not considered as driver files. For our analysis all files related to such a library file are considered to be in the same family (i.e. subsystem).

- Object files (e.g *sata_promise.o* and *sata_sil.o*) which appear once in a Makefile are considered as driver files.

- If an object file (e.g *sata_promise.c*) appears on the same line as a library file (e.g. *libata.o*), then the object file is considered as part of the subsystem called *libata.*

- If an object file (e.g. *in*2000.*o*) appears alone on line without a library file, then we have to manually examine the file's comment and reading additional system documentation to determine if it is a driver or not and which subsystem it should be mapped to. For example, when we manually examine the *in*2000.*c* we find that it is a device driver for the Always IN2000 ISA SCSI card. In grouping such files (ie. files with no libraries), we had two options either to group them according to the vendor or according to their chipset. Each group criteria would result with a different system decomposition, a system expert may decide one criteria over the other. For our study we decided to group such files by chipset in order to be consistent with the

grouping created by the Makefile. The grouping obtained from the Makefile, in the previous steps, is based on the chipset.

This process has helped us identify 109 drivers and we created 17 driver subsystems (i.e. families). Our automatic Makefile clustering has helped us cluster 56 drivers. The remaining drivers are clustered manually.

4.3.3 Clone Cohesion and Coupling (CCC) Graph

Figure 4.5 shows a screenshot of our Clone Cohesion and Coupling graph for the SCSI driver subsystems. The figure shows a zoomed out view of the visualization. On the right side of the figure we mark a few noteworthy nodes. The figure is generated using the aiSee tool [1] which permits us to zoom in and zoom out the diagram. The forced-based graph layout permits us to see the degree of clone coupling between subsystems. For example, IOMEGA and FUTUREDOMAIN are more tightly coupled than ATA and NCR53C9x. In our study we focus on the hot spots (large red diamond nodes and large boxes). Our visualization indicates that there is a large amount of cloning within the ATA and IOMEGA subsystems (i.e. both subsystems have high clone cohesion). We also investigated two of the largest diamond nodes since they indicate high coupling between subsystems).

ADAPTEC#IOMEGA is one of the biggest super clone nodes (Number 5 in Figure 4.5). It contains 864 lines of cloned code and has 5 driver files across two subsystems (ADAPTEC and IOEMA). By manually examining source code, we discover that this super clone node is superfluous. The clones are code segments that contain case switch statements. It is a false clone produced by CCFinder. CCFinder tokenizes the source code and recognizes the similar code structures.

ULTRASTOR#EATA is another big super clone node (Number 1 in Figure 4.5). A closer analysis of this super clone node reveals that it contains 14 clone classes and all the

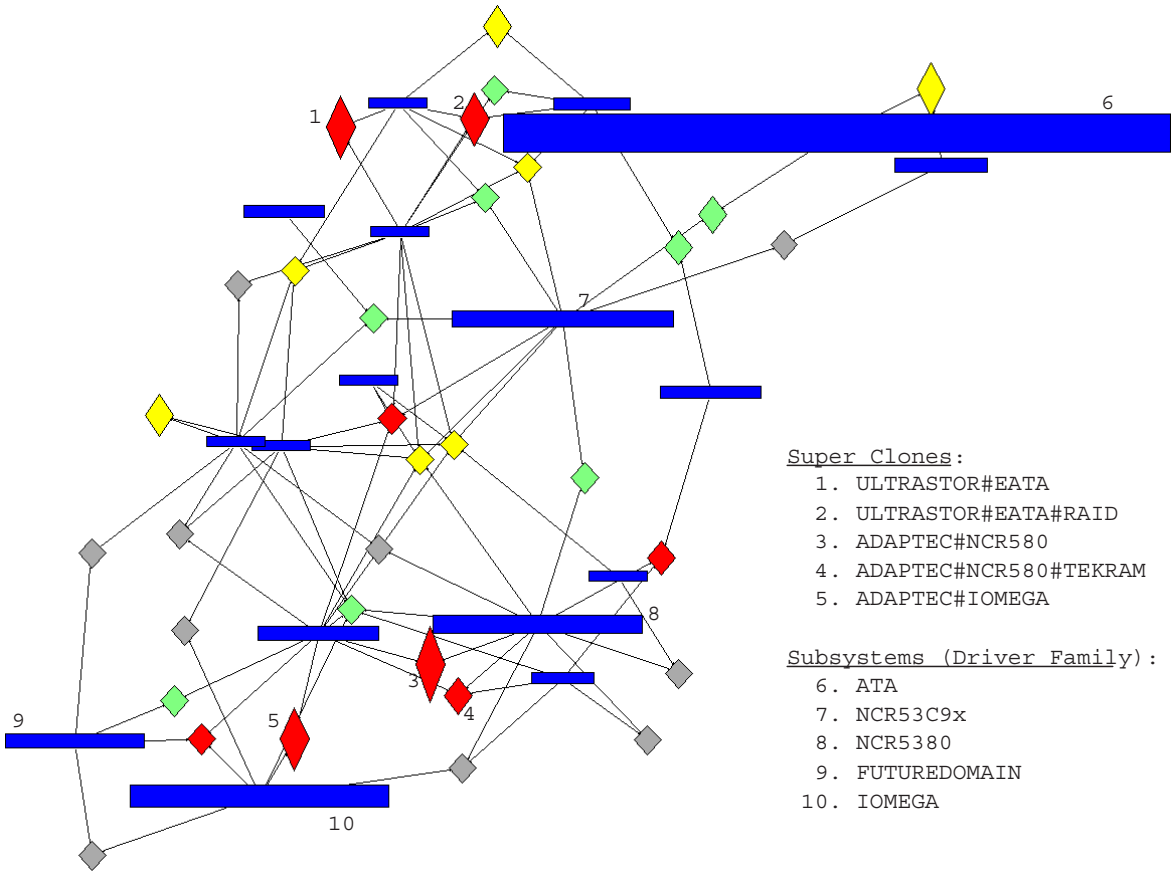


Figure 4.5: Annotated Screenshots of the CCC graph for the Linux SCSI drivers.

cloning occurs between only two files: *eata.c* from the EATA family and $u14{-}34f.c$ from the ULTRASTOR family. They are neither from the same vendor nor do they have a common hardware chipset. *eata.c* is the Low-level driver for EATA/DMA SCSI host adapters and $u14-34f.c$ is the Low-level driver for UltraStor 14F/34F SCSI host adapters. We decided to explore the reason behind such large degree of coupling between both subsystems (in particular both files). We manually inspected the change logs for both files. The change logs indicate that changes to both files are almost identical and that changes occur almost at the same date throughout the lifetime of both files. Moreover, we discovered that the copyright for both files is attributed to the same person. We suspect that the same developer has cloned one of the files as part of knowledge transfer from one driver to the other. As development progresses, the clones have been maintained synchronously.

The visualization has been able to highlight the most noteworthy clones across subsystems and within subsystems. Using the visualization we are able to quickly locate these noteworthy and investigate them instead of investigating a large number of clone pairs in an ad-hoc manner.

4.4 Usage Guideline

We summarize the steps for using our visualization. Researchers can follow this guidelines to process, visualize and analyze cloning for other software systems.

Overall Process: Take the above case study for example. Inside Linux scsi subsystem, cloning can occur among drivers which share same hardware platform, or from the same manufacture, etc. Therefore, there can be different criteria to group files into subsystems. So, it is recommended to produce several CCC graphs using different subsystem decomposition and cross-examine the interesting spot. A thorough

empirical clone study on SCSI drivers should examine the subsystem level cloning according to different subsystem decomposition. For example, driver files can be grouped by parsing the Makefiles (check Section 4.3.2) or by file name similarity (such as "sun3_NCR5380.c" and "atari_NCR5380.c" are similar) or by the length of file sizes (files with similar sizes are grouped together), etc.

Using each subsystem grouping, a CCC graph is generated and analyzed. The aim is to investigate places where it has heavy cloning. For example, we need to investigate subsystems which have heavy internal cloning to see whether it is justifiable as well as examining big super clones to see whether it is desirable.

Data Processing: Lifting refers to the process of aggregating the cloning data from the file level to the subsystem level. Lifting process is repeated until it reaches to the level of system abstractions desired. The lifting process can be stopped at the lowest subsystem level or be performed all the way up to the top level subsystems or to any intermediate levels in between.

Once lifting is done, merging combines the clone classes into one bigger clone classes. Note that, merging is invoked only if clone classes contains exactly the same set of subsystems.

Graph Analysis: We now describe a few issues that require attention for:

Thin Rectangle Nodes are subsystems that contain a lot of duplicated code segments but each clone is relatively small. This type of nodes is worth investigating since it could possibly be a cross-cutting concern or just repeated code idioms.

Flat Rectangle Nodes are subsystems that contains very few cloned segments

but a lot of code gets duplicated. This could possibly be a copy of entire source code file.

Red Diamond Nodes are a group of clone classes which have the largest number of cross-subsystem cloning. We need to further investigate why these subsystems are tightly coupled.

Diamond Nodes with Several "#": we name the merged clone class as the names of the clone classes to be merged separated by "#"s. For example, if we merge clone class 1 and 2, the super clone class is 1#2. If a super clone class has several "#"s, this means that clones are cross-cut across many subsystems. We need to further investigate the reason behind this cloning. Is it due to our system decomposition, these files should be grouped into one subsystem? Or is it a coding idiom? Or is it something else?

In addition, researchers need to consult other references, such as documentation, the source code itself, static dependencies, etc., to uncover the original rationale behind cloning.

4.5 Conclusion

The chapter proposes Clone Cohesion and Coupling (CCC) graph, which visualizes code cloning at the subsystem level. The graph shows the amount of internal cloning and external cloning in each subsystem. In particular, the force-based graph layout and heat colouring of the super clone class nodes highlights the surprising cloning relations among subsystems.

Chapter 5

Clone System Hierarchical(CSH) Graph

In this chapter we propose *Clone System Hierarchical (CSH)* graph, which visualizes cloning data in a directory tree.

The goal of this thesis is to develop tools and techniques to assist researcher to better analyze code cloning in large software systems. A major obstacle researchers face is how to handle large volume of cloning data. Chapter 4 presents *Clone Cohesion and Coupling(CCC) Graph*, which displays the cloning information at subsystem level. It provides users with an overview of the amount of internal and external cloning of the subsystems. Unfortunately, the CCC graph lacks of cloning details; as it only displays cloning information for one level of subsystems. It is unclear whether heavy cloning between two subsystem is due to a small number of files or a large number of files. We need a visualization tool which shows the details of the code duplication and preferably highlights the spread of the cloning.

Knowing the spread of cloning at the file level is important because the more spread

clones are, the more effort is required to modify the code base such as propagating bug fixes selectively to clone instances or to perform re-engineering tasks such as refactoring common code to eliminate clones. For example, "drivers/net/3c501.c" in Linux Kernel version 1.0 has 11 files that have cloning relationships. It is relatively harder to maintain than "drivers/FPU-emu/reg_add_sub.c", which has code duplications with only 1 file.

