AN OBJECT-ORIENTED APPROACH TO
COMPUTER ARCHITECTURE SIMULATION

by

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September 1991

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An object-oriented approach to modeling and simulating computer architectures is presented. This approach yields a 'generic' class hierarchy that supports the simulation of basic computer microarchitecture components found in most computers. This is accomplished by concentrating on the more generic concepts of processors, memories, registers etc., rather than concentrating on a specific system. The 'generic' class hierarchy is tested by developing microarchitecture simulators for two different microarchitecture designs.

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An Object-Oriented Approach To Computer Architecture Simulation

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I. INTRODUCTION

Designing a new computer architecture is a complex process. This process produces a complicated device, composed of many interdependent components. Since the final product is a piece of hardware, it is expensive and time-consuming to design, test, alter, and then re-test the various components.

It is difficult to directly measure the performance of new hardware as it is being designed. Performance parameters include items such as how many memory accesses occur and how many times the registers exchange data in a given time period for a given program. In order to measure these parameters directly, costly monitoring equipment must be connected directly to the hardware. The problems of monitoring and testing become even more pronounced when evaluating Very Large Scale Integration (VLSI) Hardware, as it may be impossible to connect external monitoring equipment to some of the internal components. It is also important to test the effects that each component has on all others. These effects can be both electronic and logical; only the logical effects are addressed in this thesis.

One solution to the problem of component testing and hardware evaluation is to simulate the new hardware in software. This allows separate testing of individual components as well as testing of the complete system. A complete simulation environment should model the architecture as closely as possible, yet remain as general as possible. Reusability is the main attraction of using simulation for hardware and system design.

The majority of computer architecture simulations in the past have been implemented using conventional programming languages and techniques. This thesis examines the advantages of implementing computer architecture simulation using an object-oriented (OO)
approach. Encapsulation of methods and variables facilitates the reusability of code, inheritance and composition allow the building of more complex components and systems. Two computer architectures have been simulated using Prograph\(^1\) (Cox and Pietrzykowski, 1989), an object-oriented programming (OOP) language, as part of this thesis.

A. OBJECT-ORIENTED PROGRAMMING

1. Object-oriented programming terminology

It is assumed that the reader has at least some familiarity with object-oriented programming concepts. This section provides a brief introduction to object-oriented programming and terminology as applied in this thesis.

Object-oriented programming may be summarized by the following equation:

"object-oriented = objects + classes + inheritance" (Wegner, 1987, p.168)

The backbone of an object-oriented programming language is the object. Objects are autonomous entities that respond to messages (operations) and have a state. An object's state is defined by its variables (attributes), and its operations are defined via its methods (procedures). An object's state can only be manipulated by its methods. Therefore, to change an object's state from the outside, a message must be sent to the object telling it which method to invoke\(^2\).

A class is a template from which objects may be created (Wegner, 1987, p.168). An object is an instance of a class. The variables making up an object's state can be divided into class variables and instance variables. A class variable is defined as a variable that has the same value for all instances of a particular class. An instance variable is one that has a unique value for each instance of a class.

---

1 Prograph is a trademark of The Gunakara Sun Systems, Ltd (TGSSystems).
2 This assumes an encapsulated approach; although most OOP languages support this idea, not all enforce it.
For example, a class Person could be defined which has the instance variables name (the unique identifier of this object), and where (the current location of the object), and a class variable People (a list of names of all the instances of this class)\(^3\). Three instances of class Person are:

- (name: canniball, where: left, People: (caniball, canibal2, missionary1))
- (name: cannibal2, where: right, People: (caniball, canibal2, missionary1))
- (name: missionary1, where: left, People: (caniball, canibal2, missionary1))

Even though these instances of Person each have a different state, they all share the same operations, (e.g., walk, sleep, etc.), because they are all instances of the same class.

Inheritance allows the creation of classes of objects that are almost like another class of objects with a few incremental changes (Stefik & Bobrow, 1986, p.40). This results in a formal code sharing mechanism. A subclass inherits all of the variables and methods defined for its superclass. A simple example of inheritance is when the class person (instance variables: name, where; class variable; people methods: walk, sleep) is inherited by class Cannibal. Thus Person is the superclass and Cannibal is the subclass. The subclass Cannibal inherits all of the variables and methods of Person (i.e., the code is shared); the user may also add other variables and methods in defining the subclass Cannibal. The inheritance hierarchy can be many levels deep and complex. Single Inheritance is when a class can have only one superclass (usually referred to simply as inheritance). Multiple inheritance occurs when a class can have several superclasses.

A composite object (or aggregate object) is an object that contains other objects. That is, its variables may themselves be instances of other classes. For example, an airplane object can be defined as containing the objects wings, propeller, wheels, etc; the wing object contains flaps, covering, cables, etc.

---

\(^3\)This example is taken from a classroom project involving the implementation of the missionaries and cannibals problem (CS 4114, Winter, 1990).
An abstract class is a class which does not have any instances (Nelson, 1990, p.6), while a concrete class is one which does have instances. For example, if the class Missionary and the class Cannibal are both subclasses of the class Person and no instances of Person are allowed, then the class Person would be an abstract class. However, both the subclasses inherit all of the variables and methods defined for the class Person. If the classes Missionary and Cannibal do have instances, then they are concrete.

Object-oriented programming also supports encapsulation. Encapsulation is the strict enforcement of information-hiding (Micallef, 1988, p.13). Encapsulation refers to an object's ability to hide implementation details behind the object interface (i.e., the operations/methods defined for the object's class). When a message is sent to an object, the object performs a method which may manipulate one or more of the object's variables without the message sender being concerned with how (or even if) those variables are manipulated.

2. Prograph

All programs implemented in this thesis use the Prograph programming environment on the Macintosh computer. Prograph is a pictorial, object-oriented dataflow language (Cox and Pietrzykowski, 1989, p.1). This environment was chosen because it is pictorial in nature, it easily describes class hierarchies and variables, and it is easy to use. The following discussion is not intended to be a tutorial in Prograph programming, but rather to introduce the terminology and principles of Prograph.

A simple class hierarchy represented in the Prograph environment is presented in Figure 1.1. There are three classes: Person, Missionary and Cannibal; each one

---

4 Abstract classes are not enforced by Prograph, or by any OOPL that we know of (i.e., it is only a concept).
5 Macintosh is a trademark of Apple Computer, Inc.
depicted by a hexagonal shaped icon in the *classes window*. The icon is divided in half; the left half represents the class and instance variables and the right half represents the methods associated with the class. To open the associated window the user 'double-clicks' on the desired half of the icon. The links between class Person and the classes Missionary and Cannibal indicate that Person is a superclass of the classes Missionary and Cannibal.

![Figure 1.1 Example of Class Hierarchy and Class Attributes](image)

The attributes *window* of the class Person is presented in Figure 1.2. In Prograph a class variable is referred to as a *class attribute*, and an instance variable is called an *instance attribute*. An attribute window is denoted by the inverted triangle next to the window name. The class person, in Figure 1.2 has two instance attributes (*name* & *where*) and one class attribute (*People*). Those attributes above the horizontal line represent class attributes and the attributes below the line represent instance attributes. A class attribute is represented by a small hexagonal icon similar to the class icon and an instance attribute is represented by an inverted triangle.
Figure 1.2 Example of Class and Instance Attributes

An example of inherited attributes is presented in Figure 1.3. An *inherited attribute* is represented by the normal attribute icon with a small downward pointing arrow. Therefore, the attributes People, name, and where are inherited from class Person. The attribute level is defined in the class Cannibal.

Figure 1.3 Inherited Attributes
A class' methods are represented in the method window as shown in Figure 1.4. The icon with a small dataflow diagram inside it next to the window name indicates that it is a method window. The six icons inside of the window depict six different methods defined for the class Person. Double-clicking on a method icon will open the associated methods case window.

![Figure 1.4 An Example of a Method Window](image)

A case window opened from a method icon is presented in Figure 1.5 (descriptive comments are in bold type outside of the window). The window title is composed of the class name and the method name. In the example the case window shows the method make from the class Cannibal. All case windows have input bars and output bars. These bars are used to pass data into and out of the method. The numbers 1:1 in the window title indicate that this is the first case window of one case(s). When there are multiple cases of a method, all cases must have have the same number of inputs (terminals) and outputs (roots) on the input and output bars. The number of terminals or roots is defined as arity. Since Prograph is a dataflow language, the data flows from the top to the bottom of the case window, following the datalinks.
The shape of the icon indicates what type of operation will be performed and the name inside of the icon determines which class, attribute, or method is executed. The icon with convex left and right sides (the top leftmost operation, containing the word Cannibal) of Figure 1.5 is a *instance generator*. This generator is used to make an instance of the class Cannibal. The two operations with convex left sides below the Cannibal instance generator, are *set* operations. The set operation is used to set the value of an instance or class attribute. The text inside the icon determines which attribute will be set. The left terminal is used to pass the particular instance to be operated on, and the right terminal is used to input the value the instances attribute is to be set to.

The *Update Class Attribute* operation in Figure 1.5 is a *Local Operator*. Local operators are used to reduce the clutter in a case window, and are defined by the programmer. The operations inside of the local operator icon are still logically inside of the case window in which it resides; they are just grouped together in an attempt to make the
window more readable. Figure 1.6 shows the contents of the local operator Update Class Attribute from the Cannibal/make window. Notice that the arity of this window is exactly the same as the arity in the associated local operator icon in the Cannibal/make case window.

![Update Class Attribute](image)

**Figure 1.6 An Example of a Local Operator Window**

The first operation labeled People (concave left side) in Figure 1.6 is a get operation. This get operation takes a Cannibal instance as input and gets the value of the People class attribute. The operation in Figure 1.6 labeled attach-r is an example of a primitive operation. Primitive operations are supplied by the Prograph programming environment, and are represented by an icon with a horizontal line near the base of the icon. In this case the instance of Cannibal coming into the window is added to the People class attribute (which is a list) with the attach-r primitive. The People set operation (convex left side) simply indicates that the value of the People class attribute has been set to the value returned by the attach-r operation.

There are several ways of calling a message to invoke a desired method in Prograph. Figure 1.7 gives three examples of the various representations of message
calling. The text inside the operation boxes represents the message being sent. The terminals above the box are the data passed to the method, and the root leaving the box is the result of invoking the method. Regardless of the form of message passing, if the method is not found the environment searches for a method higher up in the inheritance tree. Operation A is an example of an explicit reference. This message tells the class Cannibal to invoke the make method. Operation B is an example of a data-determined reference. The message will invoke the method make from the class that matches the instance presented at the left input terminal. Operation C is an example of a context-determined reference. This type of message will invoke the method make from the class that matches the case window in which the operation resides.

<table>
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<tr>
<th>Cannibal/make</th>
<th>/make</th>
<th>/make</th>
</tr>
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<tbody>
<tr>
<td>A.</td>
<td>B.</td>
<td>C.</td>
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**Figure 1.7 Message Passing**

Prograph has two ways to handle persistent\(^6\) data. Class attributes are used to store persistent data that is related to a specific class. This data can only be accessed via an instance of that class. Persistents are used to store persistent data that is not class specific. These persistents can be accessed globally. An example of the use of a persistent is presented in Figure 1.8. The persistent is represented by an oval icon (Total in Figure 1.8). Referring to Figure 1.8, the top persistent (with the root) is being read, and the persistent on the bottom (with the terminal) is being written to. Since Prograph is a dataflow language, program flow follows the datalinks. Using Figure 1.8, the first persistent Total is read, then the data is used and manipulated in the present? operation.

