Understanding Software Systems Using Reverse Engineering Technology[†]

Hausi A. Müller Kenny Wong Scott R. Tilley

Department of Computer Science, University of Victoria
P.O. Box 3055, Victoria, BC, Canada V8W 3P6
Tel: (604) 721-7294, Fax: (604) 721-7292
E-mail: {hausi, kenw, stilley}@csr.uvic.ca

Abstract

Software engineering research has focused primarily on software construction, neglecting software maintenance and evolution. Observed is a shift in research from synthesis to analysis. The process of reverse engineering is introduced as an aid in program understanding. This process is concerned with the analysis of existing software systems to make them more understandable for maintenance, re-engineering, and evolution purposes. Presented is reverse engineering technology developed as part of the Rigi project. The Rigi approach involves the identification of software artifacts in the subject system and the aggregation of these artifacts to form more abstract system representations. Early industrial experience has shown that software engineers using Rigi can quickly build mental models from the discovered abstractions that are compatible with the mental models formed by the maintainers of the underlying software.

Keywords: Legacy software, program understanding, reverse engineering, software engineering education, software evolution, structural redocumentation.

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1 Introduction

Suppose we could turn back time to 1968—to the first software engineering conference held in Garmisch, Germany. This NATO conference, which was held in response to the perceived software crisis, introduced the term *software engineering* and significantly influenced research and practice in the years to follow. What advice would we give to those software pioneers, given our experience and the state-of-the-art in software engineering we have today? This advice might have changed history in the process. Are there software engineering problems we face today that did not exist in 1968?

These software pioneers did not anticipate that their software, constructed in the 1960's and early 1970's, would still be used and modified twenty-five years later. Today's developers inherit a huge legacy of such *heritage* software systems. Such software includes telephone switching systems, banking systems, health information systems, avionics systems, and pervasive computer vendor products. In switching systems, new functionality is added periodically to reflect the latest market needs. Banks have to update their systems regularly to implement new or changed business rules and tax laws. Health information systems must adapt to rapidly changing technology and additional services. Computer vendors are often committed to supporting their products (for example, database management systems) indefinitely, regardless of age. Evolution is a natural phenomena for such systems; it is not that someone forgot a requirement—the requirements inevitably change. There will always be old software, as new software written today will be in use for decades to come.

These systems are inherently difficult to understand and maintain due, in part, to their size and complexity, as well as their evolution history. The average Fortune 100 company maintains 35 million lines of code and adds an additional ten percent each year just in enhancements, updates, and other maintenance. As a result of maintenance alone, software inventories will double in size every seven years.

Since legacy systems cannot be replaced without reliving their entire history, managing long-term software evolution is critical. These systems embody substantial corporate knowledge such as requirements, design decisions, and business rules that have evolved over many years and are difficult to obtain elsewhere. This knowledge constitutes significant corporate assets totalling billions of dollars. Consequently, long-term software maintenance and evolution are as important (if not more) as new software construction—especially if we consider the economic impact of these legacy systems.

The next section discusses the need for increased emphasis on software analysis. Section 3 describes an approach to aiding program analysis and understanding using reverse engineering technologies. Section 4 outlines the Rigi approach to reverse engineering. Section 5 summarizes the paper.

2 Balancing act

Our main advice to the software pioneers of 1968 would be to carefully balance *software analysis* and *software construction* efforts in both research and education. This advice, which might have changed history, is still valid today.

Over the past three decades, software engineering research has focused mainly on new software construction and has neglected software maintenance and evolution. For example, numerous successful tools and methodologies have been developed for the early phases of the software life cycle, including requirement specifications, design methodologies, programming languages, and programming environments. As such, there has arisen a dramatic imbalance in software engineering education, for both academia and industry, of favoring original program, algorithm, and data structure construction. There is a need to focus more on understanding.

Computer science and computer engineering programs prepare future software engineers with a background that encourages fresh creation or synthesis. Concepts such as architecture, consistency and completeness, efficiency, robustness, and abstraction are usually taught with a bias toward synthesis, even though these concepts are equally applicable to analysis. The study of existing, real-world software systems is often overlooked. Instructors rarely provide assignments that model the normal mode of operation in industry: analyzing, understanding, and building upon existing systems. Contrast this situation with electrical or civil engineering education, where the study of existing systems and architectures constitutes a major component of the curriculum.