Knowing the spread of cloning at the subsystem level is useful, since it helps to have a deeper understanding of the design of the systems because it can uncover certain functional relations or cloning patterns which are usually not documented. If we examine the cloning of file system (fs) inside Linux Kernel, subsystems like "fs/ext2", "fs/minix" have a lot of external cloning with each other but little internal cloning. This is a sign of potential "forking" pattern [11].

This chapter introduces *Clone System Hierarchical (CSH)* Graph which embeds the cloning information in the directory tree. Although the cloning information can be embedded into other backbone structures like subsystem decompositions, we feel directory-structure tree is the most suitable framework for several reasons. Our visualization is used to study the cloning phenomenon and developers are more comfortable working with directories. They navigate through directories and copy-paste code between files. Therefore, it is more natural to conduct the cloning study within the directory trees. Our CSH graph provides the details of copying at different levels of system abstractions. Researchers can easily spot the amount of internal cloning and external cloning for each file and subsystem. In addition, the CSH graph highlights the cloning relation for individual files and subsystems, through mouse pointing and clicking.

The rest of this chapter is organized as follows: Section 5.1 explains the steps to lift the cloning data to the system hierarchical level. Section 5.2 presents the Clone System Hierarchy (CSH) graph. Section 5.3 provides some discussions with our visualization and

presents some future work. Finally, Section 5.4 presents a short guideline for researchers who are interested in using our visualization.

5.1 Clone System Hierarchy Extraction Framework

Before we can visualize cloning relationship at the subsystem level, we need to abstract cloning data to the system level. Figure 5.1 illustrates the process. In order to communicate among different tools and steps in our framework, we use a set of data schemas. Each step in our framework expects data in the appropriate schema. The schemas are shown in Figure 5.2. The schemas are at two level of abstractions: Clone-Class-Code-Segment Level and Clone-Class-File-Subsystem Level. Our framework first lifts the cloning data from **Clone-Class-Code-Segment Level schema**, and aggregates the cloning information from lower subsystems to **Clone-Class-Subsystem Level schema**. We present below the different steps in our framework.

Data Pre-Processing

Similar as the Clone Recovery Framework described in Section 4.2.1, the first two steps in the framework are the data pre-processing step. We choose CCFinder as our clone detection tools and set 30 as the minimum number of common tokens to qualify as clones when comparing two segments of code. Then we use textural filtering to remove false clones. Details are presented in Section 4.2.1

Figure 5.2(A) shows the Clone-Class-Code-Segment Level schema after the clone detection and filtering steps. The data contains four types of entities: source code segments, files, clone pairs and clone classes. A file contains one or more source code segments; each clone pair consists of two code segments; and each clone classes consists of at least one

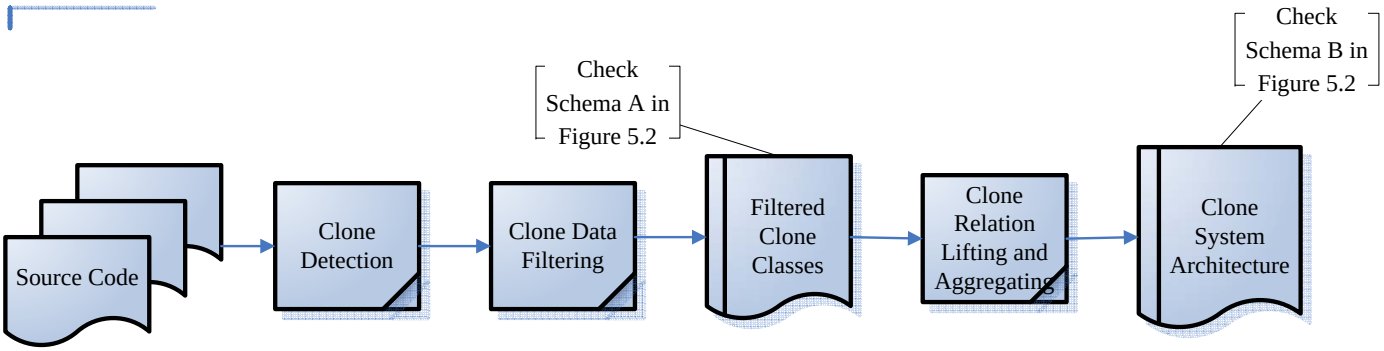


Figure 5.1: Our Clone System Hierarchy Extraction Framework.

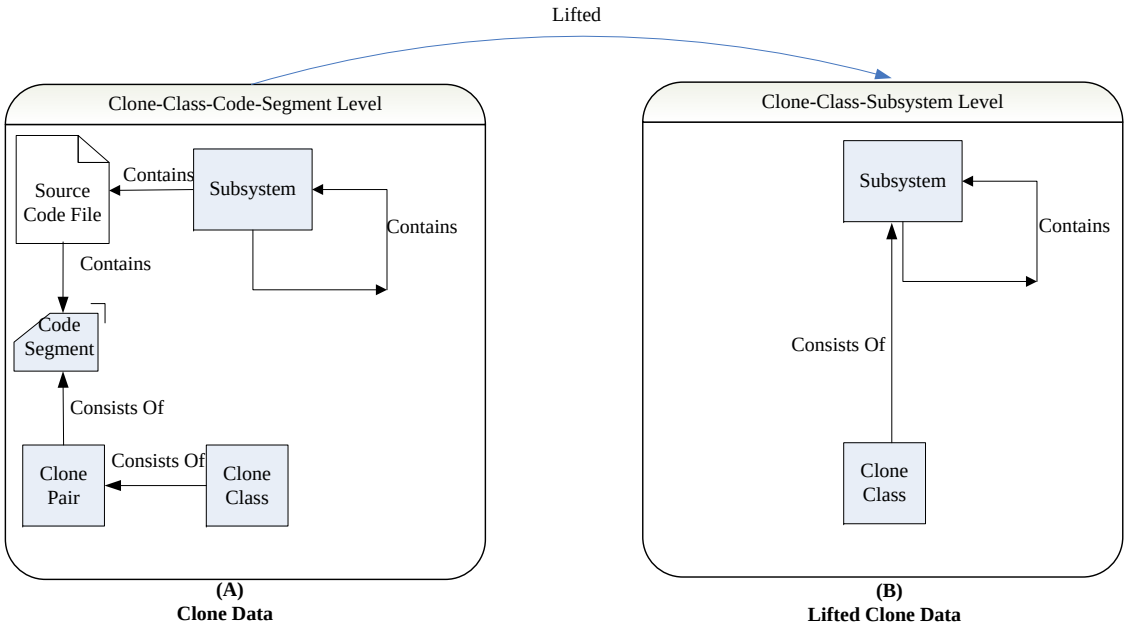


Figure 5.2: Schemas Used in Our Framework.

clone pair.

Clone Relation Lifting and Aggregating

Now each clone class contains cloning relations among code segments from different files. The lifting operation is also the same as the lifting processes in Section 4.2.1. We first lift the cloning information from code segment level to file level, the from file level to lower level subsystem level, followed by lifting from lower level subsystem level to higher subsystem level until all the way up to the top level subsystems. The only difference is that, in Clone Recovery Framework the information before lifting is discarded whereas the cloning information from the lower level entities (files, subsystems) are preserved. (In this and the following chapters, we consider directory structure as the software architecture decomposition. We use the term directory and subsystem interchangeably. Note that, for other software architecture decompositions, we can use similar technique to lift the cloning data and visualize it in the graph.) This processed in illustrated an an example shown in Figures 1.6 and 1.7.

5.2 Clone System Hierarchical (CSH) Graph

The main goal of our visualization is to show the spread of cloning at different levels of granularity: from top level directories to the lower level directories and lastly to the file level.

As shown in Figure 5.3, our tool consists of 4 components: *Node Name*, *Clone System Hierarchical Tree*, *Selection Menu*, and *Clone Information Panel*. *Node Name* shows the name of the node currently examining. *Clone System Hierarchical Tree* is an interactive graph that allows the user to point and click nodes to highlight the spread out of the

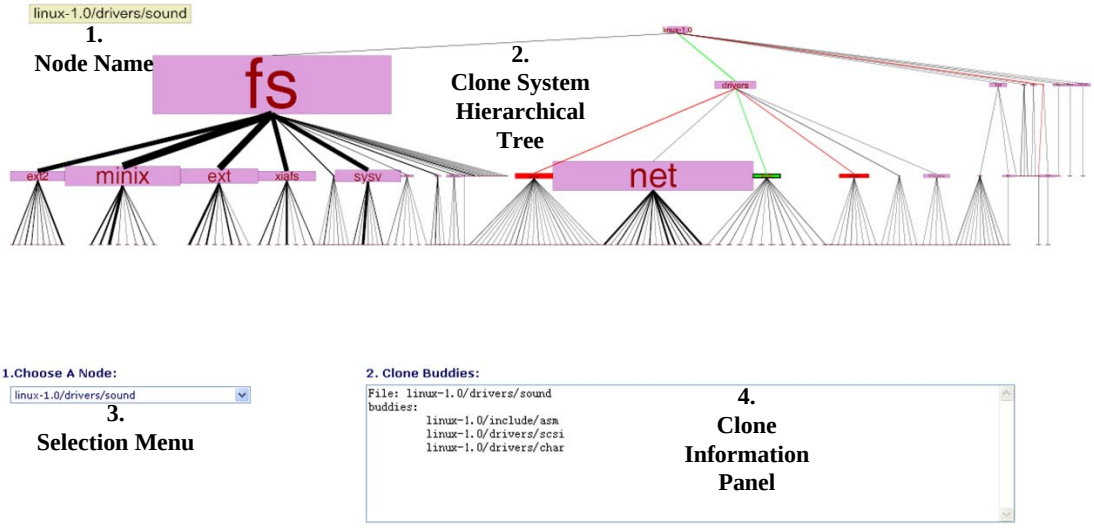


Figure 5.3: Annotated Screenshots of the CSH Graph for Linux Kernel 1.0.

cloning within the directory tree structure. *Selection Menu* allows you to select either a file or a directory to highlight the cloning information on the *Clone System Hierarchical Tree*. Finally, *Clone Information Panel* displays the cloning instances which have duplications with the currently selected node.

Our visualization can be further divided into three sub-views: Static View, Interactive View, and Animation View. We now demonstrate the usage of these three sub-views by analyzing the cloning of Linux Kernel version 1.0 as a case study.