---

\(^6\)Prograph uses the term persistent to describe data which is not part of a specific object.
followed by the results being stored back into the Total persistent. There is only one Total persistent, but it can be read and written as often as the programmer specifies.

**Figure 1.8 Multiplexes, Persistents and Program Control**

Program flow control, an important aspect of any language, is implemented using *case control*. As previously mentioned, a case window can have multiple windows. When a case has multiple windows there must be a method to control which window will be accessed. When Prograph calls a method containing multiple case windows, it will always start execution at the first case window of the series by default. If the case window has any case control it will check that control first. Figure 1.8 also presents an example of a typical case control. The box (labeled X) in the upper right of the window is a simple case control. The X indicates that if the data that arrives at the control’s terminal does not match what is in the control’s box then control will transfer to the next case window of the series. There are other control symbols to perform the following: jump to next case if match, and terminate this method if match/no match.
A multiplex is the multiple execution of a method, which is represented as an icon that looks like a stack (i.e., several boxes, one on top of the other). The present? operation in Figure 1.8 is an example of a multiplex. There are several ways of controlling the number of times a particular multiplex is executed. The present? multiplex in Figure 1.8 has two multiplex operators. A method becomes a multiplex when one of the roots or terminals is changed from a simple root/terminal to a list or loop root/terminal. The ellipses terminal on the upper left of present? is a list terminal. This terminal will cause present? to execute once for each element of a list presented to its list terminal. The root/terminal pair of arrows on the right of present? is a loop multiplex. These always come in pairs. This allows the multiplex method to pass variables from one execution of the multiplex method to the next execution. The data is passed to the method on the first execution, the method uses/alters this data and passes it out of the loop multiplex where it will be passed to the input of the present multiplex method as its execution continues or it will be passed as output upon termination.

This section has presented the most basic essentials of Prograph to give the reader enough information to understand the Prograph programs used in this thesis. For more information on Prograph, please see the Prograph Reference Manual (The Gunakara Sun Systems, 1990).

B. COMPUTER ARCHITECTURE

1. Computer Microarchitecture

The microarchitecture level of a computer is the level that directly interacts with the actual hardware. This is the level of the computer that will be simulated in this thesis. We chose this level because it is easy to pick real components and model them as software objects. The components defined in this section are implemented as objects/classes in the following chapters.
Most computers have several common components, including: registers, memories, buses, arithmetic logic units (ALUs), and multiplexers (muxs). The computer's microarchitecture is controlled either by a microprogram or by hardwired decoding. This thesis discusses only microarchitectures that are controlled by a microprogram. The purpose of the microprogram is to "control the machine's registers, memories, buses, ALUs, and other hardware components" (Tanenbaum, 1984, p.118). This section provides a brief introduction to the microarchitecture level components of a typical computer.

All processors (often referred to as the central processing unit or CPU) contain at least a small number of registers. Registers are located on the CPU chip and are used to store data. A register is characterized by the number of bits of data it can hold. For example, if a register can hold 16 bits it is referred to as a 16 bit register. The register's short access time is due to the simple circuitry required to determine the register being accessed (i.e., a relatively small number of logic gates), and also because the register is contained in the CPU chip. The CPU typically has general purpose registers which are used for storing and retrieving data encountered in instruction execution, as well as registers which have some specific function(s), such as the program counter (PC), stack pointer (SP), instruction register (IR), and accumulator (AC). All of the registers together are often referred to as a register bank.

A computer's memory is similar in construction to a register bank, except that the memory is much larger and is located some distance from the CPU (i.e., usually not on the CPU chip itself); memory is also slower than registers. Typically, a memory bank consists of many thousand locations. Like registers, memory is characterized by the number of bits of data each location can hold. It is also characterized by the number of memory locations possible. One of the reasons that memory is slower than registers is that it has many more locations which can be accessed. The larger the number of locations to
access; the more digital logic required to determine the access point. The increase in the amount of access logic increases the time delay of the signals, thus producing a time delay for the desired data to be returned.

Data passed into memory is communicated via the Memory Buffer Register (MBR), while the desired address of the data (location of where the data is to be stored) is loaded into the Memory Address Register (MAR). A write control is activated causing the value in the MBR to be stored into the desired memory location. To read a value from a particular location in the memory the process is reversed using a read control. Thus, the memory bank interfaces with the rest of the world via an MAR, MBR, and two control signals.

A bus is used to transmit signals from one device to another. Physically, a bus is a collection of wires that transmit a group of signals in parallel from one location to another. Many devices can be physically connected to the same bus. The bus is considered to be an inert device. That is, if data is electrically placed on one end of the bus, the information will show up on the other end. The bus itself does not actively control the signals; rather, the bus is controlled by the equipment connected to it. If multiple devices attempt to transmit simultaneously, the values of each bit of the bus will be garbled and the data will be useless. Thus, many devices can simultaneously read data from the bus, but only one device may be transmitting at any time. Therefore, there arises a need for some central controlling device to synchronize the control of all devices writing on the bus. This will be discussed later.

Devices may receive inputs from several other devices/buses, but can only process one input at a time. This gives rise to the need for a multiplexer. A multiplexer is a device that has several data input lines and a single data output line. It also has several control inputs that determine which data input will be selected. The output of the
A multiplexer is connected to the input line of the device, and data selection is based on the multiplexer control signal. A multiplexer has \(2^n\) data inputs and therefore has \(n\) control inputs.

The heart of the computer is the *Arithmetic Logic Unit (ALU)*. The ALU typically has two inputs for data, one output for data, several control inputs, and several result output indicators. The control inputs are used to select the operation(s) to be performed on the input data. Standard ALU operations typically include: AND, OR, NOT, and ADD. The result output indicators are simple one bit signals which indicate that output of the ALU is negative, zero, overflow, etc. *Shifters* are used to shift the bits of an input to the left or right depending on the input control signals. The shifter may be placed at the output of an ALU, or it may be a part of the ALU itself.

This section has addressed the many components typically found in the *data path* side of a microarchitecture. A typical data path taken from Tanenbaum (Tanenbaum, 1984, pp.127) is shown in Figure 1.9. It includes a bank of registers, an ALU, a shifter, a Memory (including MBR and MAR) and an Amux (multiplexer).
Figure 1.9 Data Path (Tanenbaum, 1984, p.127)

Figure 1.9 shows many devices along with input signals ($F_0$, $F_1$, $S_0$, etc), and output signals ($N$ and $Z$). The input signals are generated from the control side of the
microarchitecture. The control side is presented along with the data path in Figure 1.10. The control devices consist of: the Micro instruction register (MIR), the Control Store, and the Microprogram counter (MPC).

![Diagram of microarchitecture](image)

**Figure 1.10 Example Microarchitecture (Tanenbaum, 1984, p. 132)**

The control store holds the entire microprogram, which consists of microinstructions. When a microinstruction is read from the control store, it is placed in the MIR. The MIR has output leads from each control field to all of the control inputs of each device in the data path side of the machine. The sequence of microinstructions is
controlled by the MPC. The MPC sends its counter value to the control store, the appropriate microinstruction is retrieved from the control store and placed into the MIR, and then the MPC is incremented or changed depending on the output status signals of the ALU. This process repeats as the microprogram execution continues.

This section has introduced the many devices found in a typical computer microarchitecture. The data path consists of registers, memory, ALU, shifter, buses and multiplexers. It is controlled by the microprogram which is implemented in the MPC, control store, and MIR. Each microinstruction controls the entire microarchitecture's device control inputs. It is the continuous cycling of the microprogram which controls the fetching, decoding, and executing of higher level instructions. These components will be seen again in Chapter III where they will be simulated as software objects.

2. Simulation of Computer Architectures

Simulation of computer architecture is the use of a computer program on one computer to model the performance of another computer. Papazoglou, et. al. says that “Simulative modelling, like every other modelling approach, does offer the option that the working representation of a not yet existing system is possible” (Papazoglou, Pawlak, and Wrona, 1989, p.1). In the past, computer architectures have been modeled using classic structured programming languages. Only recently have object-oriented languages begun to be used. To model a specific architecture via a conventional language, a specific program was written to model that architecture. Whenever a simulation of a new architecture was needed, an entire new program was written to support the simulation. Papazoglou et. al. outlines the following requirements for modeling an architecture (Papazoglou, Pawlak and Wrona, 1989, p. 213):

- the model must have the same logical structure as the modelled computer system.
- it must comprise an integrated model of both the complete system hardware and software.
• it should be able to model the different parts of the system at different levels of abstraction.
• it should allow different sets of output statistics each time it is rerun with a new set of input parameters, and like any well disciplined good program it is structured, modular, reliable, efficient and extensible.

Modeling a computer architecture in an OOP language fulfills all four of these requirements, and particularly excels with the last two.

C. OVERVIEW

Chapter II is a detailed survey of the literature pertaining to previous work completed in the areas of computer modeling and object-oriented design. Chapter III is a detailed discussion of the implementation of the computer programs (developed in Prograph) simulating various computer architectures (the actual code is included in appendices C and D). Chapter IV presents the conclusions of this research effort, along with recommendations for future research and a summary of the thesis.
II. REVIEW OF THE LITERATURE

Object-oriented simulation of computer architectures is still in its infancy. The majority of the effort is in the simulation of multiprocessor systems. Most of the simulator systems that were reviewed have a very simple text based user interface; only one group is working on a simulator in which the main concern is the user interface and its ease of use. Only one group was found to be interested in hardware simulation for classroom instruction purposes. Some groups emphasize the usefulness of the object-oriented approach for the reuse of code.

To date, there is no system that incorporates reusable objects, has an intuitive user interface, was developed with commercial software, and runs on a commercially available microcomputer. Of course, a system that meets these objectives would also be economical enough to be available for classroom use. This is because most systems are not being built using commercially available software. This section discusses the various research in the field of architecture simulation, with an emphasis on object-oriented approaches.

A. SIMULATION OF COMPUTER ARCHITECTURES

A system developed at Acadia University uses a Pascal-like Register Transfer Level Language (RTLL) that operates on microcomputers (Tomek, 1985). This system was designed for the instruction of computer organization and architecture. They point out there is currently very little educational software in this field. Their package allows the user to "write descriptions of simpler CPU's, controllers and similar devices and experiment with their operation" (Tomek, 1985, p.493). The package consists of the following modules: RTLL description editor, RTLL simulator, Screen layout generator, Memory file generator, System description generator, and Organization descriptor.
The RTLL description editor is a syntax-directed editor used to develop an RTLL program. The RTLL simulator executes the program developed by the RTLL description editor. The Screen layout generator “allows the user to specify the format in which the results of the simulation are to appear on the screen” (Tomek, 1985, p.494). The memory file generator allows manipulation and loading of the memories’ contents. The system description generator specifies CPU interfaces with other components. Finally, the organization descriptor is used to specify the CPU organization and timing constraints. Unfortunately they do not describe the methodology used in the development of the system or the programming language used in its implementation.

Object-oriented design has been applied to multimicrocomputer hardware and software simulation in the development of the MUDS system (Papazoglou, Pawlak, and Wrona, 1989). “MUDS constitutes an extension of the SIMULA language, and has been designed for developing prototypes of distributed software and for appropriately simulating the extension of these software prototypes on a model hardware” (Papazoglou, Pawlak, and Wrona, 1989, p.215). Thus the MUDS system is used for the simulation of hardware and software for multiprocessor computers. They introduce the design methodology used in the development of MUDS.