Knowledge of architectural concepts in large software systems is key to understanding legacy software and to designing new software. These concepts include: subsystem structures; layered structures; aggregation, generalization, specialization, and inheritance hierarchies; resource-flow graphs; component and dependency classification; event handling strategies; pipes and filters; user interface separation; and distributed and client-server architectures. The importance of architecture is now recognized; courses on the foundations of software architecture [1] have recently emerged at several universities.

The bias toward synthesis has also resulted in a lack of tools for the software maintainer. To correct the imbalance, a shift in research from synthesis to analysis is needed. This would allow the software maintenance and evolution community to catch up. Once the repertoire of tools and methodologies for analysis becomes as refined as that for synthesis, software maintenance and evolution will become more tractable. Experimental software engineering should concentrate on software evolution. The development of software evolution strategies is a great challenge—and a great opportunity.

In 1990, the Computer Science Technology Board of the U.S. proposed a research agenda for software engineering [2]. Their report concluded that progress in developing complex software systems was hampered by differing perspectives and experiences of the research community in academia and of software engineering practitioners in industry. The report recommended nurturing a collaboration between academia and industry, and legitimizing academic exploration of complex software systems directly in government and industry. Software engineering researchers should test and validate their ideas on large, real-world software systems. An excellent example of providing such arrangements in Canada is the IBM Centre for Advanced Studies (CAS) in Toronto, where there is a Program Understanding (PU) project.

3 Program understanding via reverse engineering

One of the most promising approaches to the problem of software evolution is *program understanding*. It has been estimated that fifty to ninety percent of evolution work is devoted to program comprehension or understanding [3]. Hence, easing the understanding process can have significant economic savings.

Programmers use programming knowledge, domain knowledge, and comprehension strategies when trying to understand a program. For example, one might extract syntactic knowledge from the source code and rely on programming knowledge to form semantic abstractions. Brooks's work on the theory of domain bridging [4] describes the programming process as one of constructing mappings from a problem domain to an implementation domain, possibly through multiple levels. Program understanding then involves reconstructing part or all of these mappings. Moreover, the programming process is a cognitive one involving the assembly of programming plans—implementation techniques that realize goals in another domain. Thus, program understanding also tries to pattern match between a set of known plans (or mental models) and the source code of the subject software.

3.1 Reverse engineering

For large legacy systems, the manual matching of such plans is difficult. One way of augmenting the program understanding process is through computer-aided *reverse engineering*. Although there are many forms of reverse engineering, the common goal is to extract information from existing software systems to better understand them. The subject software system is represented in a form where many of its structural and functional characteristics can be analyzed. This knowledge can then be used to improve subsequent development, ease maintenance and re-engineering, and aid project management [5]. This knowledge can help defend against brittle software systems that resist graceful change. Problems can be exposed and corrected if reverse engineering is applied preventatively during evolution. As maintenance and re-engineering costs for large legacy software systems increase, the importance of reverse engineering will grow accordingly.

The reverse engineering process involves two distinct phases [6]. The first identifies the system's current components and captures their dependencies; the second discovers design information and generates system abstractions. The second, discovery phase of reverse engineering is a highly interactive and cognitive activity. The user may build up hierarchical subsystem components that embody software engineering principles such as *low coupling* and *high cohesion* [7]. Discovery can also include the reconstruction of design and requirements specifications (often referred to as the "domain model") and the correlation of this model to the code. One classic use of this information is to redocument a software system whose documentation is missing or out-of-date.

Improved understanding of the software is beneficial to project management processes [8]. These processes are complex and involve human elements, funding, schedules, politics, trends, and marketing. The technical and organizational complexity of the project can threaten to overwhelm even the most prepared managers. To make informed decisions, managers need both a high-level perspective of the entire system and in-depth information on selected components. This information is particularly important for risk analysis: where to allocate scarce resources, where to place personnel, what is the impact of changes, and where to focus effort for maximal benefit. It is better to depend on objective data (verifiable against the actual source code) than relying only on gut feelings and experience. The required information entails another perspective on the software system (complementing the programmer's view).

During the reverse engineering process, the source code is not altered, although additional information about it is generated. In contrast, the process of *re-engineering* typically consists of a reverse engineering phase followed by a forward engineering phase that moves from high-level abstractions to physical implementations and reconstitutes the subject system into a new form. Moreover, re-engineering consists of many feedback loops between the old and new versions—opportunities for understanding to occur. Re-engineering can help an organization to recoup or extend its software investment and salvage corporate knowledge.

