A CONCEPTUAL MODEL FOR MEGAPROGRAMMING

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Will Tracz

MD 0210
IBM Federal Sector Division
Owego, N.Y. 13827

OWEGO@IBM.COM
(607) 751-2169

Abstract

"Currently, software is put together one statement at a time. What we need is to put software together one component at a time." — **Barry Boehm, at the Domain Specific Software Architecture (DSSA) Workshop, July 11-12, 1990.**

Megaprogramming, as defined at the first ISTO Software Technology Community Meeting, June 27-29, 1990, by Barry Boehm, director of DARPA/ISTO, is component-based software engineering and life-cycle management. The goal of this paper is to place megaprogramming in perspective with research in other areas of software engineering (i.e., formal methods and rapid prototyping) and to describe the author's experience developing a system to support megaprogramming.

The paper, first, analyzes megaprogramming and its relationship to other DARPA research initiatives (CPS/CPL — Common Prototyping System/Common Prototyping Language , DSSA — Domain Specific Software Architectures, and SWU — Software Understanding). Next, the desirable attributes of megaprogramming software components are identified and a software development model (The 3C Model) and resulting prototype megaprogramming system (LILEANNA — Library Interconnection Language Extended by Annotated Ada) are described.

Keywords: domain modeling, formal methods, inheritance, parameterized programming, rapid prototyping, software engineering, and software reuse.

1.0 Introduction

> *"Megaprogramming is the type of thing you can go into a 3-star general's office and use to explain what DARPA is going to do for them to make their software less expensive and have better quality."* – Barry Boehm, at the ISTO Software Technology Community Meeting, June 27-29, 1990.

Software researchers and developers have long pursued the goal of increased software productivity and quality. As the programming profession matures and basic research into programming languages and formal methods advance, opportunities are emerging to apply some of these results to the software development process. This paper is about component-based programming or ***megaprogramming***, a term coined by Barry Boehm[2] at DARPA/ISTO, which is an essential element of the DARPA Software Strategic Plan[1]. Reusing software components, instead of re-writing them, is a long held[16], intuitively appealing, if not obvious, approach to increasing productivity and quality. Systems developed based on reusable software artifacts, in principle, should cost less (partially attributable to a shorter schedule), and contain fewer defects because of the "tried and true" parts used in its composition. Unfortunately, a one-dimensional view of quality as being the "absence of defects" is not sufficient to explain the necessary attributes of software that make it reusable (i.e., portability, flexibility, reliability, useability, and understandability are other essential attributes). The observation that "quality can not be tested into a program, but needs to be designed into a program," is especially applicable to megaprogramming.

The goal of this paper is to examine the technical foundations of megaprogramming and to assess their effectiveness for increasing the interoperability, adaptability, and scaleability of its components (i.e., the quality of its components). To this end, this paper is organized into three sections. The first section summarizes and analyzes the megaprogramming vision initially presented as part of the DARPA Software Technology Plan[21]. The next section introduces a conceptual model for reusable software components (the 3C Model[23]) based on separating a component's context (what can change) from the concept it encapsulates (the interface it exports) and its content or implementation. The final section describes work in progress on a megaprogramming implementation, LILEANNA[24] (Library Interconnection Language Extended by Annotated Ada), which combines the formal methods of ANNA[14] and the parameterized programming capability of OBJ[11]

2.0 Megaprogramming Vision

> *"Software productivity improvements in the past have been accidental because they allow us to "work faster". DARPA wants people to "work smarter" or to avoid work altogether."* – Barry Boehm, at the Domain Specific Software Architecture (DSSA) Workshop, July 11-12, 1990.

Megaprogramming is envisioned as a giant step toward[2] increasing "development productivity, maintenance productivity, reliability, availability, security, portability, interoperability and operational capability[2]." Megaprogramming will incorporate proven, well-defined components whose quality will evolve, in the Darwinian sense. Megaprogramming requires the modification of the traditional software development process to support component-oriented software evolution. Domain-specific software architectures need to be defined and implemented according to software composition principles and open interface specifications. The resulting software assets need to be stored and accessed in a repository ideally built on a persistent object base, with support for heterogeneous software components in distributed environments. Finally, additional environmental capabilities (e.g., hypermedia) are needed to provide software understanding at the component and architectural levels.

The subsections that follow describe some of the focal points of the DARPA Software Technology Plan[21] related to megaprogramming. In particular, an environment to support megaprogramming (Megaprogramming Software Team) and the generation and promotion of megaprogramming components (Megaprogramming Software Interchange) are addressed.