The basis of MUDS rests on the development of classes used to represent hardware and software. These classes are chosen such that “the structure of a designed microcomputer system may be extended with an arbitrary number of instances of the classes being modelled” (Papazoglou, Pawlak and Wrona, 1989, p.216). They emphasize that a powerful simulator can be attained with an appropriate object-oriented language, but it is essential that a proper implementation of object-oriented design techniques be used. The authors also show that the advantages of an object-oriented language (data hiding,
abstraction, classes as templates, etc.) allow for a better representation of the hardware/software being modeled.

Modeling of a system can occur at various levels, For example, the microarchitecture level, macroarchitecture level, etc. The Virtual Stack Machine, a programming system for generating and interpreting code for von-Neumann machines is an example of one such level or several levels (Frei, 1989). A virtual stack machine (VSM) simulator is used to perform "VLSI netlist logic design rule checks" (Frei, 1989, p.5/1). This relatively simple architecture, modeled at the macro level, consists of three major elements: a central processing unit, a data stack, and a direct access data memory. The instruction set for the central processor is implemented as methods in one of the classes in the hierarchy. This research concluded, as with other similar research, that a class library is needed for the many objects, and that object-oriented design techniques greatly reduce the coding effort.

Nearly all hardware simulators have a very simple user interface. Only one of the systems reviewed considered the user interface as an essential facet of the simulation model. A simulator has been developed that is used for the writing and debugging of microprograms for hardware under design (Sugimoto, Abe, Kuroda, and Katou, 1988). This system was developed in a LISP-based object-oriented language, VEGAMS, which was also developed by the authors. The user interface presents a bus and component structure which graphically represents the actual hardware. This graphical representation allows the simultaneous display of the bus, register, and various other components as the simulation progresses. Having all the pertinent data available on the screen allows the microprogram developer to quickly realize mistakes and correct them immediately. Another feature is the representation of data by color coding. The microprogram is displayed in an assembly language format and an editor is provided for the system. This allows the user to
alter the microprogram and reenter it into the control store while remaining in a single
application.

One of the system's major features is its ability to stop at a breakpoint and roll-back
the execution to some earlier time. This allows the user to examine the state variables at
that time. The user can alter any variables and change the microprogram and continue
execution from that point. The roll-back capability is implemented by keeping a complex
linking of objects over time. Thus, to roll-back to a certain cycle number, the appropriate
pointer is referenced and its data is loaded.

Although some portions of code are hardware specific, a significant portion is
common to almost all computer architectures. It is claimed that developing simulators
using an object-oriented language lead to approximately 62% reusability of code for other
hardware simulations. As with other object-oriented applications, the design of the class
hierarchy is crucial to the extensibility of the code. (Sugimoto, Abe, Kuroda, & Katou,
1988, p.55)

Simulation efforts are not limited to only object-oriented or classical languages. The
simulation of concurrent real-time systems using the object-based language Ada has also
been investigated (Mulcare, 1990). In the design of real-time systems, "superficial design
descriptions" (Mulcare, 1990, p.184) are performed prior to attempted implementation. Of
course, this leads to problems that appear during construction of the system. A formal
design process followed by a comprehensive simulation of the system is easily attainable
using Ada task types to model the various processes involved. The firing of a Pr-T net
transition "may correspond to a task entry call" (Mulcare, 1990, p.186). Through the use
of Ada generic packages, any number of various architecture components (tasks) may be
instantiated. Their design methodology is described through the example design of a
simple bus with interacting components which consists of specification, then Pr-T net
modeling followed by Ada task/package coding. The results of the experiment concluded that very little effort was required to model the system. Also, any components modeled can become a portion of a growing reusable library of components. The author emphasizes that “the Pr-T net served to focus the entire simulation development” (Mulcare, 1990, p.189).

B. OBJECT-ORIENTED DESIGN

There are many textbooks and papers emerging on the subject of object-oriented design methodologies. Unfortunately, “To date, there is no design methodology that is universally accepted by the object-oriented community” (de Paula & Nelson, 1991, p.203). After reviewing various textbooks and papers, the design methodology proposed by de Paula and Nelson was selected (because of its ease of use) for development of systems in this thesis. The major steps of their design methodology is presented below (de Paula & Nelson, 1991, pp. 204-205):

(1) Identification of the objects and classes.
   (a) Initial definition of the objects and classes.
   (b) Analysis of the object’s variables.
   (c) Analysis of the object’s methods.

(2) Refinement of the objects and classes.
   (a) Addition of necessary information.
   (b) Elimination of redundant information.
   (c) Determination of class and instance variables.
   (d) Identification of composite objects.

(3) Organization of the classes into a hierarchy.
   (a) Analysis of the implementation language.
   (b) Construction of the hierarchies.
   (c) Review of the classes’ variables/methods.

The power of OOP lies in its natural ability to closely map the system to the actual environment the programmer is trying to model. The first step (Identification of the objects and classes) of the procedure identifies the objects and classes necessary to build the desired model. Classes and objects can initially be derived from the problem domain, from
sources such as the following: Tangible things (cars, houses), Roles (pilot, programmer), Events (birthday, graduation), Interactions (meeting), People (manager, bricklayer), Places (Areas set aside for people or things), Things (Physical objects that are tangible), Organizations, Concepts, and Events (de Paula & Nelson, 1991).

The next step in the design process is “Refinement of the objects and classes”. This step examines the methods and variables defined in the previous section. This step outlines a procedure designed to simplify the classes in preparation of building a class hierarchy.

The final step (Organization of The Classes Into a Hierarchy) of the design process organizes the classes defined in the previous steps into a class hierarchy. Class hierarchy organization has some dependency on the particular language used to implement the application.

The most important guideline de Paula and Nelson give for construction of a hierarchy is to "factor common methods as high as possible" (de Paula & Nelson, 1991, p.207). This allows the common attributes (methods and variables) of a class to be shared by all the subclasses via inheritance. If two or more classes have attributes in common but share no common superclass, an abstract class can be created as a superclass to allow these common attributes to be inherited.

de Paula and Nelson point out that when reviewing the classes' variables and methods it is necessary to look for classes that inherit unwanted variables and methods from their superclasses (de Paula & Nelson, 1991, p.6). If the inheritance of unwanted variables/methods cannot be removed, then some of the classes may have to be modified.

There is no standard format for representing class hierarchies. A simple method for specifying a class definition in a language-independent manner is given by Nelson (Nelson, 1990, p.3) as presented in Figure 2.1. This format is used for representing classes in the text of this thesis.
C. CONCLUSIONS

This chapter introduced the various research in the area of computer architecture simulation. This chapter also introduced the basic concepts of object-oriented design, and described the methodology used in this work. It showed that several of the researchers are interested in developing class libraries to model computer hardware objects. Most of the researchers pointed out that the design of the class hierarchy is the crucial portion of the design of any simulator. I feel that the research outlined in this chapter demonstrates a need for a system with the following features: incorporation of reusable objects, an intuitive user interface, and development using commercial software on a commercial microcomputer. It should also be affordable for education purposes.
III. SOLUTION

Chapter I introduced the concepts necessary to understand OOP, Prograph, and the basic components of a computer microarchitecture. This chapter begins by discussing the construction of a 'generic' microarchitecture class hierarchy and the objects necessary to simulate a typical computer microarchitecture. This chapter also outlines the class hierarchy and program construction for the implementation of two different microarchitecture simulators.

A. DESIGNING A 'GENERIC' MICROARCHITECTURE CLASS HIERARCHY

This thesis uses the object-oriented design methodology presented in de Paula and Nelson's paper for the construction of class hierarchies (de Paula & Nelson, 1991). Previously discussed in Chapter II, the following is an outline of their design methodology (de Paula & Nelson, 1991, p.2):

(1) Identification of the objects and classes.
   (a) Initial definition of the objects and classes.
   (b) Analysis of the object's variables.
   (c) Analysis of the object’s methods.

(2) Refinement of the objects and classes.
   (a) Addition of necessary information.
   (b) Elimination of redundant information.
   (c) Determination of class and instance variables.
   (d) Identification of composite objects.

(3) Organization of the classes into a hierarchy.
   (a) Analysis of the implementation language.
   (b) Construction of the hierarchies.
   (c) Review of the classes’ variables/methods.

This methodology can be easily applied to the problem of designing the objects and classes of a computer microarchitecture.
1. Identification of the Objects and Classes

a. Initial definition of the objects and classes

In Chapter I, the components of computer microarchitectures that are common to most computers were introduced. These include: register, memory, ALU, muxs MAR, MBR, shifter, MIR, control store, and MPC. These components can be thought of as the initial set of classes.

Next an initial definition of the variables and methods associated with each of these classes must be specified. The following is the initial set of class definitions for typical components found in a computer microarchitecture as specified above:

Class: ALU
Variables: none
Methods: and, or, not, math, zero?, positive?
Description: Represents a combinational circuit; thus, it has no state. Methods are provided that perform logical operations on a stream of input data.

Class: CONTROL STORE
Variables: varies
Methods: load, read
Description: Holds the entire microprogram. It must be loaded with the microprogram prior to any simulation execution.

Class: MAR
Variables: contents (string of bits)
Methods: mar, read, write
Description: Contains an address of a MEMORY LOCATION within a MEMORY BANK. The method mar accepts a control signal which determines if a value is to be stored into the MAR.

Class: MBR
Variables: contents (string of bits)
Methods: mbr, read, write
Description: Models the data interface to the memory bank. The method mbr accepts a control signal which determines if the data input will be written to the MBR.

Class: MEMORY BANK
Variables: contents (array of MEMORY LOCATIONs)
Methods: initialize, load, read, write
Description: A read or write to a MEMORY BANK implies a read or write to a specific MEMORY LOCATION contained in the MEMORY BANK. The method load is used to load a user program or data into the MEMORY BANK.

Class: MEMORY LOCATION
Variables: contents (string of bits)
Methods: initialize, read, write
Description: Used to describe the contents of a location in a MEMORY BANK.

Class: MIR
Variables: contents (string of bits)
Methods: decode, read
Description: Contains the various control signals. The method decode is used to parse the register contents into required control fields.

Class: MPC
Variables: contents (string of bits)
Methods: set, increment, read, jump
Description: Models a microprogram counter.

Class: MUX
Variables: none
Methods: mux
Description: Models a combinational circuit. The output is one selection from the many inputs.

Class: REGISTER
Variables: contents (string of bits)
Methods: initialize, read, write
Description: Defines how the data is represented in a system, (i.e., how many bits represents a register/memory location).

Class: REGISTER BANK
Variables: contents(array of REGISTERs)
Methods: initialize, load, read, write
Description: Similar to a MEMORY BANK.

Class: SHIFTER
Variables: none
Methods: shift_left, shift_right, no_shift
Description: Models a combinational circuit. Methods take a binary input and perform a binary shift to the left or right.
b. Analysis Of The Object's Variables

This step looks at the variables associated with the objects defined in the previous section. de Paula and Nelson recommend looking for the following (de Paula & Nelson, 1991, p.3):

1) variables that are common to groups of objects (classes)
2) variables having the same value for all objects of a class
3) variables that can be calculated or derived from other variables
4) variables that can be decomposed into more elementary variables
5) variables defined for only a single class

Applying de Paula and Nelson's guidelines to the previously described classes, we determine the following: The classes REGISTER, MAR, MBR, MIR, and MPC, all share a common variable contents (guideline #1 above). However, for this application the value of contents for MPC is an integer value. Thus, the variable contents of the class MPC cannot be treated the same as the variable contents of the classes REGISTER, MAR, MBR, and MIR. Yet, the MPC class still requires a read method like the previously mentioned group of classes. The classes CONTROL STORE, MEMORY BANK, and REGISTER BANK also share the variable name contents but in this context contents refers to an array of the respective location types (i.e., MEMORY LOCATIONS for MEMORY BANK, etc.). Further observation of the class descriptions show no variables to which guidelines #2, #3, #4, or #5 may be applied.
c. Analysis of the Object’s Methods

This step looks at the methods associated with the objects defined in the previous section. The following points should be considered (de Paula & Nelson, 1991, pp. 3-4):

1) Look for methods that are common to several classes.