5.2.1 Sub-View 1: Static View

When we initially launch our visualization, it looks as shown in Figure 5.4: *Node Name* section is blank, as no node is selected; all the nodes in *Clone System Hierarchical Tree* remains as pink and edges as black. *Clone System Hierarchical Tree* is laid out as the

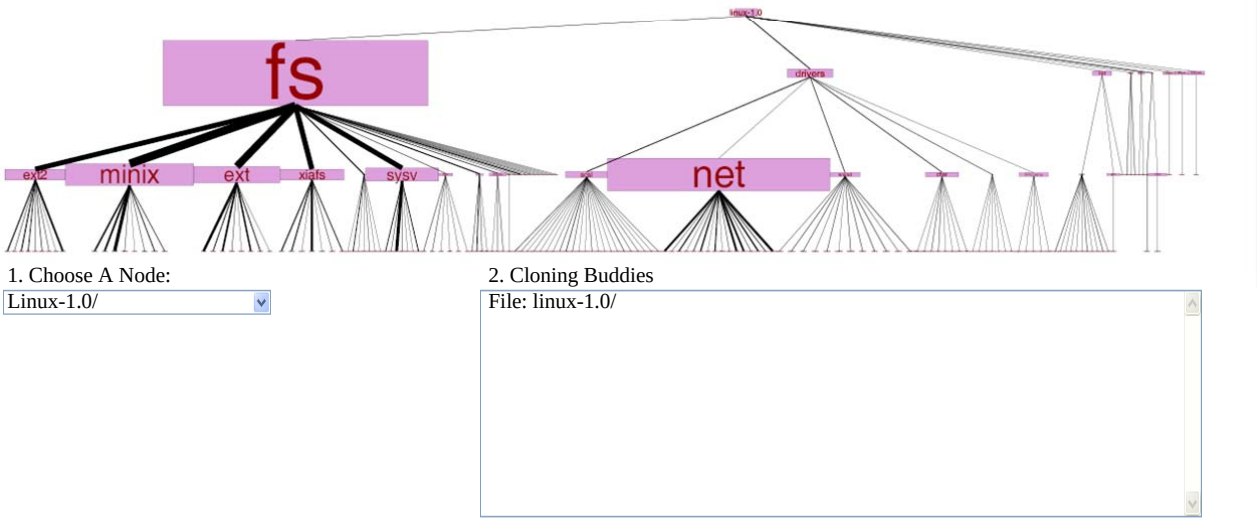


Figure 5.4: Screenshots of Static View of CSH Graph for Linux Kernel 1.0.

directory structure of Linux Kernel version 1.0. There are two types of entities: nodes and edges. The nodes represent either files (for the bottom level nodes) or directories (for the rest of other nodes). Edges indicates the containment relationship. What is more, for siblings directories (directories under the same parent directory), it is sorted by its number of children. The more number of children that directory contains, the farther left it will be placed.

This gives an overview of the amount of internal and external cloning of different levels of directories as indicated by the size of nodes and the thickness of the edges. The width of the directory nodes shows the number of duplicated lines; whereas the height is proportional to the number of internal cloning classes. Flat node implies that the subsystem contains very few clone classes but these clone classes contain a large amount of duplicated code. Thin node indicates that the subsystems contains a lot of small clone code fragments. Thickness of the edges shows the degree of external cloning from that node. The thicker

the edges, the larger the amount of external cloning from that node. At the top level directory, as implied from the size of the nodes: "fs" has more internal cloning than "drivers" and "net". Within "fs", directories like "ext2", "minix2", "ext", "xiafs", and "sysv" have a lot of external cloning as indicated by the thickness of the edges. We decide to use the same size for the file nodes mainly for scalability concerns: if we embedded the cloning information into the dimension of the file nodes it would be too big to fit them in the screen; as there are too many files.

In addition, the CSH graph also provides us with a rough idea of the degree of code duplication within each directory. For example, "drivers/scsi"(the SCSI device drivers) is the left-most directory among directories within "drivers"(all the device drivers). This implies that "scsi" contains the largest number of files among its siblings directories. However, it contains less cloning than "drivers/net"(network device drivers); since it is shown as a smaller node and the thickness of outgoing edge does not differ too much.

5.2.2 Sub-View 2: Pointing and Clicking View

We got an overview of the cloning situation. Our second sub-view: *Pointing and Clicking View* can help user to explore and investigate the cloning instances for certain directory or file. There are three modes to query the cloning information for certain nodes. Each approach is used at different occasions.

- **Pointing**

  Table 5.2.2 summarizes the actions and changed entities at the pointing mode. There are two actions associated with this mode: mouse over a node and mouse away from that node.

  When the user moves the mouse over a certain node, there is a couple of noticeable

Action	Entities	Effect
Mouse Over A Node	the pointed node	*green/blue*
	path from the pointed node up to the root	*green*
	clone instance nodes	*red*
	path from the pointed node up to the root	*green*
	path from clone instance nodes up to the root	*red*
	Node Name area	*name of the pointed node*
	Selection Menu	*name of the pointed node*
	Clone Information Panel	*names of the clone instances*
Mouse Away	previously pointed node	*pink*
	path from previously pointed node up to the root	*black*
	clone instance nodes	*pink*
	path from previously pointed node up to the root	*black*
	path from clone instance nodes up to the root	*black*
	Node Name area	*blank*
	Selection Menu	**name of the previously pointed node**
	Clone Information Panel	*blank*

Table 5.1: The Actions and Effects for the Pointing Mode

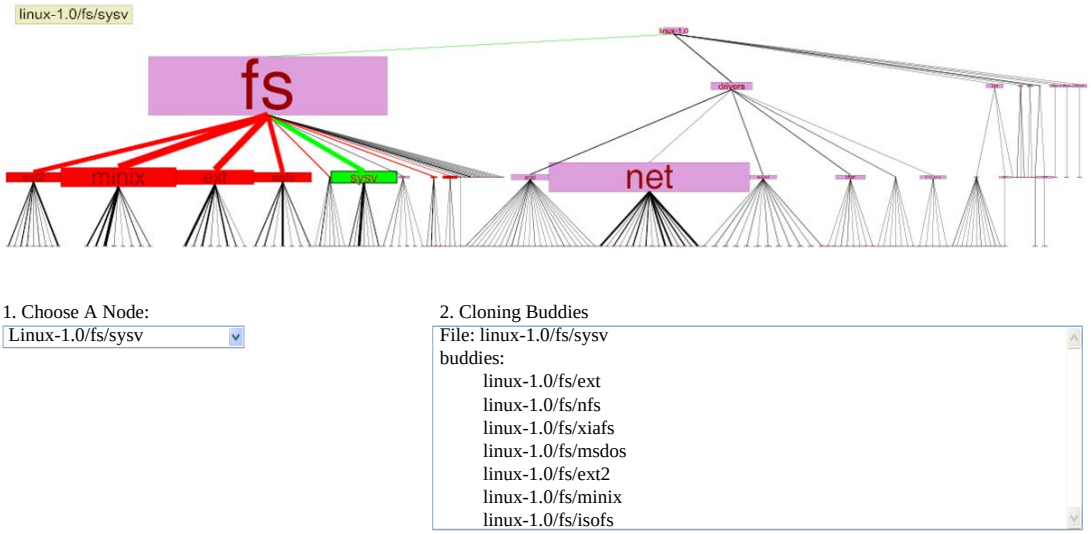


Figure 5.5: Pointing and Clicking View of CSH Graph for Linux Kernel 1.0.

changes. First the node name will appear in the *Node Name* section; as well as in the *Selection Menu* section. Furthermore, the colour of the node as well as the colour of certain edges will change. The pointed node will turn green if it has cloning instances; and blue if it does not. The cloning instances for the pointed node will be coloured in red. In addition, the path coming from the currently pointed node up to the root directory will be highlighted in green. Meanwhile, the path coming from its cloning instances up to the root directory will be highlighted in red. Finally, the *Clone Information Panel* will display the name of the currently selected node as well as names of all the associated cloning instances.

Figure 5.5 shows how the graph appears like when the user moves the mouse to the node "fs/sysv": the node name is shown in the upper left corner; the pink node "fs/sysv" turns into green; all its cloning instances are highlighted in red; the path

from "fs/sysv" to the root is colored in green and red for the paths from its cloning instances to the root(notices the red path from "fs" gets covered by the green path as the query node and its cloning instance share the same path segment from "fs" up to the root node); the name is displayed in the *selection menu*; and finally the *Clone Information Panel* displays the corresponding information: all the cloning of "fs/sysv" happens within "fs"; there is no external cloning which involves subsystems outside of "fs".

When we move the mouse away from that node; it will undo all the visual changes mentioned above, and revert it back to the *Static View*. Consequently, if you move the mouse back to this node or some other node; all the four components will change accordingly. For example, if this time we place our nodes on "drivers/net". As shown in Figure 5.6, all the changes associated with cloning of "fs/sysv" are undone and the graph is adjusted accordingly. Notice that there is no external cloning for "drivers/net" thus the node is coloured in blue as well as there is only one path (coloured in green) going from the node up to the root. Consequently, there is no cloning instances displayed in the *Clone Information Panel*.

- **Clicking** "Pointing" action is useful when developers trying to quickly explore the directory tree and looking for interesting scenario to examine. Once they have found the interesting node they want to "pause" the graph to further investigate the highlighted information. This calls for the "clicking" action.

  Table 5.2.2 shows the actions and effects for the clicking mode. The effect of "Clicking" mode is similar as the "pointing" mode except once clicked all the cloning information stay the same independent of the mouse movement. When you mouse over a different node; the only change is that the Node Name area will display the

Action	Entities	Effect
Clicking A Node	the clicked node	*green/blue*
	path from the clicked node up to the root	*green*
	clone instance nodes	*red*
	path from the clicked node up to the root	*green*
	path from clone instance nodes up to the root	*red*
	Node Name area	*name of the clicked node*
	Selection Menu	*name of the clicked node*
	Clone Information Panel	*the clone instances*
Mouse Over A Node [1]	Node Name area	*name of the pointed node*
Unclicking The Node	previously clicked node	*pink*
	path from previously clicked node up to the root	*black*
	clone instance nodes	*pink*
	path from previously clicked node up to the root	*black*
	path from clone instance nodes up to the root	*black*
	Node Name area	*blank*
	Selection Menu	**previously clicked node**
	Clone Information Panel	*blank*