In comparison, business process re-engineering re-examines and streamlines the way businesses work. Information technology is often introduced into the workplace to simply automate old ways of doing business. Such simple optimizations do not lead to major benefits. There is a need to rethink these tasks in an organization-wide setting to better exploit the computer technology. This form of re-engineering involves changing an organization's fundamental work processes and is necessary for businesses to survive in an increasingly competitive world.

Software re-engineering involves many risks. Before embarking on a significant re-engineering project, the goals must be very clear. What characterizes a successful re-engineering process? What is a "good" re-engineering technology? What kinds of applications are amenable to re-engineering? Choosing the right toolset is critical; one must avoid subscribing to obsolete, incomplete, or incompatible methodologies.

3.2 Reverse engineering approaches

Many research groups have focused their efforts on the development of tools and techniques for program understanding. The major research issues involve the need for formalisms to represent program behavior and visualize program execution. Reverse engineering has many supporting aspects. It may focus on features such as control flows, global variables, data structures, and resource exchanges. At a higher semantic level, it may focus on behavioral features such as memory usage, uninitialized variables, value ranges, and algorithmic plans. At an even higher level of abstraction, it may focus on business rules, policies, and responsibilities. Each of these points of investigation must be addressed differently.

There are many commercial reverse and re-engineering tools available; catalogs such as [9, 10] describe several hundred such packages. Most commercial systems focus on source-code analysis and simple code restructuring, and use the most common form of reverse engineering: information abstraction via program analysis. Such capabilities extend computer-aided software engineering toolsets.

Research in reverse engineering consists of many diverse approaches. Three sample ones are formal transformations, pattern recognition, and reuse-oriented approaches. Formal transformation approaches include: concept recognition and transformation [11], least common abstractions [12], program refinements and transformations [13], and meaning-preserving restructuring [14]. Pattern recognition approaches look for matching patterns and include: defect filtering [15], syntactic clichés (SCRUPLE) [16], user interface analysis [17], graph parsing [18], characterizing design decisions [19], function abstraction [20], information abstraction (CIA, CIA++) [21, 22], maverick identification [23], and graph queries (GraphLog, G+) [24]. Approaches based on reuse include: reuse-oriented software development [25], design recovery (DESIRE) [26], and teleological maintenance (IRENE) [27].

4 The Rigi project

Rigi [28] is a framework under development at the University of Victoria for program understanding, software analysis, reverse engineering, and programming-in-the-large. One major goal is to extract abstractions from software representations and transfer this information into the minds of software engineers for software evolution purposes. The chief benefit is to reduce maintenance and evolution costs. The focus is on summarizing, querying, representing, visualizing, and evaluating the structure of large, evolving software systems. One end-product is better documentation.

Reconstructing the design of existing software is especially important for complex legacy systems. Documentation has always played an important role in program understanding. There are, however, great differences in documentation needs for software systems of 1,000 lines versus those of 1,000,000 lines. Typical software documentation is *in-the-small*, describing the program in terms of isolated algorithms and data structures. Moreover, the documentation is often scattered about on different media. The maintainers have to resort to browsing the source code and piecing disparate information together to form higher-level structural models. This process is always arduous; creating the necessary documents from multiple perspectives is often impossible. Yet it is exactly this sort of *in-the-large* documentation that is needed to expose the overall architecture of large software systems.

For a large software system, the reconstruction of the structural aspects of its architecture is beneficial. This process may be termed *structural redocumentation*. As a result, the overall structure of the subject system can be derived and some of its architectural design information can be recaptured. Software structure is the collection of artifacts used by software engineers when forming mental models of software systems. These artifacts include software *components* such as procedures, modules, and interfaces; *dependencies* among components such as client-supplier, inheritance, and control-flow; and *attributes* such as component type, interface size, and interconnection strength. The structure of a system is the organiza-