2) Every concrete class should have, as a minimum, a set of methods to create, delete, maintain, and display its instances.

3) In order to enforce encapsulation, it may also be necessary to define methods for accessing and updating each variable.

The following is a summary of significant observations made by applying the above design guidelines to each object’s methods: The classes REGISTER, MEMORY LOCATION, MAR, MBR, MIR have the common methods read and write. REGISTER and MEMORY LOCATION also share the method initialize. The similar classes MEMORY BANK, and REGISTER BANK share the methods initialize, load, read, and write. Also, the class CONTROL STORE shares the methods load and read with MEMORY BANK and REGISTER BANK.

2. Refinement of the Objects and Classes

a. Addition of Necessary Information

The methods BINARY READ and BINARY WRITE were added to the classes MEMORY BANK and REGISTER BANK. These classes require two types of read and write methods. Due to programming concerns it is necessary to read from and write to a storage/memory location using an integer or binary input. Therefore the BIN-read and BIN-write methods were added to these classes to allow this flexibility. The binary version of the read and write methods use the corresponding integer
version of these methods, by converting the binary address to its integer equivalent and calling the integer version.

Closer examination of the object CONTROL STORE shows that there is still a need to determine how the microprogram will be represented. Each step in a microprogram has the same type of data, which determines what control signals will be sent. The object CONTROL STORE should be made up of this data. This data format can be clearly represented by introducing a new class, MICROINSTRUCTION, which will define the various fields necessary to make up a microprogram microinstruction. Thus, CONTROL STORE will consist of many instances of MICROINSTRUCTION. This new class MICROINSTRUCTION also affects the class MIR, in that the MIR contains a single MICROINSTRUCTION.

Examination of the classes REGISTER, MEMORY LOCATION, MAR, MBR, and MIR shows that each of these classes has the instance variable contents. If one considers the meaning of contents applied to each of these classes it becomes apparent that the value of contents for an instance of REGISTER, MEMORY LOCATION, MAR, MBR, and MIR consists of a single n-bit value (representing the contents of a register), while the value of contents for an instance of CONTROL STORE, MEMORY BANK, and REGISTER BANK will consist of an array of many n-bit numbers (one for each storage location). Each one of these storage locations can be described by an instance of that class related individual storage type. This results with the instance variable contents containing an array of REGISTER, MEMORY LOCATION, or MICROINSTRUCTION for its corresponding store type.

At this point, a design decision was made to represent the instance variable contents as a list. This allows great flexibility as Prograph provides very powerful list primitives. Representing contents as a list allows the application program to
represent storage locations with variable lengths. In the case of REGISTER, MAR, MBR, MIR, and MPC, where contents represents a single binary number, contents can be represented as a list of booleans, where each boolean represents a bit of the binary number. In the case of CONTROL STORE, REGISTER BANK, and MEMORY BANK, the value of contents represents many binary numbers so contents can be represented as a list of instances of the respective location type.

b. Elimination of Redundant Information

Redundant data is simply data which is not necessary to store directly as it may always be derived from some other data. There is no redundancy in the data maintained by the various classes defined so far.

c. Determination of Class and Instance Variables

The variables in the classes discussed above have unique values for each instance of each class. This means that these variables can be represented as instance variables.

d. Identification of Composite Objects

There are no variables in the above mentioned classes that decompose into more elementary variables. Thus, there are no composite objects.

3. Organization of The Classes Into a Hierarchy

a. Analysis of the Implementation Language

The following questions should be considered (de Paula & Nelson, 1991, p.2):

1) Does the system provide single, multiple, or selective inheritance?
2) If multiple inheritance is supported, what are the conflict resolution rules?
3) Can inherited methods be redefined (overridden) in the subclasses?
4) Can inherited variables be redefined (overridden) in the subclasses?
The implementation programs supporting this thesis are implemented in Prograph, an object-oriented programming environment. Prograph supports single inheritance only, which answers question one above and makes question two not applicable. In answer to question three, Prograph allows inherited methods to be modified or redefined, allowing the superclass to keep its original definition while allowing modifications in the subclass method. Prograph also allows inherited variables to be redefined which answers question four. Therefore, the object-oriented programs for this thesis will have the following features: 1) single inheritance; 2) inherited methods can be redefined in subclasses; and 3) inherited variables can also be redefined in subclasses.

b. Construction of the Hierarchies

In section A.1.b it was determined that REGISTER, MEMORY LOCATION, MAR, MBR, MIR, and MPC have the same instance variable contents. These classes also share several methods. The classes MAR, MBR, MIR, and MPC represent specific applications of the more general class REGISTER which allows these classes to be subclasses of the class REGISTER. Since the classes REGISTER and MEMORY LOCATION share a common instance variable, and several methods, but share no common superclass, it was decided to add the abstract class STORAGE LOCATION. With the class STORAGE LOCATION defined, the methods initialize, read and write can be moved up to the STORAGE LOCATION class.

Further examination of the above class descriptions also reveals that the classes CONTROL STORE, MEMORY BANK, and REGISTER BANK share a common instance variable and many common methods, but no common superclass. Thus, the abstract class STORAGE BANK was defined as a superclass for these classes. The
methods initialize, read write BIN-read, BIN-write, and load can then be moved up to the STORAGE BANK class.

The remaining classes ALU, MICROINSTRUCTION, MUX, and SHIFTER have no commonalities with any other class, and are therefore unrelated to other classes by inheritance. Figure 3.1 presents the class hierarchy that results from the above discussion.

![Diagram of class hierarchy]

**Figure 3.1 'Generic' Class Hierarchy**

We can now present a revised list of the 'generic' computer microarchitecture class definitions:

```
Class: ALU
Superclass: none
Variables: none
Methods: and, or, not, math, zero?, positive?
```
Class: CONTROL STORE
Superclass:
Variables: contents: (array of MICROINSTRUCTIONs)
Methods: none

Class: MAR
Superclass: REGISTER
Variables: none
Methods: mar

Class: MBR
Superclass: REGISTER
Variables: none
Methods: mbr

Class: MEMORY BANK
Superclass: STORAGE LOCATION
Variables: contents: array of MEMORY LOCATIONs
Methods: none

Class: MEMORY LOCATION
Superclass: STORAGE LOCATION
Variables: none
Methods: none

Class: MICROINSTRUCTION
Superclass: none
Variables: instruction (string of bits)
Methods: none

Class: MIR
Superclass: REGISTER
Variables: none
Methods: decode

Class: MPC
Superclass: REGISTER
Variables: none
Methods: set, increment, jump

Class: MUX
Superclass: none
Variables: none
Methods: mux

Class: REGISTER
Superclass: STORAGE LOCATION
Variables: none
Methods: none

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c. Review of the classes' variables/methods

The constructed class hierarchy does not introduce any unnecessary variables or methods in any class. We believe that it provides the basis for an accurate model of the real world situation.

B. IMPLEMENTATION OF TANENBAUM'S MICROARCHITECTURE

With the class hierarchy of a general microarchitecture designed, it is now relatively easy to implement the design for a specific microarchitecture. A simple microarchitecture presented by Tanenbaum (Tanenbaum, 1984, pp. 126-149) can be modeled using the classes presented in section A.3.b. A complete block diagram of his microarchitecture design is reproduced in Figure 3.2 below:
1. Operation of the Tanenbaum Microarchitecture

This section is a summary of the design and operation of Tanenbaum's example microarchitecture; for more detail on this design refer to (Tanenbaum, 1984, pp. 126-149). This microarchitecture design is divided into two main subsections; the datapath and the control path. The left side of Figure 3.2 is the data path and the right side is the control path. The data path side of this design consists of a 16 location register bank, AMUX,
ALU, SHIFTER, MAR, MBR, and memory. The bus width of the datapath is 16 bits, all registers and memory locations are also 16 bits. Some of the register locations are for general use and others are for specific use; a summary of the purpose of the various register locations is summarized in Figure 3.3.

<table>
<thead>
<tr>
<th>Location</th>
<th>Purpose</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>Program Counter</td>
<td>PC</td>
</tr>
<tr>
<td>01</td>
<td>Accumulator</td>
<td>AC</td>
</tr>
<tr>
<td>02</td>
<td>Stack Pointer</td>
<td>SP</td>
</tr>
<tr>
<td>03</td>
<td>Instruction Register</td>
<td>IR</td>
</tr>
<tr>
<td>04</td>
<td>Temporary Instruction Register</td>
<td>TIR</td>
</tr>
<tr>
<td>05</td>
<td>Zero</td>
<td>0</td>
</tr>
<tr>
<td>06</td>
<td>+1</td>
<td>1</td>
</tr>
<tr>
<td>07</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>08</td>
<td>AMASK (address mask)</td>
<td>0FFF (hex)</td>
</tr>
<tr>
<td>09</td>
<td>SMASK (stack mask)</td>
<td>00FF (hex)</td>
</tr>
<tr>
<td>10-15</td>
<td>General Purpose Registers</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.3 Microarchitecture Register Uses

Two of the registers can be read simultaneously and placed on the A and B buses. The A bus signal is fed into the AMUX along with a signal from the MBR. Depending on the control signal (0-A bus, 1-MBR) to the AMUX (a simple two input multiplexer), one of the two inputs will be passed on to the left input of the ALU. The value on the B bus is fed directly into the right input of the ALU. The value on the B bus is also routed to the input of the MAR, if the control signal to the MAR is TRUE the value of the B bus will be read into the MAR.

Two control signals, F₀ and F₁, cause the ALU to perform one of the following operations: A+B, A AND B, A, ¬A (where A and B represent the data on the respective buses). The ALU generates one data output and two control outputs. The data output feeds to the input of the shifter. The two control output signals are Z (true if data result is
zero) and $N$ (true if the data result is negative). These two signals feed into the microsequencing logic.

The shifter shifts the input data one bit to the left or right, or it can pass the data through to the C bus without alteration. The shifter has two control signals as input, $S_0$, and $S_1$. The output of the shifter is placed on the C bus and can be fed to the register bank and the MBR. The value of the C bus will be loaded into the desired location in the register bank if the ENC control is TRUE. The value of the C bus will be loaded into the MBR if the MBR signal is also TRUE.

The MAR and MBR in this design can be considered to be the interface between the memory and the CPU. When the MBR receives a READ signal of TRUE it will read the contents of the memory location pointed to by the MAR and place that location’s value into the MBR. When the MBR receives a WRITE signal of TRUE it will place the contents of the MBR into the memory location pointed to by the value of the MAR. As discussed in the introduction, the access speed of memory is usually slower than the access speed of the CPU’s registers. In this design it takes two complete machine cycles to read from or write to memory. This means that register access is twice as fast as memory access.