Table 5.2: The Actions and Effects for the Clicking Mode

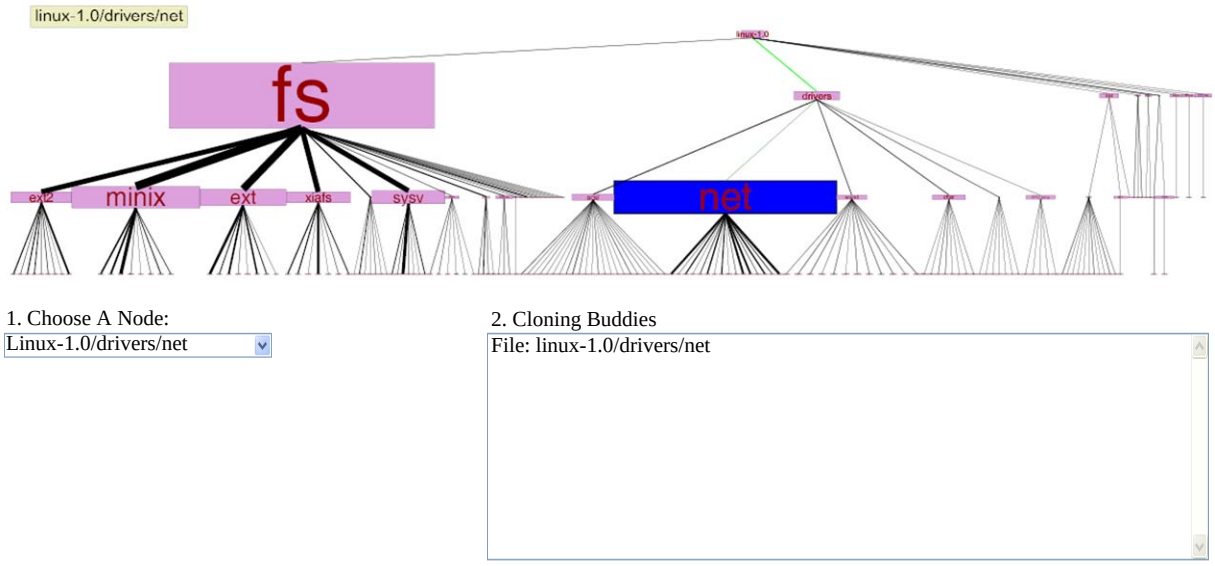


Figure 5.6: Another Pointing and Clicking View of CSH Graph for Linux Kernel 1.0.

name of the currently pointed node. Clicking the same node for the second time revert the graph back to *Static View*. In fact, there is another possible action in this mode: clicking another node when there is one node currently has been clicked. The action is equivalent of unclicking the previously clicked node and click the newly selected node.

- **Selecting** "Pointing" and "clicking" on the graph is useful, since it allows users to navigate and query the cloning information interactively. However, certain nodes (like file nodes) are too small for mouse to be properly positioned at or nodes can be too close together to have the mouse properly pointing to the correct node.

  To solve this problem, the drop-down list from the *Selection Menu* can be used to locate node. Once we select an item from the drop-down menu, all the same visual changes described above will appear, except the current selected item will be

highlighted in the *Selection Menu*. It is equivalent to "clicking" one node on the *Clone System Hierarchical Tree*.

This sub-view enables a user to pick a node and understand how spread the cloning is compared to its siblings. For example, even through "fs/minix" has bigger external cloning as the edge from "fs/minix" to "fs" are thicker; "fs/iosfs" has 9 cloning instances whereas "fs/mininx" has 7 cloning instances.

5.2.3 Sub-View 3: Animation View

The bonus feature in our visualization is that it helps users to find cloning patterns and anti-patterns among files within the same directory. Once we have selected an item from the *Selection Menu*; it is highlighted. Then if we move the up and down arrow keys, the graphs will animate the changes accordingly. Since files are grouped under the same directory; it enables us to spot patterns and anomies by using the arrow keys.

As we navigate through files in the "fs" directory, we notice that all the cloning happens among one or two files inside the sibling directories as shown in the upper half in Figure 5.7. "fs" is the file system subsystem in Linux kernel. It contains a number of subsystems which are different types of subsystems like minix ("fs/minix") or ext2 ("fs/ext2") or nfs ("fs/nfs"). This is the "template" pattern in [11]. Inside each individual file systems, there is a set of structs which contains function pointers for each specific operations. For example, $file.c$ is contained in all the file systems. It contains definitions for structs like "inode_operations", or ""file_operations". "inode_operations" is an interface for the inode related operations. It contains function pointers for creating and removing directories, etc. "file_operations" is an interface for the file related operations. It contains function pointers for reading and writing to a file, etc. To implement each file systems, developers need to implement specific purpose functions like reading and writing to file, creating and

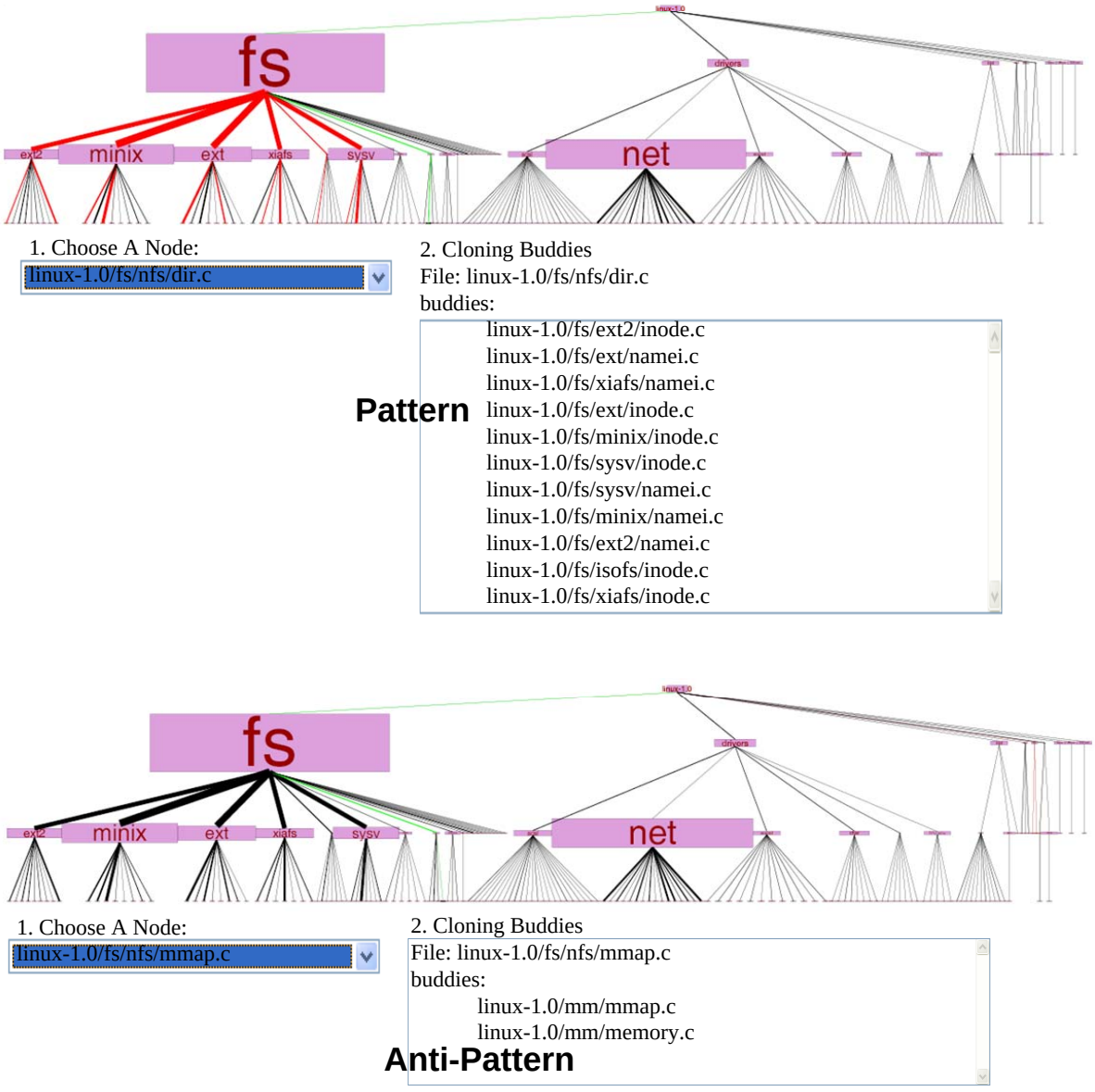


Figure 5.7: Animation View of CSH Graph for Linux Kernel 1.0.

removing a file; then set the appropriate function points to these functions in the struct. Thus, "file.c" in one file system is similar to "file.c" in other file systems.

However, the pattern does not apply to "fs/nfs/mmap.c". As it does not have any cloning instances from files within the "fs" directory. Furthermore, as displayed in the lower half of Figure 5.7, it shares common code with files from the top level "mm"(memory management) directory! It is a bit surprising since not all file systems contains file *mmap.c*. The source code comments of this file states that code is borrowed from "mm/mmap.c" and "mm/memory.c"; which explains the cloning relations.

5.3 Discussion and Future Work

Comparison with CCC Graph: The CSH graph embeds the cloning information within a directory tree. The dimension of the nodes implies clone cohesion and the thickness of the edges implies clone coupling. Rather than showing the cloning information just at one level of system hierarchy as in the CCC graph, the CSH graph contains cloning relations at different levels of abstractions: from file level up to the top level directories. Its adaptive feature allows users to pick an individual node and highlights the spread out of the cloning. However, one disadvantage for the CSH graph is that the notion of coupling is not as well indicated as in the CCC graph, as we do not know the strength of coupling among various subsystems.

Layout: Over-plotting is the problem when there are too many nodes and edges trying to fit into limited screen space. An over-plotted graph is hard for human to comprehend. The CSH graph uses the directory structure as the back-bone to display cloning information. When system contains too many files and the directory structure is shallow; our visualization will run into the risk of over-plotting. In the future, we are

going to experiment other layout algorithms, such as the radial layout.

Pruning: As mentioned above, our visualization can run into the risk of over-plotting when the directory structure is shallow and there are a lot of files contained in the system. Our approach to solve this problem is to use filtering to remove uninteresting or redundant information. There are two types of filtering we can use: level filtering and subsystem filtering.

Level pruning means removing all the nodes and edges if they are below the threshold value. For example, if the directory tree is 6 levels deep and we set threshold of level filtering to be 3, then all the nodes and edges that are at levels 4, 5 and 6 are filtered. This is effective; since the deeper into tree, the more nodes we have. Obviously, the file level, which is at the lowest level of the trees, contains the largest number of nodes. We apply level filtering when we are interested to examine cloning relations among subsystems.

Subsystem pruning means removing all the cloning information which is unrelated to one specified subsystem. Take Linux Kernel for example. If set subsystem filtering to be "fs"(file system), then all the cloning relations not related to "fs" will be removed from the data set. We apply subsystem filtering when we want to closely examine the cloning details for one subsystem.

Other Applications: Depending on the information embedded, this graph can be used for other purposes as well. For example, we can display the dependency graph or the co-change graph using the same visualization technique.

5.4 Usage Guideline

We summarize the steps for using our visualization. Researchers can follow this guideline to process, visualize and analyze cloning for other software systems.

Overall: The CSH graph shows the details of cloning at every level of system abstraction as well as highlighting the spread of cloning for each individual file and directory.

Data Processing: When we lifting the clone classes, if it is an internal clone class at the lower level; upon lifting it will still be an internal clone class. For external cloning classes, if all the entities in the set are under the same parent directory; then it will become an internal cloning class after lifting. Otherwise, it is an external cloning class.