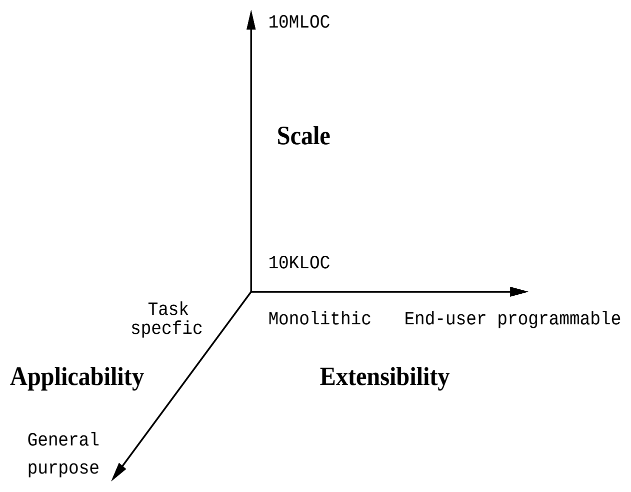

Figure 1: Reverse engineering design space

tion and interaction of these artifacts [29].

4.1 Key requirements

To be considered successful, a reverse engineering tool must be flexible with respect to its applicability to multiple domains, it must be extensibile with respect to its functionality, and it must support the analysis of large ($O(10^6)$ LOC) programs. These three requirements form a *design space* [30] for reverse engineering tools, as illustrated in Figure 1.

Flexibility: Because program understanding involves many different scenarios and target domains, it is wise to make our approach as flexible as possible for use in many different domains. An approach is flexible if it can be easily adapted to a variety of situations. In particular, we mean extensibility, tailorability, and configurability of the reverse engineering methodology and supporting environment. Most reverse engineering tools provide a fixed palette of extraction, selection, filtering, organization, documentation, and representation techniques. One important need is to provide a way for users to extend the tool's functionality. This may involve user-defined algorithms or integration with other external tools. Moreover, by making the tool user-programmable, it becomes domain-retargetable rather than domain-specific—allowing the user to tailor the tool to fully exploit aspects of the problem that make its solution easier.

Scalability: Effective approaches to program understanding must be applicable to huge, multi-million line software systems. Such scale and complexity necessitates fundamentally different approaches. Program representation, search strategies, and human-computer interfaces that work on systems "in-the-small" often do not scale up. For very large systems, the information accumulated during program understanding can be over-whelming. Current repository technology does not easily manage complete and detailed program representations for huge systems. It may be perfectly acceptable to ignore certain details for program understanding tasks. To obtain manageable repositories, coarser-grained artifacts can be extracted, partial systems can be incrementally investigated, and irrelevant parts can be ignored. To gain useful knowledge, the information must be effectively summarized and abstracted. In a sense, a key to program understanding is deciding what information is material and what is immaterial: knowing what to look for—and what to ignore [31].

4.2 Rigi framework

The most recent results of the Rigi project include: a reverse engineering environment consisting of a parsing subsystem, a distributed, multi-user repository, and an interactive graph editor [32]; a representation for software structure based on $(k, 2)$-partite graphs [33]; a reverse engineering methodology [34]; measures for evaluating the quality of structural abstractions [35]; a documentation strategy using up-to-date views [36]; a facility to understanding document structure [37]; and an extension mechanism via a scripting language [38]. Output from this environment can also serve as input into conceptual modeling, design recovery, and project management processes.

Much work on program understanding still makes heavy use of human cognitive abilities. There are tradeoffs in program understanding environments between what can be automated and what should (or must) be left to humans. The best solution seems to lie in a combination of the two. The extraction phase in Rigi is initially automatic and involves parsing the source code of the subject system and storing the extracted artifacts in the repository. This produces a flat resource-flow graph of the software. To manage the complexity, this phase is followed by a largely semi-automatic one that exploits human pattern recognition skills and features language-independent subsystem composition techniques. Rigi depends heavily on the experience and domain knowledge of the software engineer using it; the user makes all the important decisions. Nevertheless, the process is one of synergy as the user also learns and discovers interesting relationships by exploring software systems with the Rigi environment.

Subsystem composition is the methodology used in Rigi for generating layered hierarchies of subsystems, thereby reducing the cognitive complexity of understanding large software systems. It is a recursive process whereby building blocks such as data types, procedures, and subsystems are grouped into composite subsystems. This builds multiple, layered hierarchies for higher-level abstractions [39]. The criteria for identifying these "clusters" depends on the purpose, audience, and domain. For program understanding purposes, the process can be guided by dividing the resource-flow graph using established modularity principles such as low coupling and strong cohesion. Exact interfaces between subsystems and modularity/encapsulation quality measures can be used to evaluate the generated software hierarchies and assess the extent of changes. One goal is to expose properties and anomalies of the software structure for managing risk and deciding personnel assignments. For example, highly complex "central" components (as opposed to simpler "fringe" components) are best handled by the senior maintainers. The partition can also be based on other criteria such as business rules, tax laws, message paths, personnel assignment, or other semantic information.