This architecture uses a microcoded program to control its components. The microprogram is stored in the Control Store. At the beginning of each clock cycle, the contents of a location (pointed to by the MPC) of the control store is loaded into the MIR. The MIR is divided into various fields, each field holding a control signal for a specific component. These control signals are routed to the various hardware components in the microarchitecture. As soon as the desired microinstruction is loaded into the MIR, the signals are routed to these components for the entire clock cycle. The status of the microprogram is maintained by the MPC. After the MPC is read its value is incremented and the result is presented to the Mmux. Two of the fields of the microinstruction are the
ADDR and the COND fields. The value of the ADDR field is presented to the input of the Mmux. The Mmux chooses between the ADDR and increment inputs for an output. The selection depends on the output of the micro sequencing logic (based on the outputs of N and Z) and the value of the COND read from the MIR. The COND code is summarized in Figure 3.4 (Tanenbaum, 1984, p.134):

<table>
<thead>
<tr>
<th>COND Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Do not jump; next microinstruction is taken from MPC + 1</td>
</tr>
<tr>
<td>1</td>
<td>Jump to ADDR if N = 1</td>
</tr>
<tr>
<td>2</td>
<td>Jump to ADDR if Z = 1</td>
</tr>
<tr>
<td>3</td>
<td>Jump to ADDR unconditionally</td>
</tr>
</tbody>
</table>

**Figure 3.4 COND Code Definitions**

This result determines if the next microinstruction executed will be the next instruction in the control program’s sequence or a jump to some other portion in the microprogram.

Each clock cycle is divided up into four subcycles. The following events occur during these subcycles (Tanenbaum, 1984, p.131):

1. Load the next microinstruction into the MIR, send control signals to various components.
2. Gate registers onto the A and B buses, increment the MPC.
3. Allow ALU and shifter time to produce stable outputs and load MAR if required.
4. Store the C bus into the desired register location if desired and load the MBR if required.

2. Design of The Class Hierarchy

The design of a class hierarchy to implement a simulation program for Tanenbaum’s microarchitecture begins with the general microarchitecture classes outlined in section A.3.b. and building from them into a full Macintosh application. Appendix C contains the complete Prograph source code listing for the simulation of Tanenbaum’s
A design decision was made to allow the microarchitecture to simulate memories and registers with a variable bit width. This allows for quicker test runs and also allows the simulator to model memories of various sizes.

a. Review and Modification of the General Class Hierarchy

No modifications (from section A.3.b) are required to the following classes: ALU, MAR, MBR, MIR, MUX, MEMORY LOCATION, MICROINSTRUCTION, REGISTER, REGISTER BANK, SHIFTER, STORAGE BANK, and STORAGE LOCATION. The following classes were modified (The revised 'generic' class descriptions are located in Appendix A):

**Class: CONTROL STORE**
Modification: Added a load method that invokes the inherited load method from storage bank to assign appropriate variable values.

**Class: MEMORY BANK**
Modification: 1) Added a load method that invokes the inherited load method from storage bank to assign appropriate variable values. 2) Overshadowed inherited methods read and write (from STORAGE BANK) to support read/write using MAR/MBR interaction with the memory.

**Class: REGISTER BANK**
Modification: Added a load method that invokes the inherited load method from storage bank to assign appropriate variable values.

**Class: MPC**
Modification: 1) Added instance variables cycles & counter for simulation support. 2) Added methods set cycles and get counter. Set cycles is used to set the cycle counter to zero and store the desired number of clock cycles in an instance of MPC. The method get counter, passes the counter value of an instance of MPC to its calling method.

**Class: MICRO SEQUENCER**
Superclass: none
Variables: none
Methods: generate signal
Description: Simulates the micro sequencer component of Tanenbaum's architecture. The method generate signal sends a signal to the mux for controlling logic and addressing of the MPC.

The source code listing in Appendix C also includes several other classes that have not been discussed thus far. These classes include: System, Application, Menu, Menu Item, Window, sim and Time. The time class is supplied in a class library provided by TGS systems (The TGS systems bulletin board). This class is used to convert system time to strings for I/O purposes. The 'About Micro Simulator' menu item displays a dialog box that gives program credits and the date and time. The sim class is a class added to the hierarchy (inheriting variables/methods from the class Window) which contains methods that implement input/output for simulation purposes. The other classes are all System classes supplied with the Prograph interpreter/compiler (TGS Systems, 1990, p.109). These classes must be included with any application; they include the attributes and methods necessary to handle menus, windows, and event control for stand alone applications.

3. Design of the Micro Simulator

a. The user interface

The Micro Simulator was designed to be a stand alone Macintosh application. This means that the user interface consists of a menu bar for controlling the program and windows and dialog boxes for facilitating input/output. The Menu Bar is shown in Figure 3.5.
Referring to Figure 3.5, the first menu item under the File menu is Load Memory. This selection is used to load a text file that represents the initial memory map into the memory bank. A sample program that can be loaded into memory using the Load Memory selection is presented in Figure 3.6.

<table>
<thead>
<tr>
<th>#</th>
<th>Opcode</th>
<th>Macro Instr</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>01111000000000100</td>
<td>LOCO 4</td>
<td>Loads the constant 4 into the AC</td>
</tr>
<tr>
<td>01</td>
<td>1111010000000000</td>
<td>PUSH</td>
<td>Push the contents of the AC onto the stack</td>
</tr>
<tr>
<td>02</td>
<td>0011000000001100</td>
<td>SUBD MEM[12]</td>
<td>Subtract memory loc #12 contents from AC</td>
</tr>
<tr>
<td>03</td>
<td>0101000000000101</td>
<td>JZER 5</td>
<td>if AC = 0 then PC := 0</td>
</tr>
<tr>
<td>04</td>
<td>0110000000000001</td>
<td>JUMP 1</td>
<td>Set PC := 1</td>
</tr>
<tr>
<td>05</td>
<td>01100000000000101</td>
<td>JUMP 5</td>
<td>Stay running idle</td>
</tr>
<tr>
<td>06</td>
<td>0000000000000000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>07</td>
<td>0000000000000000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>08</td>
<td>0000000000000000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>09</td>
<td>0000000000000000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0000000000000000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>0000000000000001</td>
<td>Constant 1</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>0000000000000001</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.6 Sample Object Program Text Format

This is a simple program that loads the constant 4 into the accumulator and then pushes copies of it five times on top of the stack. The numbers preceding the dash are the desired memory location. The numbers following the dash are the instruction opcodes or memory values. These are the actual values loaded into the memory. Any characters
following the opcodes are considered comments and are not loaded. The first column following the opcode is a macro description of the preceding opcode. The column following the macro description contains general comments. The text file has to be as long as the program requires, if the program contains 13 instructions then the text file must contain 13 lines. Notice that locations six through 11 have no values; that is because they are used as place holders for an actual constant value at location 12. If these place holders were not used the constant that should have been loaded at location twelve would instead be loaded at location 6.

Referring once again to the File menu of Figure 3.5, the Load Registers selection operates exactly the same as the Load Memory selection, except that the data is directed to the Register bank. The Load Control Store selection similarly loads a text file into the Control Store. The Quit selection is used to quit the Micro Simulator application.

The Edit menu selection of Figure 3.3 is a standard Macintosh menu bar selection and must be present for all Macintosh applications. For more information on this selection, refer to Inside Macintosh Volume I (Apple Computer, 1985, p.58).

The Controls menu of Figure 3.4 is the menu which implements the features of the Micro Simulator. The Define Memory selection is used to initialize the simulator’s register and memory configuration. This selection causes a dialog box to be displayed as shown in Figure 3.7. The first three entries are self explanatory. They determine the width, in bits, of the memory/registers and the respective number of locations for each. MAR size determines the desired bit width of the MAR. This allows the simulation to limit the address space allowed for the memory interface.
Referring once again to the Controls menu of Figure 3.4, the Alter Register command displays a dialog box which allows the user to input a desired register location (by number) and the new value to load into that register from the keyboard. Cycle causes the simulator to execute one microinstruction. Single Instruction causes the simulator to execute one macro instruction. The Multiple Instructions command displays a simple dialog box that requests the desired number of macro instructions to be executed; this causes the simulator to execute that number of macroinstructions. The Set MPC command displays a dialog box which allows the user to set the MPC. The Run # of Cycles command displays a dialog box asking for the desired number of clock cycles to be executed, then executes the desired number of clock cycles and stops.

Status of the simulator is displayed in a window (Micro Simulator) which includes a diagram of the data side of the microarchitecture along with the values of the various components. A reduced copy of the Micro Simulator window is presented in Figure 3.8. Any values displayed are for the last microinstruction executed.
Figure 3.8 The Micro Simulator Window

The various check boxes (ENC, MBR, MAR, etc.) represent control signals sent from the last microinstruction. An activated box ('x' inscribed in the box) indicates that the corresponding control signal is true, and an unactivated box indicates a control signal of false.

The rectangles containing text display the contents of the respective object. The boxes labeled A bus and B bus indicate the values of the respective buses. The smaller boxes above those values indicate what register locations (by binary number) were loaded on the respective buses. There are also text boxes to indicate the contents of: MAR, MBR, and C bus storage location. The text boxes associated with the ALU, AMUX, and Shifter indicate the outputs of those devices. The boxes under MPC Last and Next indicate the number of the previous microinstruction executed and the number of the next
microinstruction to execute. The Counter text box indicates how many clock cycles since the last time MPC was set. The text box below the Counter box presents the mnemonic of the last complete macro instruction executed. Two scroll boxes are used to display the contents of the memory and register banks.

b. Micro Simulator Program Structure

The dataflow nature of Prograph allows for the Micro Simulator program structure to be relatively simple. As stated in section B.1, each clock cycle is divided into four subcycles. A universal method Cycle is a method that contains four local operators that each contain their respective subcycle. Figure 3.9 presents the logical dataflow modeled by the Prograph source code. This code simply gets the Micro Simulator window and then executes each subcycle sequentially. The dataflow implementation automatically forces each subcycle (like a precedence graph) to run to completion before the next subcycle can execute. Several universal methods are provided to drive the Cycle method for the following: one complete cycle, several cycles, and to completion of a single macro instruction.
Program state in the Micro Simulator is maintained by using Prograph persistents. These persistents are presented in Figure 3.10. These persistents are initially loaded during the execution of the initial universal method, and get updated during various stages of subcycle execution.
C. IMPLEMENTATION OF A SIMPLE COMPUTER (ASC)

Tanenbaum’s microarchitecture was easily implemented with few modifications using the ‘generic’ class design presented in section A.3.b of this chapter. The best way to fully test this class design was to implement an architecture of a significantly different design. This section introduces another architecture called “A Simple Computer” (ASC) which is presented by Shiva (Shiva, 1991, pp. 220-273). A brief description of the design and operation of the ASC and the implementation of its simulator using the ‘generic’ classes refined in section B (revised description of ‘generic’ classes are located in Appendix A) is now presented.

1 Operation of the ASC Microarchitecture

A simplified block diagram of the ASC is presented in Figure 3.11. Like Tanenbaum’s microarchitecture, the ASC has a datapath side and a control path side. The datapath side consists of three buses, various registers, memory bank (including
MAR/MBR), index register bank, constant registers (1 and -1 hard wired) and alu. All components on the datapath side of the ASC are sixteen bits wide, and numbers are represented using two’s complement arithmetic. BUS1 and BUS2 direct data from the various registers into the ALU. BUS3 directs data from the output of the ALU back to the various registers.

Figure 3.11 ASC Microarchitecture Block Diagram (Shiva, 1991, p.229)

Each register (other than the Index Registers) is a unique single entity. This means that all the appropriate control signals are routed to each of these devices separately (write to BUS1/2, read from BUS3). It should also be noted that not all registers can write to both BUS1 and BUS2. The design of the microprogram ensures that only one register

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at a time writes to each bus. BUS1 and BUS2 also have the sixteen bit constant values ‘1’, while BUS1 also has the sixteen bit constant value ‘-1’. These ‘values’ act like registers with read only capability.

The ALU receives six signals from the microcontrol unit and receives sixteen bit data from BUS1 and BUS2. Only one control signal can be applied at a time. These control signals control the following functionality to the ALU:

1) **ADD**, add the values on BUS1 and BUS2 and place the results on BUS3.