Graph Analysis: We summarize the different functions of each sub-view and discuss a few aspects in the graph that require attention:

Static View is the view when the graph initialized. We get an overview of how deep the directory structure is, how many entities are actually contained in this graph.

Pointing and Clicking View enables user to highlight cloning relations for individual nodes. We need to pay special attentions to the following nodes: wider nodes since they contain some big internal clone class; thinner nodes since they contain many small internal clone classes; nodes which have thicker edges coming out can be alarming as well, since it contains large number of external cloning.

Animation View allows us to quickly spot the cloning patterns and anomalies by using the drop down selection menu.

In addition, researchers need to consult other references, such as documentations, the source code itself, and static dependencies, etc., to uncover the rationale behind cloning.

5.5 Conclusion

This chapter proposes Clone System Hierarchical (CSH) graph, which lays out code cloning information in a directory tree. It shows code cloning relations at different system abstraction level varying from the file level, lower-level-subsystem level, and all the way up to the top-level-subsystem level. In addition, it highlights individual cloning relations for each files or subsystems by mouse movements.

Chapter 6

Clone System Evolution (CSE) Graph

This chapter proposes visualization techniques to help researchers to study software evolution. The visualization techniques are *ULOC* plot, which examines the evolution of unique features and *Clone System Evolution (CSE)* graph, which highlights changes in code cloning over time.

To fully understand code cloning, researchers want to see how current cloning situations are and why clones evolve to this stage. The previous two views (*Clone Cohesion and Coupling (CCC)* graph and *Clone System Hierarchical (CSH)* graph) focus on visualizing clones for single software release. We consider them to be snapshot views. They are important since we need to know the severity of code duplication of current software system.

To answer why the system ends up with such cloning situation, we need to study how clones evolve over time, especially the cases when there are lots of clones gets added or removed. For example, if many clones are added over a short period of time; then we may

wish to investigate the effects on code quality. If many clones are removed, then we need to be careful since there might be a major refactoring occurred and the interface or system documentation need to be updated accordingly.

This chapter is organized as follows: Section 6.1 motivates the clone evolution study by showing the evolution of system growth with or without cloning. Section 6.2 explains our visualization technique, which highlights the clone changes over time. Section 6.2.4 presents some discussion about the clone evolution. Finally, section 6.3 gives a short guideline for researchers who are interested in using our visualization.

6.1 Software Evolution

Software systems evolve over time to accommodate changes such as introduction to new features, modifications for bug fixes and support for additional platforms, etc.

There are two schools of thoughts about the software development models: the traditional in-house commercial software development and the open source development model.

It happens that the in-house commercial software development has longer release cycles. For example Microsoft releases new version of Windows every two or three years. In addition, they impose tighter coding guidelines. For example, companies like IBM require developers to prefix their variable names with the module names; some companies even require strict code ownership: developers need to ask for permission if they want to modify certain parts of the code which are not owned by them. Furthermore, they incorporate strict quality assurance procedures before they release their product. Finishing products are evaluated on a number of aspects such as peer code review, functionality testing, regression testing, etc.

On the other hand, open source development often seems to takes an opposite approach:

as most of the developers are volunteer based; it has a less strict release schedule since it would be hard to force volunteer to work hard to meet up the deadlines. Furthermore, since developers contribute to the project according to their interest; it would be hard to incorporate the idea of code ownership. What is more, because such projects are volunteer based, imposing a strict code guidelines would drive away potential contributors. Finally, since most of the open source developers are also its users; the software incorporates lazy testing. Lazy testing means software is released without doing any rigorous testing and it relies on user feedback to report bug. The philosophy behind is called "Linus's Law" [37]: "Given enough eyeballs, all bugs are shallow." User feedbacks should catch most of the software defects.

Research shows the growth rate for these two development models follows different models. Lehman et al. [29] devised a set of laws about software evolution based on his studies on several large E-type legacy software systems, which adopt the in-house commercial software development model. Subsequently, Godfrey et al. [31] studied the evolution of open source software and discovered that the growth rate does not follows these Laws. They picked the Linux kernel as their case study and found out that the project grows at the super-linear rate. Their further analysis shown that one of the subsystems "drivers" grows at a much faster rate than the rest of subsystems, which is the main reason Linux follows a much faster growth rate. Robles et al. [19] performed similar case studies on Linux and a number of other open source software systems. Their results also confirmed with Godfrey et al.'s findings that the growth of open source software systems do not follow Lehman's Law of Software Evolution, which are derived from studies of traditional commercial software systems. In addition, as pointed in the subsequent work [18], Godfrey et. al. discovered that "drivers" subsystems have exhibit a large degree of code duplication. Their findings are: drivers tend to be stand-alone and implement a uniform interface.

What is more, lots of code copying occur among drivers which come from same hardware vendors, or interact with same hardware chips or even drivers written by the same developers, etc. We expect much less cloning happening among commercial software; as they require a tighter code reviewing policy. So it is quite natural to ask the following question, how about we perform a control experiment: what is the growth rate of Linux excluding the cloning factor?

Most of the recent software evolution research papers, such as [31, 19] use *SLOC* as the main metric to measure the growth and the complexity of the software systems. In our study, we introduce the concept of *ULOC*. *ULOC*, which measures the number of unique lines, is different from *SLOC*, which measures the number source code lines. For example, if we have two pieces of code segments, which are duplicates of each other; in *SLOC* we are going to count both of them whereas in *ULOC* we are going to count only one of them.

The rest of this section is organized as follows, we are going to first explain our methodology and then present a small case study of Linux kernel.

6.1.1 Our Methodology

As the name of *ULOC* suggests, it is "unique lines of source code". The idea is simple: we reduce total lines of source code(*SLOC*) by the amount of duplication. It takes two steps to find the amount of duplicated code: clone data collection, and code duplication aggregation.

- **Calculation of SLOC:** In our study, we use a perl script and unix command "wc -l" to calculate *SLOC*. There are two main reasons not to choose existing tools like "sloccount" [40]:

  First, this study is intended to compare our findings with existing research, especially

with [31]; so it would be easier to adopt the similar metrics and similar measurement methods.

Second, as most of the clone detection tools report code duplications using line intervals, we choose the lines of codes with comments to be consistent with the output of the clone detection tools. These intervals contain source code as well as blank lines and comments. The perl script we write, recursively searches for the source code files (.c or .h files); invokes "wc -l" on them and aggregates the results.

- **Clone Data Collection:** Clone data collection step requires clone detection and then clone filtering. We choose CCFinder as our clone detection tool and textual filtering as our filtering technique. The details are described in Section 2.2.

- **Code Duplication Aggregation:** The next step is to calculate the amount of duplication. Note that we do want to keep one copy of duplicates. We achieve these by extracting the information of clone classes. For tools which only outputs clone pairs, we can form clone classes from the set closure property: as any two elements in the clone class forms a clone pair. For example, as shown in Figure 1.1, although (A), (B), and (C) are duplicates of each other and they form a clone class. Then to obtain the amount of duplicated code, we just need to add up all the duplicated lines but one. In the above example, we need to pick any two code segments from (A), (B), and (C) in our calculations. Since each of them have 10 lines duplicated with each other, thus would be 20 lines counted as duplicated lines.

6.1.2 Examining the Evolution of Linux using *ULOC*

Previously there have been two parallel releases for the Linux kernel: the stable releases and the development releases. Stable releases contains relatively less bugs and is preferred

to use for production; whereas development releases contains more features and are mainly used for testing purposes.

The format of the release number usually looks like $A.B.C$. Stable releases use even numbers for the middle digit(B), whereas development releases use odd numbers for the middle digit. Prior to version 2.6, there have been five series of stable releases (1.0.x, 1.2.x, 2.0.x, 2.2.x, 2.4.x) and five series of development releases (1.1.x, 1.3.x, 2.1.x, 2.3.x, 2.5.x). After that, there are no such distinctions; as everything goes under 2.6 series. Since new features and bug fixes are going under the same series, the conversion of version numbering also changes. The usual format for 2.6 series is 2.6.C.D. As the fourth digit(D) is used for minor revision changes such as bug fixes.

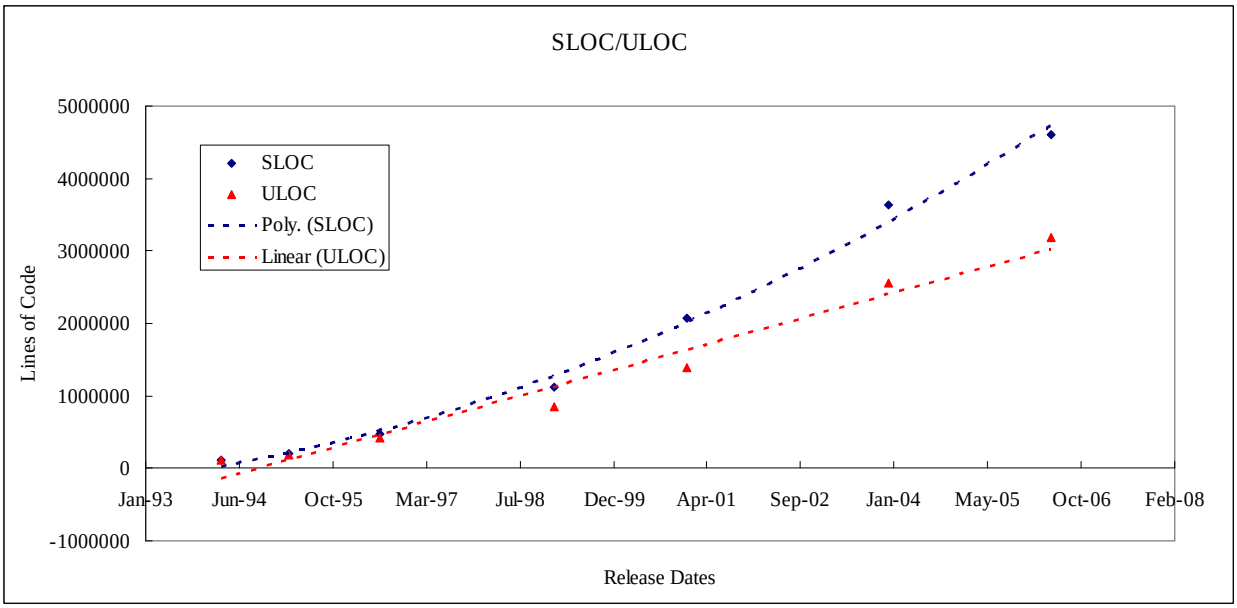


Figure 6.1: SLOC and ULOC plots for Linux stable releases

A plot of *SLOC* on software releases over time shows the growth rate of the system,

whereas a plot of *ULOC* shows the growth rate for essential features. We conduct our analysis on 9 stable versions of Linux, raging from Linux-1.0 (released on March 1994) to Linux-2.6.16.13 (released on May 2006). We plot both the *SLOC* and *ULOC* graph for these 9 releases.