Software engineers rely heavily on internal documentation to help understand programs. Unfortunately, this documentation is typically out-of-date and software engineers end up referring to the source code. There is a need to link the documentation and source code together. The Rigi environment eases the task of redocumenting the subject software by presenting the results using interactive *views* (somewhat similar to database views) [40]. The focus is to construct readable, accurate, and up-to-date system documentation. A view is a bundle of visual and textual frames that contain, for example, call graphs, overviews, projections, exact interfaces, and annotations [41]. A view is an adaptive snapshot that reflects the reverse engineering state contained in the graph model, repository, and editor user interface; retrieving a view reconstitutes a particular reverse engineering state from which to highlight pertinent maintenance constraints or to help illustrate problems. Moreover, this state captures the actual, operational structure of the software. Thus, a view remains up-to-date.

The economic cost of understanding a software system is significant, especially for every time a new person must learn the system. The created views can lessen the time required to understand the system. Programmers are often assigned to specific components and lack the big picture; managers may understand the overall design but lack details on specific parts. Views can accurately capture co-existing architectural decompositions, providing many different perspectives at various levels of detail for later inspection.

Reverse engineering approaches are diverse and depend on aspects of the application domain, the implementation domain, and the reverse engineering domain. It is impossible to know in advance all that will be needed to understand a software system. What is needed is flexibility and an approach that allows users to adapt the environment to exploit domain-specific knowledge themselves. Rigi supports a scripting language that allows users to customize, combine, and automate reverse engineering activities in novel ways. The language allows an analyst to complement the built-in operations with external, possibly application-specific, algorithms for graph layout, complexity measures, pattern matching, slicing, and clustering. Complex analysis tasks can be automated for more consistency and repeatability. Efforts are proceeding to make the user interface and configuration settings more user-customizable [42]. This approach permits analysts to tailor the environment to better suit their needs, providing a smooth transition between automatic and semi-automatic reverse engineering [43].

These results have been applied to several industrial software systems to validate and evaluate the Rigi approach to program understanding. In 1990, we analyzed the *Practice Manager*, a 57000 line COBOL program for managing physician's practices in British Columbia [44]. The main purpose of the analysis was to build up-to-date logical subsystems, assess the maintainability of the system, and identify components for re-engineering. In 1991, we analyzed a 82000 line C program for the isotope separator experiment at TRIUMF (TRI-University Meson Facility) in Vancouver. Early experience has shown that we can produce views that are compatible with the mental models used by the maintainers of the subject software. That is, the views we create are presenting information about the system at the right level of abstraction. Over the past year, we analyzed the source code of the SQL/DS system as part of the IBM CAS PU project [45, 46]. The goal was to apply reverse engineering technology to improve the quality of subsequent maintenance.

5 Summary

There will always be old software that needs to be understood. It is critical for the software industry to deal effectively with the problems of software evolution and the understanding of legacy software systems. Since the primary focus of the industry is changing from completely new software construction to software maintenance and evolution, software engineering research and education must make some major adjustments. In particular, more resources should be devoted to software analysis in balance with software construction.

Program understanding tools and methodologies address the problems of software evolution by helping software engineers to understanding large and complex software systems. Effective reverse engineering technologies can have a significant impact on the maintenance and evolution of these systems.

The Rigi environment focuses on the architectural aspects of the subject software under analysis. The environment provides many ways to identify, explore, summarize, evaluate, and represent software structures. More specifically, it supports a reverse engineering methodology for identifying, building, and evaluating layered subsystem hierarchies. These hierarchies are documented through views—snapshots of reverse engineering states. The views are used to transfer information about the abstractions to the minds of the software engineers. A scripting language permits analysts to adapt the environment to their needs and support automatic reverse engineering. This methodology of building subsystems, creating views, and writing scripts is applicable to other instances of structural understanding (for example, large technical documents and hypertext). The results of the Rigi project have been successfully applied to several industrial software systems.

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