2) **COMP**, take the two’s complement of BUS1 and output the results to BUS3.

3) **SHR**, shift the value of BUS1 one bit to the right, with the high order bit replacing the low order bit, and output the results to BUS3.

4) **SHL**, shift the value of bus1 one bit to the left, replacing the low order bit with zero, and output the results to BUS3.

5) **TRA1**, directs the value of BUS1 to BUS3.

6) **TRA2**, directs the value of BUS2 to BUS3.

Notice that in the ASC design the shifter functionality is included within the ALU. The ALU also updates the value of the PSR (Processor Status Register). The PSR consists of 4 bits, C, N, Z, and O; these values stand for carry, negative, zero, and overflow respectfully. The ALU updates the PSR only when the accumulator register is written to. The overflow bit is set when the sum operation results in a number larger than $2^{15}-1$. The negative bit is set when the result of an ALU operation is negative. The zero bit is set when the result of an ALU operation is zero. The carry bit is set when a carry out from the high order bit results from an addition operation.

The MAR and MBR registers are used as an interface between the memory and the CPU. When the MBR receives a READ signal it reads the contents of the memory pointed to by the MAR and place that location’s value into the MBR. When the MBR receives a WRITE signal it will place the contents of the MBR in the location of memory.
pointed to by the value of the MAR. In this design it takes two complete machine cycles to read from or write to memory (i.e., register access is twice as fast as memory access).

The ASC design supports four types of addressing; direct, indexed, indirect, and indexed-indirect addressing (preindexed-indirect). The addressing modes are directly controlled by fields of the ASC's macroinstruction. The ASC's microarchitecture design relies specifically on this macroinstruction format. As mentioned above, all instructions used by ASC are sixteen bits wide. The ASC's instruction format is divided up into various fields as presented in Figure 3.12.

![Figure 3.12 ASC Instruction Format](image)

This implementation of the ASC supports 16 macroinstructions, thus four bits in the macroinstruction is needed to describe the opcode (bits 12-15). Bit 11, the opcode extension bit, can be used to increase the number of opcodes to 32. Bit 10, the indirect flag, is set when indirect addressing is used. The two bit index flag (bits 8 & 9) has two purposes: when the flag is set to '00', the index flag indicates that indexed addressing mode is not in use; when the flag is set to the values '01' through '11', it indicates that indexed addressing is in use with the corresponding index register. The eight bit address field (bits 0-7) is used for direct addressing, or combined with the other addressing modes.

For a complete description of the actual instruction set refer to (Shiva, 1991, p.193).

The control side of the ASC microarchitecture consists of a Microcontrol unit, MPC, MIR, Decoder, and a Control Store. This configuration is presented in Figure 3.13.
The MPC points to the next line of the microprogram to fetch (from the control store). A microinstruction is 21 bits wide and can be in one of two different formats. The formats are distinguished by the high order bit. If the high order bit is zero, it is a type zero microinstruction. If the high order bit is 1 the instruction is a type one instruction. A type zero instruction actively sends control signals to the various components of the microarchitecture; each bit represents a control signal. A type one microinstruction uses input status signals to alter program flow of the microprogram. Therefore, a type one microinstruction will cause the MPC to be set to some address other than the next instruction in the control store. For a more detailed description of the microinstruction formats and control signal outputs see (Shiva, 1991, pp. 267-268).

![Figure 3.13 Block Diagram of ASC Microcontrol Hardware](image)

The Microcontrol unit receives status signals from the PSR, instruction register (IR) and index registers. Based on the status signals and the type of the microinstruction,
the microcontrol unit will either load a new address into the MPC and load a new microinstruction into the MIR, or it will take the present contents of the MIR and decode it into control signals, increment the MPC, and repeat the process.

2. Design of The Class Hierarchy

The design of a class hierarchy to implement a simulation program for the ASC microarchitecture also begins with the 'generic' microarchitecture classes presented in Appendix A and building from them into a full Macintosh application. Appendix D contains the Prograph source code listing for the simulation of the ASC microarchitecture.

a. Review and Modification of the General Class Hierarchy

This section reviews each class defined in Appendix A ('generic' classes) and describes the modifications necessary to implement these classes in the ASC design.

No modifications (from Appendix A) were required to the following classes: CONTROL STORE, MAR, MBR, MPC, MEMORY LOCATION, MEMORY BANK, REGISTER, REGISTER BANK, SHIFTER, STORAGE BANK, and STORAGE LOCATION. The classes MUX and MICROINSTRUCTION were not used. MUX was not used because the ASC design contains no mux's. The MICROINSTRUCTION class was not used because simple instances of register were used to hold microinstructions. The ALU class includes message passing to the shifter class in its math method. This enables shifter functionality in the ALU in accordance with the ASC microarchitecture design. The following classes were modified or added:

Class: ALU (modified)
modification:
1) Added the method overflow to determine if the output of the ALU is causing an overflow condition.
2) Modified the method math to account for the ASC specific functionality (actual operations) including the updating of the PSR.
Class: MICRO CONTROL (added)
Superclass: none
Variables: none
Methods: mcu, read control store, Bus1 Data, Bus2 Data, Bus3 Signals, ALU Signals, Memory Signals.
Description: Contains methods to read microinstructions, generate control signals, and branch microprogram control flow.

Class: MIR (modified)
modification: Added the methods decode 0, and decode 1 to decode the type zero and one microinstructions.

Class: INDEX BANK (added)
Superclass: STORAGE BANK
Variables: none
Methods: zero index
Description: Describes the data structure and methods necessary for implementing an index bank for the ASC. The zero index method generates a signal to determine if the contents of an index register is zero.

Class: IR (added)
Superclass: REGISTER
Variables: none
Methods: parse
Description: The parse method separates the contents of the instruction register into the various fields.

Class: PSR (added)
Superclass: REGISTER
Variables: none
Methods: decode
Description: Contains an instance variable that maintains the value of a status register. Includes a method to decode its contents for use in the microcontrol unit.

The source code listing in Appendix D also includes the various system classes supplied by prograph and the class sim, as discussed in Section B.2.a.
3. Design of the ASC Simulator

a. The user interface

The ASC simulator, like the Tanenbaum simulator, was implemented using Prograph on the Macintosh microcomputer. This section discusses the general design of the ASC simulator and its user interface.

Figure 3.14 presents the menu bar for the ASC simulator. The ASC simulator application menu bar and most of its controls have the same functionality as the Tanenbaum micro simulator menu bar. Since the ASC does not use a general purpose register bank, the Alter Register menu selection under the Controls menu was removed. This menu selection allows the user to enter a value from the keyboard by entering the register number and its new value. The Register menu was added to the menu bar to enable keyboard entry changes for the program counter (Update PC).

<table>
<thead>
<tr>
<th>File</th>
<th>Edit</th>
<th>Controls</th>
<th>Register</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load Memory</td>
<td>Define Memory</td>
<td>Cycle</td>
<td>Update PC</td>
</tr>
<tr>
<td>Load Registers</td>
<td>Single Instruction</td>
<td>Multiple Instructions</td>
<td></td>
</tr>
<tr>
<td>Load Control Store</td>
<td>Set MPC</td>
<td>Run # of Cycles</td>
<td></td>
</tr>
<tr>
<td>Quit</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.14 ASC Simulator's Menu Bar

The File menu is exactly the same as the Tanenbaum Micro Simulator, and its selections provide the same functionality. The required data format for the input text files is also the same. The Edit menu selection contains the standard Macintosh editing features.

The Define Memory function was changed because the ASC simulator was designed to operate with a fixed memory/register bus width of 16 bits. Also, since the
ASC uses individual registers, there is no need to specify the required number of registers in the register bank. This selection still initializes the memory bank to the desired number of memories. This resulted in a Define Memory Dialog Box with one input, 'Enter Desired Number of Memories:'. This dialog box is presented in Figure 3.15. All other menu selections have the same functionality as the Tanenbaum micro simulator.

![Define Memories Dialog Box](image)

**Figure 3.15** The Define Memory Dialog Box (ASC)

Status of the simulator is displayed in a Window (Micro Simulator) which includes a diagram of the data side of the microarchitecture along with the values of the various components. A reduced copy of this window is presented in Figure 3.16. The values in the various boxes indicate the value of the respective components after each microinstruction is executed. Several new items were added: MIR, Index Bank, CNZV (PSR), and the constant values (1 and -1). The CNZV output gives the status of the PSR, while the constant values are placed on the associated input buses by the microcontrol unit. The MIR box gives the bit string of the last microinstruction executed.
b. **ASC Simulator Program Structure**

The ASC simulator’s main program uses the universal method Cycle (as in the Tanenbaum simulator), but the ASC’s design does not use subcycles. The Cycle universal method is the main program and brings together all the various classes’ methods to work as a complete simulator. The other universal methods used in the Tanenbaum simulator were also integrated seamlessly in the ASC simulator (generic conversions between bit strings and boolean strings, etc). Program state is maintained by using Prograph persistents (see Appendix D).
D. COMPARISON OF THE TWO SIMULATORS

Both architectures possess many similarities. Their designs have a classic layout that consists of a data path and a control path. The data path side consists of some type of register configuration (including a program counter, instruction register, and accumulator), memory with a MBR/MAR interface, buses, and a two bus input ALU. The data path side for these architectures is 16 bits wide. On the control side, both architectures have a control store, MPC, and MIR. Both architectures use a microprogram to control their various components for the execution of macroinstructions. Since they both use a microprogram, their macro level instruction set can be expanded or changed by altering their respective microprograms. With respect to the implementation of the simulators, both designs use the same format for textfile input of the macroprogram to the memory. Both simulators allow altering the microprogram by loading the control store with a textfile representing the microprogram.

Although the Tanenbaum and ASC designs are very similar, there are also some differences in their designs. One major difference between the Tanenbaum design and the ASC design is the layout of the registers. With the ASC, each register (other than the Index Registers) is a unique single entity. This means that all the appropriate control signals are routed to each of these devices separately (write to BUS1/2, read from BUS3). The Tanenbaum design uses a bank of registers which allows two registers at a time to send their values to the A and B Buses and one register to receive the contents of the C Bus. The registers are selected by sending the appropriate register numbers to the register bank. Thus, the ASC design requires many more control signals to manipulate the registers. In the ASC design not all registers can write to both BUS1 and BUS2, while the Tanenbaum design allows the same operations for all registers. The design of the microprogram ensures that only one register at a time writes to each bus. The
implementation of ASC requires individually initializing each of the separate registers, where the Tanenbaum simulator simply initializes the entire register bank with one operation. In the ASC design, BUS1 and BUS2 also have the sixteen bit constant values ‘1’, while bus 1 also has the sixteen bit constant value ‘-1’. These ‘values’ act like registers with read only capability. The ASC design uses an index register bank to support indexed addressing. The functionality of the index bank is similar to the Tanenbaum register bank. This required the addition of the index bank class in the ASC simulator. This class was added to support the additional functions of indexed addressing.

While both designs support direct addressing, other addressing modes are not shared by the two microarchitectures. The Tanenbaum design supports immediate addressing and includes a stack, along with stack operations such as push and pop. Immediate addressing is supported completely through the microprogram. The implementation of the stack does not require any special simulator features except a register reserved for a stack pointer (which is a general register in the Tanenbaum design) and the appropriate microprogram support.

The ASC design supports direct, indirect, indexed addressing, and indexed-indirect addressing. Direct addressing is similar to the Tanenbaum design. Indirect, and indexed addressing is supported by adding the method parse to the new class IR (Instruction Register). The parse method decodes special fields that direct the Microcontrol unit to use indirect, direct, or indexed-indirect addressing.