Figure 6.1 shows the growth rate of Linux software systems as a whole. The horizontal axis shows the release date for each point and the vertical axis shows the total lines of code. Everything relates to *SLOC* is coloured in dark blue and yellow for stuff associated with *ULOC*. *SLOC* follows the super-linear growth; as shown in the graph with the dark blue dotted line, it best fitted with a polynomial with degree 2. The *ULOC* follows a much slower rate, it can be nicely fitted with both a linear growth rate, as shown in red dotted line. Therefore, we have shown that the growth rate of "essential features" follows the linear rate, slower than the overall growth rate which is the super-linear growth rate.

We dig deeper into the top level directory to investigate the variation between *SLOC* and *ULOC*. Figure 6.2 shows the growth rate of six of the biggest top level directories in Linux kernel. As we can see, "drivers" subsystem(in both SLOC and ULOC graph) dominates the growth. Despite the fact of subtraction from cloning, the size of driver code still grows much faster than cloning as indicated by the slop of two adjacent points. Therefore, we conclude that, using our newly introduced metric *ULOC*, we still end up with the same findings:

- Lehman's Law states that as software becomes more complex the growth of the system would slow down since it is harder to add in new features. However, Linux grows faster than Lehman's Law of Software Evolution has predicted.

- "drivers" subsystem suffers from heavy cloning. If we remove the duplicated code from "drivers" subsystem, it is still the fastest growing subsystems among all Linux

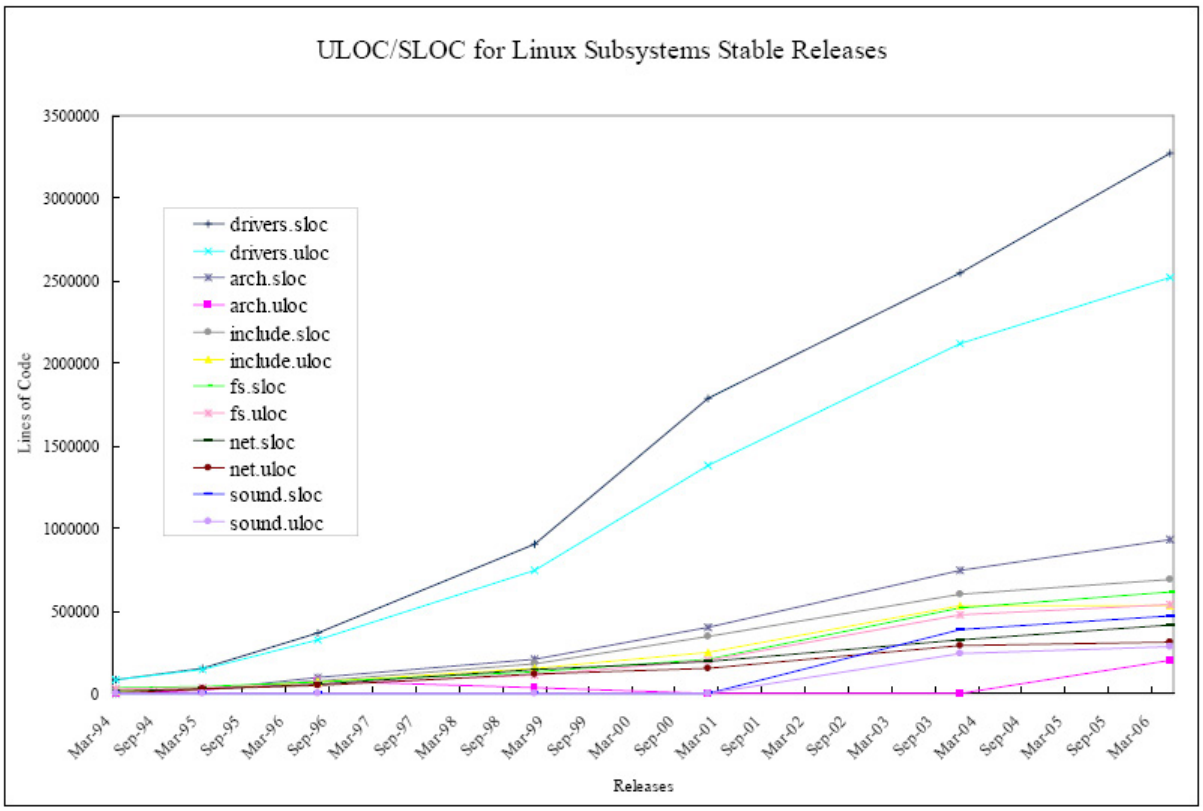


Figure 6.2: SLOC and ULOC plots for top level directories Linux stable releases

kernel subsystems. The fast growth rate of "drivers" subsystem is main reason causing the rapid growth rate of Linux compared to traditional in-house software systems.

6.1.3 An Alternative

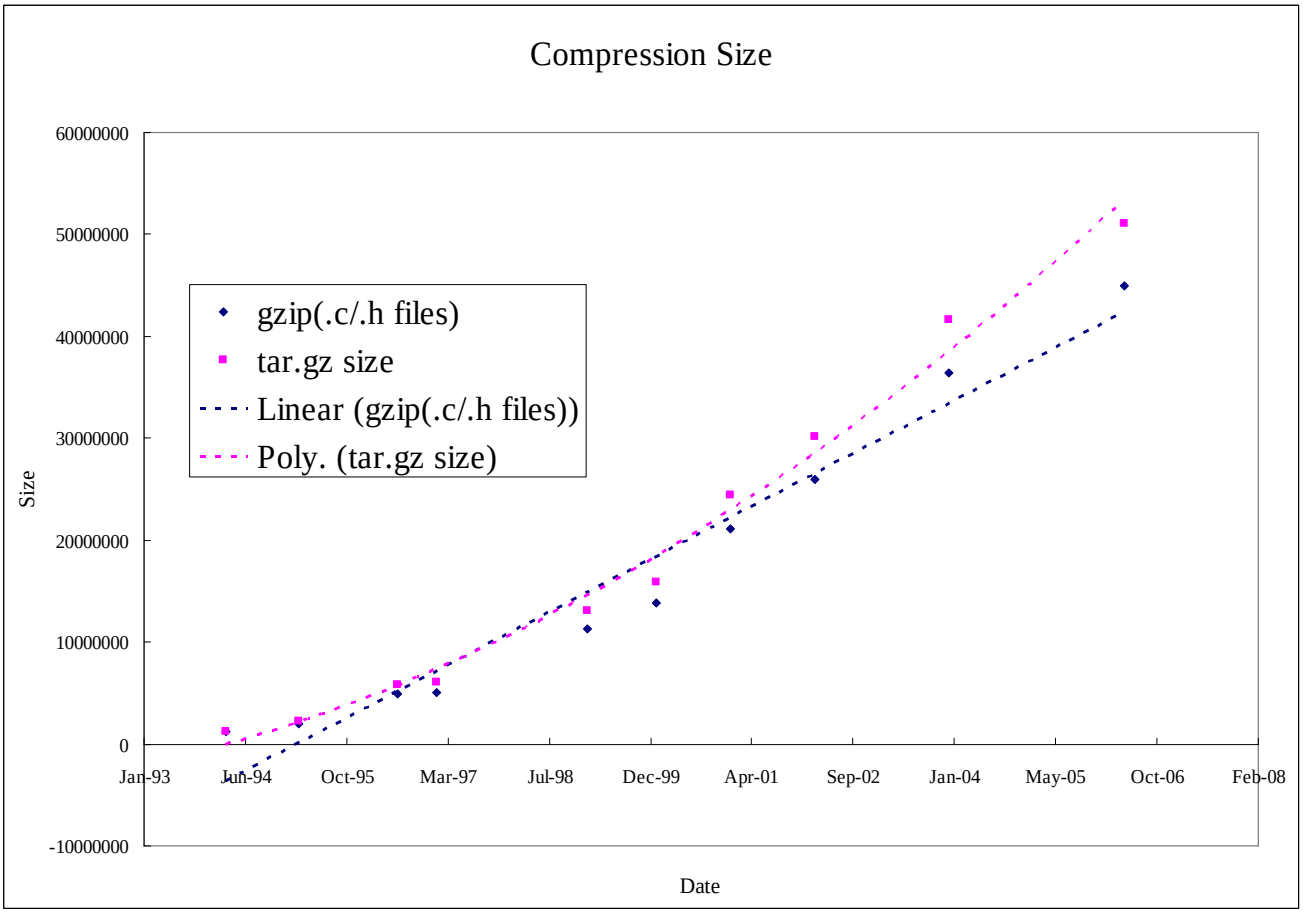


Figure 6.3: Plot of Compressed tar.gz File sizes for Linux stable releases.

Because of the enormous size of Linux, it is normally distributed in compressed form. Most of the compression algorithm reduce file sizes by looking for common patterns among

files, such as longest common sequence, etc. This idea is somewhat similar as our idea of *ULOC*. Therefore, we try to examine the growth rate of compressed tar file size(tar.gz files). However, this is one little problem: as the available compressed tar files includes all kinds of files for the Linux kernel, varying from documentation files, source code files, build configuration files, etc; whereas all of the above experiments have been conducted on source code files only. So we write a perl script that for each release it groups all the source code files (.c and .h files) into a tar file and compress the tar file into the gzip file. Figure 6.3 plots both the original tar.gz files which have everything (shown in pink) and the tar.gz files which only compress .c and .h files (shown in dark blue). As we can see the gaps between pink points and dark blue points becomes bigger and bigger indicates more non-source code files gets added as Linux evolves also these files probably resemble little similarity thus it becomes harder to compress as the size of the gaps increases over time.

In addition, the growth rate of the compressed source code files can be fitted nicely with a linear model shown in dark blue. This coincides with our ULOC case study.

6.1.4 Discussion

Motivation for Clone System Evolution Study: We have shown the difference in system growth rate with(SLOC plot) and without(ULOC plot) account for code cloning. Code clones are growing at a noticeable rate as the system evolves with introduction to new features and modifications for bug fixes. Therefore, to fully uncover the myth of how software systems evolve; it is necessary to study changes in clones over time.

ULOC as a better metric: *SLOC* has long been used as an indication of complexity of the software systems and used for estimating development costs [12]. However, it

is oblivious that the effort to write 100 lines from scratch is different from copying 100 lines and modify based on it. What is more, the cognitive efforts required to understand two cloning instances is not the same as the time require to decipher two pieces of code which are totally unrelated. Therefore, we argue *ULOC* is a better metric to measure the complexity of the system and to estimate the development cost.

How To Estimate ULOC: Even though CCFinder is relatively faster than other clone detection tools, it is still time-consuming to do clone detection on a large software system. For example, it takes more than 6 hours on a Windows Desktop machine for CCFinder to do clone detection on one release of 2.6x series. On the other hand, compressing source code files is much faster. It takes normally minutes to compress the entire source code directory. In our Linux kernel study, the growth rate of compressed tar file size coincides with the growth rate of ULOC. In the future, we are going to verify the co-relation between the size of compressed achieve file sizes with ULOC on other software systems. If such co-relation exists, we can use the size of the compression file to predict the growth rate to *ULOC*.