The microinstruction format of the two designs differs of course, but how the formats are used is also different. In the Tanenbaum design, all microinstructions are of the same type; a microinstruction is decoded and the various control signals are sent to all the components. Part of the microinstruction field contains a conditional that, based on the microsequencer output, will cause the Mmux to branch the microprogram or go to the next
microinstruction. In the ASC design, there are two types of microinstructions: a type zero microinstruction, which sends control signals to the various components; and a type one microinstruction, which controls branching of the microprogram. This difference in the microinstruction format required various additions/alterations to the ‘generic’ classes. The MIR class was modified to support the decoding of the two types of microinstructions. The class MICRO CONTROL was added (in lieu of the MICRO SEQUENCER class which was removed from the Tannenbaum simulator) to support the microcontroller functionality specific to the ASC design. This type of change would be required when switching between any different architectures. In the ASC design the Micro Control unit makes all decisions involving branching; this eliminates the need for a Mmux as found in the Tanenbaum design.

The execution of macroinstructions also differs between the two designs. The Tanenbaum design loads the macroinstruction into an instruction register. As the microprogram progresses, the macroinstruction is shifted to the left. The microprogram branches to different locations based on the value of the most significant bit of the macroinstruction. This means that, depending on the size of the opcode of the macroinstruction, the microprogram can branch for up to 8 cycles to parse the macroinstruction (the largest opcode is 8 bits). The decoding of an ASC macroinstruction is a much shorter process. The macroinstruction is fetched, and placed in the instruction register. The opcode of the macroinstruction matches the address of the microcode required to execute the macroinstruction. This results in a slightly larger microprogram, but fewer cycles are needed for each macroinstruction. These differences are accounted for in the respective simulators by microcode and their respective objects (MICRO SEQUENCER in Tanenbaum, and MICRO CONTROLLER in ASC).
The Tanenbaum design sends three signals to the micro sequencer: N (ALU output is negative); Z (ALU output is zero); and COND (microprogram branching conditions based on N and Z). The ASC design is slightly more complicated. It maintains a PSR (Processor Status Register) that has several bits (C, N, Z, and O as discussed in section C.1) representing the status of the number in the accumulator. There are more inputs to the micro controller, PSR, IR, and Index Registers contents. These differences are supported in the respective classes MICRO SEQUENCER and MICRO CONTROLLER. Also, the classes, IR, and PSR with associated methods were added to the class hierarchy for the ASC simulator.

The two designs have different ALU functionality in that they have different inputs and operations. The Tanenbaum design has two different components, an ALU and a Shifter. The ASC combines the functionality of these two components into the ALU. The method overflow was added to the class ALU and the math method was altered to provide the required functionality for the ASC design. In the ASC design, messages (from within the ALU methods) are sent to the shifter object to give the effect of the shifter residing inside the ALU.

Both designs have several small variations in some of the objects as discussed above. The various objects are brought together to form a complete simulator via the main program. Since these simulators differ, the main programs differ. The main programs for both simulators are called 'cycle' and are implemented as universal methods (in Prograph). The user interfaces differ in appearance (because the buses and components differ), but the approach for the construction of the user interfaces are exactly the same. Their menu bars and dialog boxes are almost the same; this allowed a great deal of code to be reused. These two simulators were designed by first considering the Tanenbaum design, making 'generic' classes, and then producing the Tanenbaum simulator. The ASC simulator was designed
by taking the 'generic' classes previously derived and applying the changes necessary to
give ASC functionality. This process could have easily been reversed with very little
impact on the final result.

E. SUMMARY

A 'generic' class hierarchy was designed for the application of simulating a general
purpose computer microarchitecture. A simple computer microarchitecture (Tanenbaum's)
was introduced in which a simulator was designed and built using this 'generic' class
hierarchy. Few modifications/additions were required in building the Tanenbaum simulator
from the 'generic' classes. To further test the 'generic' class design, a second computer
microarchitecture was introduced (Shiva's) in which a simulator was designed and built
using the refined 'generic' class hierarchy arrived at when designing the Tanenbaum
simulator. Once again it was discovered that few modifications were required in the refined
class hierarchy when extending its use in another simulator.
IV. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

A. SUMMARY

Chapter I developed the need for simulation of computer architectures at various levels. It introduced the notion that architecture simulation could be more easily implemented using object-oriented design and programming. The chapter further developed object-oriented concepts by giving basic definitions and terminology. Basic microarchitecture components and operation were then described using an example microarchitecture. Finally, Prograph, an object-oriented, visual, data-flow language was introduced, along with a basic description of its syntax and use applied to object-oriented programming.

Research areas related to this thesis were discussed in Chapter II. These areas included: architecture simulation for educational purposes, class hierarchy design for simulation of multimicrocomputers, object-oriented approach to VLSI routing, object-oriented approach to interactive user interface for microprogram simulators, and work being done using object-based languages such as Ada. Several of these papers pointed out that the design of the class hierarchy is a crucial portion of the design of any simulator. There is a definite interest in the areas of classroom instructional simulators using object-oriented programming languages with reusable software components and an easy to use user interface. As of yet, however, there is no work encapsulating all of these concepts simultaneously. This provided the motivation for this research.

Chapter III showed how an existing object-oriented design methodology was used in designing a 'generic' class hierarchy to implement the components of the basic computer
microarchitecture introduced in Chapter I. Tanenbaum’s microarchitecture design and operation was then introduced. The ‘generic’ classes were used in the development of a microarchitecture simulator using Tanenbaum’s microarchitecture. It was found that very little modification to the existing ‘generic’ class hierarchy was required in implementing the Tanenbaum simulator. The design and operation of Shiva’s ASC microarchitecture was also introduced. A simulator for this microarchitecture was implemented to further test the usefulness of the ‘generic’ microarchitecture class hierarchy. Once again, only a few modifications to the ‘generic’ class hierarchy were required to implement this simulator. The design and implementation of the two simulators, including the user interfaces, were also discussed.

B. CONCLUSIONS

Object-oriented programming provides a natural environment for modeling and simulation problems. This is because the implementation details are hidden, allowing objects to reflect the real-world environment. A careful class hierarchy design is, however, essential to the development of any object-oriented program.

‘Generic’ classes can be created to simulate the various objects found as components in most computer microarchitectures. Careful design of these component objects allows the reuse of the code for many different simulators. This was demonstrated through the development of simulators for two different microarchitectures. In implementing the two simulators, it was still necessary to write a ‘main’ program that puts the various ‘generic’ objects together to form a complete simulator.

It was also found that components like ALU’s, which are peculiar to each architecture, require complete remodeling; there was very little code reusability. Parts of an ALU model can be reused, like adders, but the control signals are normally different enough to warrant a complete redesign.
Each simulator required slightly different user interfaces; however, these user interfaces had almost identical menus and functionality. They only had a different depiction of the buswork and components.

The microarchitecture simulators were implemented in Prograph, a visual, object-oriented, data flow language operating on the Macintosh. It was found that although there was an initial learning curve (to adapt to the uncustomed nature of the pictorial syntax), Prograph made the implementation of the class hierarchy for the simulators relatively easy. Prograph's application builder (used to generate user interfaces) allowed rapid development of the user interfaces. Another advantage to Prograph is that it is relatively inexpensive and readily available.

Shiva's ASC microarchitecture simulator was demonstrated to an introductory computer organization class studying the ASC microarchitecture. The class found the simulator to be quite helpful in learning the concepts of the architecture as they could trace through complex microinstructions in a short period of time without having to keep track of all of the parameters.

C. RECOMMENDATIONS FOR FUTURE RESEARCH

There are several areas of research that logically follow from this work. As is often the case in research, more questions were raised than answered. With a basic 'generic' class hierarchy designed, it is possible to pursue experimenting with 'families' of architectures. The object-oriented approach should prove to be ideal for this too in that one should be able to implement the 'lowest' member of a family (such as the 68000 microprocessor in the series of 680x0 microprocessors) and inherit the features of that architecture as one moves to other more advanced members of the same family.

Even though this research was performed using Prograph, which was found to be an excellent language for the development of these systems, it should also be very interesting
to investigate other object-oriented (or object-based) languages for implementing microarchitecture simulators and comparing the development effort with the results of this thesis.

The simulators in this thesis used text files representing the object code of the macroprograms and microprograms. The micro/macroprograms were assembled by hand and represented in the text file using ones and zeros. The usefulness of the simulators can be increased by developing micro/macro assemblers which would generate text files compatible with the simulators developed in this thesis. It should be possible to use object-oriented techniques to develop 'generic' classes which model various assemblers for different simulators.

Although these simulators were very useful for classroom instruction, simulators are most often used in designing actual systems. For a simulator to be useful, it is necessary to build into the components some automatic monitoring functions. An example would be a counter that determines how many times memory is accessed for each macro level instruction execution. One could also include in each object a facility to maintain an 'execution history' that would record the usage of components and the frequency of each component's use.

As previously mentioned, a new ALU class had to be designed and coded for each microarchitecture implementation. Research into designing a 'generic' class hierarchy in support of ALU design would be another area of challenging research. This would require the specification of control signal inputs, functions based on control signals, and status outputs. All vary greatly among different ALU's.

With growing interest in multiprocessors, it would be logical to pursue multiprocessor simulators. This would require investigating timing effects of all operations.
involving each component. After obtaining timing information, new data structures will have to be introduced to account for timing constraints.

Finally, the development cycle when using the simulator to design a microprogram could be shortened by integrating a microprogram editor with the simulator. Presently the programmer is required to write the microprogram, load it into the simulator, and then run the simulator. The user then has to evaluate any required changes, stop the simulator, edit the microprogram text file and repeat the process. This could be simplified if the simulator were integrated with a microprogram editor.
APPENDIX A

This Appendix contains the revised ‘generic’ classes derived when implementing the Tanenbaum design microarchitecture simulator.

Class: ALU
Superclass: none
Variables: none
Methods: and, or, not, math, zero?, positive?
Description: Represents a combinational circuit; thus, it has no state. Methods are provided that perform logical operations on a stream of input data.

Class: CONTROL STORE
Superclass:
Variables: contents: (array of MICROINSTRUCTIONs)
Methods: load
Description: Holds the entire microprogram. It must be loaded with the microprogram prior to any simulation execution.

Class: MAR
Superclass: REGISTER
Variables: none
Methods: mar
Description: Contains an address of a MEMORY LOCATION within a MEMORY BANK. The method mar accepts a control signal which determines if a value is to be stored into the MAR.

Class: MBR
Superclass: REGISTER
Variables: none
Methods: mbr
Description: Models the data interface to the memory bank. The method mbr accepts a control signal which determines if the data input will be written to the MBR.

Class: MEMORY BANK
Superclass: STORAGE LOCATION
Variables: contents: array of MEMORY LOCATIONs
Methods: load, read, write
Description: A read or write to a MEMORY BANK implies a read or write to a specific MEMORY LOCATION contained in the MEMORY BANK. The
method load is used to load a user program or data into the MEMORY BANK.

Class: MEMORY LOCATION
Superclass: STORAGE LOCATION
Variables: none
Methods: none
Description: Used to describe the contents of a location in a MEMORY BANK.

Class: MICROINSTRUCTION
Superclass: none
Variables: instruction (string of bits)
Methods: none
Description: Defines data structure that describes a microinstruction.

Class: MICRO SEQUENCER
Superclass: none
Variables: none
Methods: generate signal
Description: Simulates the micro sequencer component of Tanenbaum's architecture. The method generate signal sends a signal to the mux for controlling logic and addressing of the MPC.