6.2 Clone System Evolutionary (CSE) Graph

As we can see the system growth rate varies significantly with or without accounting for code cloning; thus it is important to study the evolution of code cloning to fully understand how the software evolves over time. Our last visualization graph: the Clone System Evolution (CSE) graph highlights the most recent clone changes from the files all the way up to the top level subsystems.

The rest of this section covers two components: steps to compute the clone evolutionary

data and the Clone System Evolution (CSE) graph.

6.2.1 Clone System Evolution Framework

We divide the tasks of computing clone evolutionary data into two steps: Clone System Hierarchy Extraction and Historical Clone Data Encoding, illustrated in Figure 6.4.

- **Clone System Hierarchy Extraction:** for each release we perform clone system hierarchy extraction process. The details are explained in Section 5.1.

- **Historical Clone Data Encoding:** We now have obtained the clone system hierarchy information for each release through the development history of the software project. The challenge comes when we need to visualize the historical information.

  The clone system hierarchy information for each release is like a snapshot of the code duplication situation at one point of time in history. We need to super-impose these pictures one by one to form the evolutionary view. The result should satisfy two requirements: first, as cloning information changes from time to time, we need to reflect the history of changes into our visualization; second, it is would be preferable if the tool can rank the information and highlight places which are more important and deemphasizes places which are not so important. We achieve the above requirements by applying a decay function.

  We choose to encode our historical data using a decay function. Decay period refers to the period of time which information becomes stale, and not interest to us. Half life is a special kind of decay rate. Half life, originally used in radio-active substances, refers to the period of time when the mass is only half of the original weight. In our study, half life can be interpreted as the period of time when the weight of the

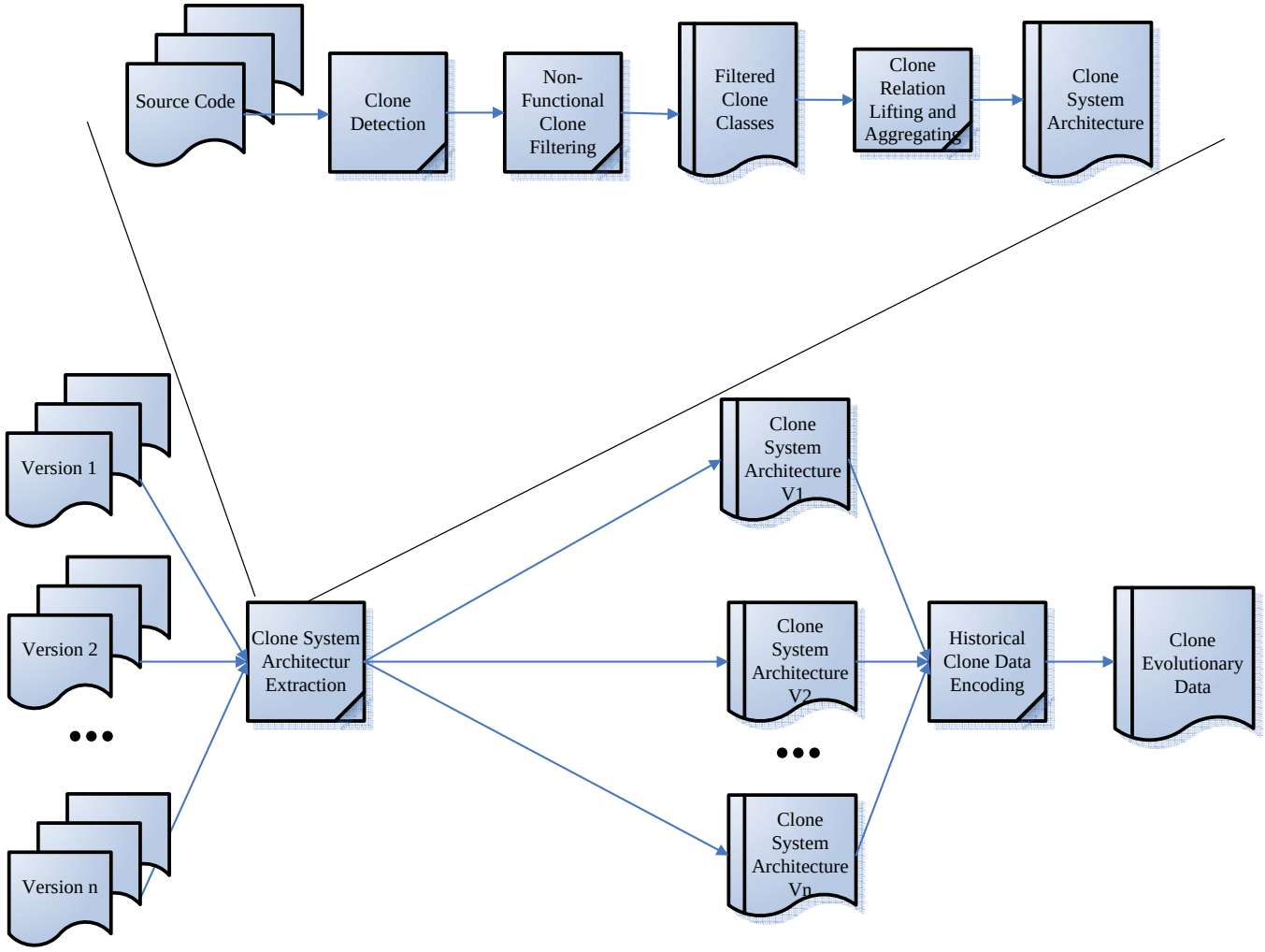


Figure 6.4: Clone Evolutionary Extraction Framework.

previous releases becomes half. So for example, if the half life is 2 releases, if there are 200 lines of cloning in the past, it becomes 100 lines in the next release.

Our decay function looks like:

$$result = (new\ value - old\ value) + decay\ rate * old\ value;$$

For example, the old value is 400 and the new value is 500; the decay rate is set to be 0.2. Then the result computed from the decay function is 180. The decay rate can be set to different values according to what kind of information users want to uncover. If users are more interested in the more recent changes, then the decay rate should be set small, as the information in the past is not so important to us. If users are more concerned with the cloning history of each entity, the decay rate should be set to high to preserve the information in the past. Our decay function is applied to both the internal cloning and the external cloning.

6.2.2 Clone System Evolutionary (CSE) Graph

Once we have encoded all the historical information. We use *Clone System Evolutionary (CSE)* graph to visualize it. Similar as Clone System Hierarchy View, it shows all the cloning information in a tree. Additionally, it uses colours to group and categorize historical cloning information. In this case, we sort subsystems under the same parent directory by the amount of external cloning from the highest to the lowest and split them by values into 4 quarters. We assign the entities in the highest quarter to be red, followed by yellow, light green and grey as shown in Figure 4.3.

6.2.3 An Example

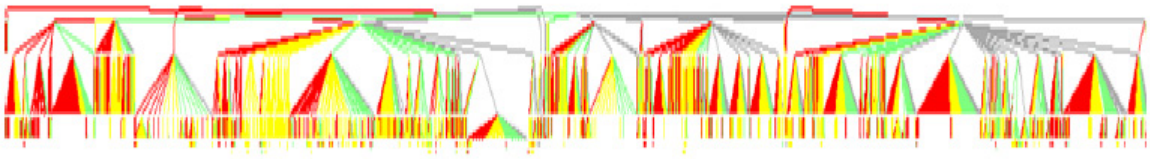


Figure 6.5: The CSE graph for 9 releases of Linux Kernel.

Figure 6.5 shows the historical cloning information for the Linux kernel. To be consistent with Figures 6.1 and 6.2; it contains 9 releases (from Linux 1.0 released in March 1994 to Linux 2.6.16.13 released in May 2006). The hierarchy tree contains 9845 .c files and 6211 .h files and 5813 directories. We set the decay rate to be 0.2, just hoping to highlight the changes between two of the most recent releases (2.6.16.13 and 2.6.0). Among the top level directories, "drivers" positioned at left-most and coloured in red has the largest amount of cloning exposed; directories like "scripts" and "lib", positioned on the right-most, are coloured in lightgrey indicating the least among of changes.

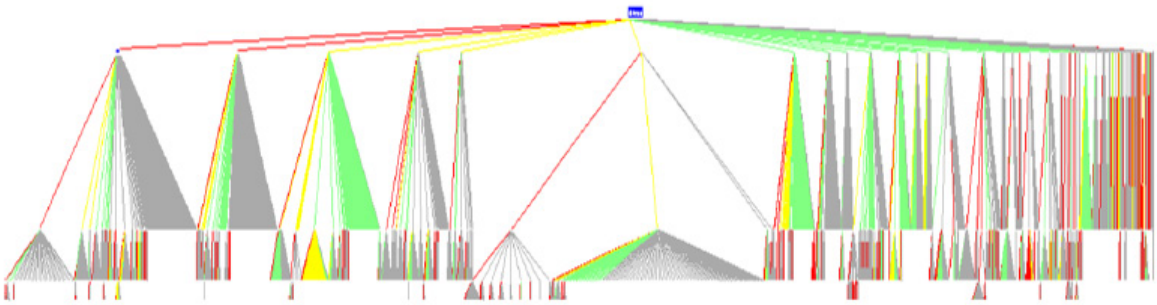


Figure 6.6: The CSE graph for drivers subsystem in 9 Linux Kernel releases.

Figure 6.6 is the zoomed in view of "drivers". As we can see, "net" and "scsi" are the

only two of the sub-directories coloured in red and on the right, there are quite a few small sub-directories such as "bluetooth", and "macintosh" coloured in grey. We then further investigate the reasons why there are so many clones get modified in two of the subsystems "net" and "scsi".

We wrote a perl script to measure the differences in clone pairs between two versions of Linux Kernel. The script first extracts the cloning information only relevant to "drivers". Then it compares the cloning data in the previous release with the next release. Finally it classifies the cloning differences into three categories: clones in new files, new clones in old files, and changes in the old clones, missing clones:

Clones in new files: refer to clone pairs that at least one of the two code segments is from newly added files. So the clone pairs can be between two newly added files or between one newly added file and one legacy file.

Missing clones: refer to the clone pairs from which files are removed in the newer releases. So for example, in the older version, it has one clone pair between "fileA.c" and "fileB.c". In the newer version, either "fileA.c" or "fileB.c" or both gets removed. Therefore, this clone pair no longer exists. We name this type of clones as *missing clones*.

New clones in old files: refer to clones in which files exist in both releases but the cloning relation only appears in the newer release. For example, between "fileA.c" and "fileB.c", there is no cloning relations in the older releases but in the newer release there are code segments from two files which are similar to each other.