Class: MIR
Superclass: REGISTER
Variables: none
Methods: decode
Description: Contains the various control signals. The method decode is used to parse the register contents into required control fields.

Class: MPC
Superclass: REGISTER
Variables: counter, cycles
Methods: set, increment, jump, set cycles, get counter
Description: Models a microprogram counter.

Class: MUX
Superclass: none
Variables: none
Methods: mux
Description: Models a combinational circuit. The output is one selection from many inputs.

Class: REGISTER
Superclass: STORAGE LOCATION
Variables: none
Methods: none
Description: Defines how the data is represented in a system, (i.e., how many bits represents a register/memory location).

Class: REGISTER BANK
Superclass: STORAGE BANK
Variables: contents: array of REGISTERs
Methods: load
Description: Similar to a MEMORY BANK.

Class: SHIFTER
Superclass: none
Variables: none
Methods: shift left, shift right, no shift
Description: Models a combinational circuit. Methods take a binary input and perform a binary shift to the left or right.

Class: STORAGE BANK
Superclass: none
Variables: contents: array of STORAGE LOCATIONs
Methods: initialize, load, read, write, binary read, binary write
Description: Defines data structure and methods for modeling a general storage object. Allows for access using both integer and binary address references.

Class: STORAGE LOCATION
Superclass: none
Variables: contents: string of bits
Methods: initialize, read, write
Description: Provides methods for accessing (read/write) a storage location in a memory or register bank.
APPENDIX B

This appendix contains a sample user session for the Micro Simulator and the ASC Simulator.

Tanenbaum Micro Simulator:

The Micro Simulator is started by double clicking on the application icon labeled Micro Simulator. This causes the application to load, the initialization of the menu bar, and the following dialog box to appear:

```
Define Registers & Memories

Register Width:    16
Number of Registers:  12
Number of Memories:  20
MAR Size:          12

OK
```

The user is required to enter values for each field in the dialog box (the above values are defaults). After all values have been entered, the user presses the Enter key or clicks the OK button. In this example, the Register Width field configures the simulator to have a 16 bit data path for buses, registers, and memory. The Number of Registers and Number of Memories fields configure the simulator to have the respective values simulated. In this case, 12 registers and 20 memories have been selected. The MAR Size field specifies the number of bits the MAR will use for addressing the memory. These bits are the low order bits passed from the data path to the MAR; this example specifies a 12 bit MAR.

The Tanenbaum design uses a set of registers, including general purpose, special purpose, and constant values (registers 6, 7, 8, and 9). Register values can either be loaded into
their respective registers individually by using the Alter Register command (discussed below), or they can be loaded from a text file by using the Load Registers command in the File menu. To initialize the registers using a text file, select the File menu (click or command-J), its choices are shown below:

<table>
<thead>
<tr>
<th>File</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Load Memory</td>
<td>%L</td>
</tr>
<tr>
<td>Load Registers</td>
<td>#J</td>
</tr>
<tr>
<td>Load Control Store</td>
<td></td>
</tr>
<tr>
<td>Quit</td>
<td>%Q</td>
</tr>
</tbody>
</table>

Choose the Load Registers selection (this can be done by either clicking with the mouse or using the command-J key sequence). This action displays the file selection dialog box as shown below:

Select the name of the text file that represents the desired register configuration (in this case register.set). There are no restrictions on naming conventions for any text files associated with this simulator. The two buttons Eject and Drive are disenabled (cannot be used) because there were no other drives mounted during this example. The contents of the register.set text file is shown below:

```
0-0000000000000000 Program Counter
1-0000000000000000 Accumulator
```
2-0000000000000000  Stack Pointer
3-0000000000000000  Instruction Register
4-0000000000000000  Temporary Instruction Register
5-0000000000000000  0
6-0000000000000000  +1
7-1111111111111111  -1
8-0000111111111111  AMASK  OFFF (hex)
9-0000000011111111  SMASK  00FF (hex)

The text file format for both register and memory descriptions is the same: any number (representing the location or address), followed by a dash ('-'), followed by 1's and 0's (which represent the bit string), followed by a comment. The numbers in the text file are for the use of the programmer only; the simulator loads all binary strings in order starting at location zero. The results of loading this text file into the simulator are shown in the register scroll box below (found in the simulator window, this example shows locations 5-10).

Next, load an object code program into the simulator's memory (this is a text file previously saved). This is done by choosing the Load Memory selection from the File menu as shown below (by clicking or command-L key combination):

File
Load Memory  %L
Load Registers  %J
Load Control Store
Quit  %Q

This causes the file input dialog to be displayed. Selection of the decrement.exe file is shown below:
The decrement.exe program is a simple program that loads a constant ‘4’ into the accumulator, pushes it onto the stack, decrements the accumulator value, and continues four more times. After completing this task the program remains idle by reaching step ‘5’ and then continuously branching back to step ‘5’. The text file of this program is shown below:

```
00-0111000000000100 LOCO 4 Loads the constant 4
01-1111010000000000 PUSH Push AC onto the stack
02-0011000000001100 SUBD MEM[12] Subtract memory loc #12
03-0101000000000101 JZER 5 if AC = 0 then PC := 0
04-0110000000000001 JUMP 1 Set PC := 1
05-0110000000000101 JUMP 5 Stay running idle
06-0000000000000000 **
07-0000000000000000 **
08-0000000000000000 **
09-0000000000000000 **
10-0000000000000000 **
11-0000000000000000 **
12-0000000000000001 Constant 1
```

Now that the program is loaded into the memory, it is necessary to determine where the stack pointer will point (recall that only 20 memory locations were defined in this example). In this example the initial stack pointer location will be initialized to ‘11’. This is done by using the Alter Register command under the Controls menu. This operation is shown below:
Selecting the Alter Register operation displays the dialog box below. We want to change the stack pointer (register 2) to a value of eleven. A 2 is entered in the Register Number field, and the appropriate string of 1’s and 0’s are entered into the Register value field. Press the Initialize Register button to enter the value into the register. The dialog box will remain displayed so that other entries can be made. Press Done to remove the dialog box.

At this point the user program is ready to execute. Execution can proceed by one of several methods which are selected from the Controls menu. The Cycle command causes the simulator to execute one microinstruction. The Single Instruction command causes the simulator to execute the necessary microinstructions to complete one macroinstruction. The Multiple Instructions command displays a dialog box requesting the desired number of macroinstructions. The user enters this value and the
requested number of macroinstructions are executed. The dialog box for this operation is shown below:

```
Enter desired number of Macro instructions to execute:
```

The Set MPC command of the Controls menu is used to reset the MPC to an input value (to alter microprogram flow). The dialog box for this operation is shown below:

```
Set MPC
Value: 0
```

The Run # of Cycles command of the Controls menu displays a dialog box similar to the Multiple Instructions command, except the simulator executes the desired number of microinstructions.

The sample program can be run with any combination of the above commands. The diagram below shows the contents of memory after the decrement.exe program has run to completion:
Referring to the above figure, it shows that the numbers 4, 3, 2, and 1 were loaded into the memory locations 10, 9, 8, 7 respectively. Notice that the first location loaded by the stack pointer is 10 (recall that the stack pointer was initialized to 11). This is because the stack pointer is decremented before the value is written into memory. The above figure also shows that location 7 is highlighted; the simulator highlights the last value written to (in both the register and memory banks).

**ASC Simulator:**

The ASC simulator is very similar to the Tanenbaum simulator. Most of the menu operations have the same effects. The following is a sample session with the ASC simulator.

The simulator is started by double-clicking on the icon named ASC. This causes the application to load, the menu bar to initialize, and the following dialog box to appear:
Define Memories

Enter Desired Number of Memories:

20

OK

This dialog box simply initializes the number of memory locations, in this case, 20. In this simulator the bus, register, and memory widths are hard coded to 16 bits. All of the registers have specific purposes, as discussed in the thesis body.

The next step is to load the sample program into memory. This is done by selecting the Load Memory command from the File menu as shown below:

File
Load Memory
Load Control Store
Quit

This action displays the file selection box shown below:
Selecting the decrement.mac text file as shown above (previously saved text file) loads the text file contents into the memory. The contents of decrement.mac are shown below. This program loads the accumulator with the value '15' (located at memory 8). It also loads index register #1 with the value '5'. It places the contents of the accumulator into the memory locations 11-15, then the program repeats. This simulator uses the same type of text file formats as the Tanenbaum simulator. Similar actions can be executed by choosing Load Control Store from the File menu. This will load a microprogram represented by the text file into the control store.

```
00-0001000000001000 LDA W/MEM[8]
01-1100000100000111 LDX INDEX 1 W/MEM[7]
02-0010000100001010 STA 10,1
03-1111000100000010 TDX INDEX 1 BRA 2
04-0101000000000001 BRU 1
05-0000000000000000 **
06-0000000000000000 **
07-0000000000000101 CONST 5
08-0000000000000111 CONST 15
09-0000000000001001 CONST 10
```

At this point the program is ready to execute. The ASC program execution controls operate with the same functionality as the Tanenbaum simulator. The Controls menu is the same as the Tanenbaum Controls menu except there is no Define Memory selection. This is because only one register can be altered, the program counter (PC) register. The PC can be
altered by choosing the Update PC selection from the Registers menu. The dialog box resulting from this selection is shown below:

![Dialog Box](image)

```
Enter Desired Register Value:

0000000000001111

OK
```

Using the various controls (as discussed in the Tanenbaum Example) the program is then run to completion. The memory contents after execution are shown below:

```
06--0000000000000000
07--0000000000000101
08--0000000000000111
09--0000000000000101
10--0000000000000000
11--0000000000000111
12--0000000000000111
13--0000000000000111
14--0000000000000111
15--0000000000000111
```

Memory locations 11-15 contain the value initially loaded into the accumulator 15. Memory location 11 is highlighted because it was the last memory value written to.
APPENDIX C

This appendix contains the source code for the Tanenbaum design microsimulator.
register

storage location

storage location

storage location/read 1:1

storage location/write 1:1
null
micro sequencer/generate signal 1:5

Jump if not

micro sequencer/generate signal 2:5

JUMP if 2:1

micro sequencer/generate signal 2:5

micro sequencer/generate signal 4:5

micro sequencer/generate signal 5:5

V NSB

NSB

NSB

8.1 General Items  Thu, Aug 16, 1990 12:31
APPENDIX D

This appendix contains the source code for the ASC design microsimulator.
Microcontrollers

Process Type 1 Microinstruction 1:1 branch 4:5

TRUE 1

FALSE 1

Process Type 1 Microinstruction 1:1 branch 5:9

TRUE 1

FALSE 1

Process Type 1 Microinstruction 1:1 branch 6:9

TRUE 1

FALSE 1

Note: Always print Process 1 DATA = 0

ABCD PDB
null
A micro control/Bus2 Data 1:1 generate bus2 signals 2:5

A micro control/Bus2 Data 1:1 generate bus2 signals 3:5

A micro control/Bus2 Data 1:1 generate bus2 signals 4:5

A micro control/Bus2 Data 1:1 generate bus2 signals 5:5

Error: generate bus signals 2:5
- Micro control/ Memory Signals 1:1, Generate memory signals 1:4

- Micro control/ Memory Signals 1:1, Generate memory signals 2:4

- Micro control/ Memory Signals 1:1, Generate memory signals 3:4

- Micro control/ Memory Signals 1:1, Generate memory signals 4:4

\( S \): Enter a generate memory signals test pattern

\( \triangleright \) shifter

- shifter

Notes: Use control signals and memory to

- Composite: out, write, mask
kiuslus 1:1 a multoe sinews fegieters 1:1

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Iont 1:1 U leaue 1:1

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