Changes in old clones: refer to clones that exist in both releases whose amount of cloning can stay the same, decrease (existing clones less lines) or increase (existing clones less lines). So a clone pair which is between "fileA.c" and "fileB.c" exists both

versions. Then depending the number of duplicated lines, we can have "existing clones with more lines" if the number of duplicated lines increases in the newer version, or "existing clones with less lines" if the number of duplicated lines decreases in the newer version, or "existing clones with equal lines" if the number of duplicated lines remains the same.

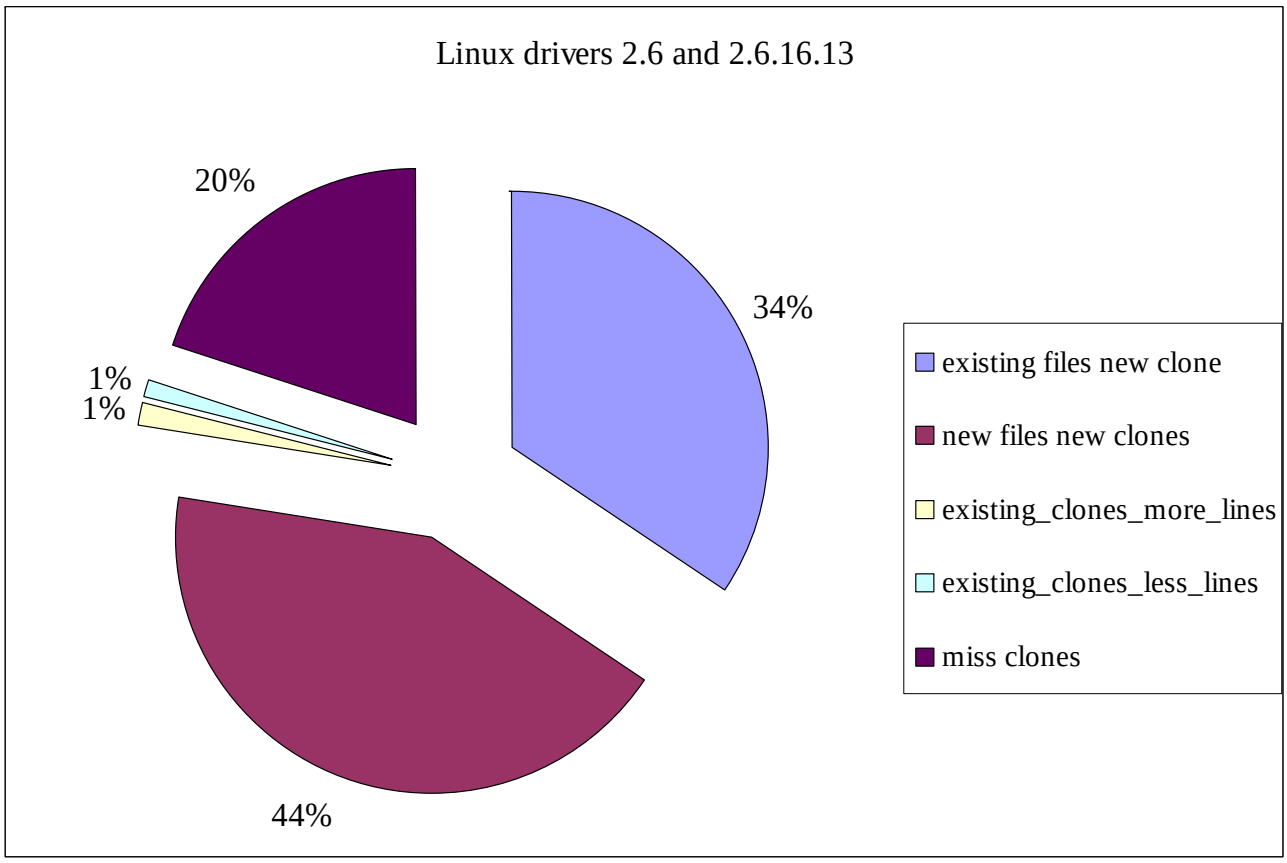


Figure 6.7: The Clone Difference Between Linux 2.6 and 2.6.16.13.

Figure 6.7 shows the break down of the differences in cloning at the "drivers" directory. We choose not to show the amount of "existing clones with equal lines" for clarity

because the focus of the study is to analyze the difference in cloning between two versions. As we can see there are little changes in existing cloning relations, the biggest amount of cloning changes are due to clones in the newly added files, followed by new clones in existing files and then missing clones by deleted files. There are a lot of cloning in newly added files. This is understandable since when developers trying to experiment new features, they first try to copy from the old code and modify based on it. For example, the newly added "drivers/mtd/nand/sharpsl.c" resembles a lot similarity as the legacy driver "drivers/mtd/nand/spia.c"; as they both implement the NAND device. This is the conventional approach to implement new drivers in the Linux "drivers" subsystem. There are a lot of new clones getting added within the existing files. They are mostly due to newly added methods. For example, there are about 1200 lines of duplicated code caused by the added method "zfcp_fsf_link_down_info_eval" within "drivers/s390/scsi/zfcp_fsf.c". In addition, a lot of files have been removed in version 2.6.16.13. For example, "drivers/macintosh/macserial.c" is missing, which leads to about 700 reduction of duplicated lines of code.

6.2.4 Discussion and Future Work

The *Clone System Evolutionary(CSH) Graph* embeds the historical cloning information and tries to highlight spots which are of interest. We use decay function as a proof of concept. We can certainly use any other functions to encode the historical information. For example, if we need to examine the places where are long-live clones and short-live clones, then it is probably better to just aggregate the cloning relation from one release to the next. As another example, if we are more interested in the amount of external and internal cloning for each file or directory, we probably set the cloning weights differently: assign weight 1 to files or directories if all the

clone instances appear to reside under the same directory and 2 if they reside in two different directories, and so on.

Layout: Developers are more comfortable to visualize the architecture in the directory structure like framework. However, our visualization technique may not up to scale. As the number of files increases, it becomes too crowed to fit in the screen. Users have to zoom in and zoom out to gain a better understanding of certain part of the diagram. In the future, we are going to experiment with different kinds of layout, especially the effectiveness of radial layout.

Filtering: Since both the CSH graph and CSE graph use tree structure layout, they suffer the same over-plotting problem. As there might be too many nodes and files cramming into the screen. Similar as the CSH graph, we use level filtering and subsystem filtering to scale down the graph.

Animation: As our view is static, it does not coincide with the dynamic nature of software evolution. However, one challenge which hinders us from animating the evolution as the hierarchical view is the "minimal impact" principle. It is preferred to keep the relative position of directories and files stable, since it is easier for user to keep track of the changes. However, if one directory gets added or removed how do we put them without affecting the relative position of other directories and files; especially in big software systems like Linux which contains millions of files and thousands of directories? In the future, we are going to look into the ways of of animating the evolution of code cloning.

6.3 Guideline

We summarize the steps for using our visualization. Researchers can follow this guideline to process, visualize and analyze cloning for other software systems.

Overall: The clone evolution graph highlights the most recent changes of cloning in the system.

Data Processing : We aggregate cloning information across releases. We first create a directory structure which contains all the directories and files ever existed. Then, we apply some decaying function to embed the historical information at the file level. Then we lift the file level information to the subsystem level.

Note that different decay function can be used to highlight different aspects of the cloning. For example, we can device our decay function to put more values on the most recent changes or we can instrument the function to put more emphasis on the spread of the clones, and so on.

Graph Analysis: The graph is highlighted to different colours. Depending on the focus on the task, we need to pay attention to different entities. In particular the red area to the left and grey area to the right of the graph.

The most recent biggest clone changes are coloured in red, this can be interesting since the rationale behind cloning to red nodes can answer questions like: Is cloning introduced for new features or for bug fixes or something else? If a lot of clones have been removed, then we want to answer questions like: is there a refactoring or system restructuring occurred; is there any the interfaces got updated, etc.

For places which have little cloning changes is coloured in grey. They could be valuable to answer questions like: why there is little cloning changes? Is it due to the

introduction of new clone-free code or is it because that part is relatively stable and little changes have been performed? If it is due to the addition of clone-free code, how many call dependencies is introduced to avoid cloning?

Others: The graph of *ULOC* over releases shows the growth rate of essential features. It is complementary to the CSE graph, which studies the changes in code duplications.

6.4 Conclusion

This chapter introduces techniques to analyze the evolution of the software systems. The ULOC plot examines the growth of the essential features; whereas the complementary Clone System Evolution (CSE) graph displays the most recent changes in code duplications.

Chapter 7

Conclusion and Future Work

This chapter summarizes the main ideas addressed in this thesis and proposes some future work in the areas of clone evolution and visualization.

As was explained in Chapter 1, clones are identical or near identical segments of code. Clones can be good or bad depending on the context. Cloning may be desirable since it speeds up the development process. Reusing the already tested components reduces the risks. Cloning can be avoidable due to language limitations or performance requirements. Cloning is bad since it leads to a bloated code base and in term requires more storage spaces. Clones are considered bad smell for code quality; since it brings challenges for software maintenance. Many of the above points are drawn either from some user experience or from the academic research. There is a lack of empirical study on the consequence of code cloning.

One of the major challenges for studying code clones in large software systems is how to handle large set of cloing data; as about 5-50% of the source code can be clones [8, 39, 7]. In this thesis, techniques and tools have been proposed to scale down and visualize the cloning data.

7.1 Major Topics Addressed

To scale down the cloning data, we have proposed three types of scaling: abstracting the data by lifting the cloning relation from the file level to the subsystem level; merging multiple similar clone classes into one big clone class; and filtering out irrelevant information.

Using the scaled data, we have proposed three types of visualization, ranging from a snapshot view of how cloning situations are to the evolutionary view showing how clones evolves over time. Three of our visualizations emphasize cloning along different dimensions:

along the quantity scale: the Clone Cohesion and Coupling (CCC) graph shows the degree of internal and external cloning among subsystems;

along the relation scale: the Clone System Hierarchy (CSH) graph puts more focus on the details of cloning, especially the spread of the cloning;

along the time scale: the Clone System Evolution (CSE) graph highlights the most recent clone changes.

We showcase our visualizations by applying them to a large open source software system: the Linux Kernel.

7.2 Future Research

First of all, this thesis demonstrates our visualization tools mainly on various case studies of Linux Kernel. In the future, we plan to work on additional software projects to evaluate the effectiveness of these three visualization techniques and hope to uncover interesting clone design patterns.

In addition, as the directory tree structure may not up to scale; various layout algorithms, such as radial layout, will be experimented with. Furthermore, as we can apply different evolution functions in *Clone System Evolution (CSE)* graph; we plan to devise a few of these evolution functions and test to see which ones are best suited to explore which aspects of clone evolution studies.

We are also interested in applying more user studies to verify and improve the effectiveness of our visualizations.

Finally, we may redo Godfrey et. al.'s study [31] but using *ULOC* to study the growth rate to a number of open source software systems.

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