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[1] Prior to Boehm's use of the term "megaprogramming", Joseph Goguen[11] suggested the term ***hyperprogramming*** to refer to a similar, if not identical, programming paradigm. The author has suggested using the term ***programming-with-the-large***.[24] to emphasize the granularity of the objects being manipulated.

[2] The analogy used by Barry Boehm was that, historically speaking, one might view machine language programming as resulting in productivity at a snails pace, assembler language programming – a turtle's pace, programming in FORTRAN, C or Ada – walking, and megaprogramming as walking with seven league boots.

2.1 Megaprogramming Software Team

"*Configuration = Components + Interfaces + Documentation*
Software Team = Configuration + Process + Automation + Control." – Bill Scherlis, at the ISTO Software Technology Community Meeting, June 27-29, 1990.

The goal of the megaprogramming software team is to create an environment to:

1. "manage systems as *configurations* of components, interfaces, specifications, etc.,
2. increase the *scale of units* of software construction (to modules), and
3. increase the *range of scales* of units of software interchange (algorithms to subsystems)[21]."

The key elements of the megaprogramming software team are:

- **Component sources** – currently, components under consideration are from reuse libraries (e.g., SIMTEL20[5] or RAPID[20]) or COTS (Commercial Off-The-Shelf) software (e.g., GRACE[1] or Booch[3] components). Application generator technology is desirable to provide for adaptable modules while re-engineered components (e.g., CAMP[17]) could provide additional resources. It is desirable to move toward new customizable components with a rapid prototyping capability.

- **Interface definitions** – currently, there exists an ad hoc standard consisting of Ada package specifications and informal documentation. It is desirable to develop a Module Interconnect Formalism (MIF) with hidden implementations supported by formal analysis and validation tools.

- **System documentation** – currently, simple hypertext systems are supporting the (often ambiguous and incomplete) textual documentation associated with software components. It is desirable to create a repository-based, hypermedia environment that provides traceability between artifacts and supports the capture, query, and navigation of domain knowledge.

- **Process structure** – currently, there exists no predictable software development process. It is desirable to develop an evolutionary development life cycle with support to domain engineering, integrated requirements acquisition, and reverse/re-engineering.

- **Process Automation** – currently, CASE tools are either stand-alone or federated (e.g., Unix[3]). It is desirable to integrate the tools and create a meta-programming environment to support process description and refinement.

- **Control/Assessment** – currently, only a priori software metrics and process instrumentation exists. It is desirable to integrate the measurement process with tool support and to create a cost-estimation capability.

The megaprogramming software team initially expects to draw resources from the STARS (Software Technology for Adaptable Reliable Systems) SEE (Software Engineering Environment) program. Future tools will be contributed by Arcadia[22], CPS/CPL[6] (Common Prototyping System/Common Prototyping Language), DSSA (Domain Specific Software Architectures)[18], POB (Persistent Object Bases), SWU (Software Understanding), and REE (Re-Engineering) programs. Interface and architecture codification will be supported by a Module Interconnect Formalism (MIF), which is an outgrowth of the CPS/CPL program.

The goal of MIF is to adequately describe a software component such that its selection and use can be accomplished without looking at its implementation. The component interfaces will include, not only the entry points, type definitions and data formats (e.g. Ada package specification), but a description of its functionality, side effects, performance expectations, degree and kind of assurance of consistency between specification and implementation (reliability), and appropriate test cases. DSSA will provide the initial avenue for the application of this technology. (An architecture is a collection of interfaces.) Incremental asset creation and customization will be guided by the CPS prototyping technology.

Asset capture and re-capture will be supported by SWU's design record, hypertext browsing capability, and REE. The design record will provide a "common data structure for system documentation and libraries[21]". The suggested data elements in a design record include:

- code,
- test cases,

[3] Unix is a trademark of AT&T Bell Laboratories.

- library and DSSA links,
- design structure,
- access rights,
- configuration and version data,
- hypertext paths,
- metric data,
- requirement specification fragments,
- PDL texts,
- interface and architecture specifications,
- design rationale,
- catalog information, and
- search points.

2.2 *Megaprogramming Software Interchange*

"*Software Interchange = Software Team + Convention + Repository + Exchange.*" – Bill Scherlis, at the ISTO Software Technology Community Meeting, June 27-29, 1990.

The goal of the megaprogramming software interchange is to "enable wide-area commerce in software components[21]". The megaprogramming software interchange, which is integrated with the megaprogramming software team, consists of the following elements:

- **Conventionalization** – currently, conventions are emerging. It is desirable to create a cooperative decision and consensus mechanism that supports adaptable, multi-configuration libraries, which present a standard search capability.

- **Repository/Inventory**– currently, repositories support code storage only. It is desirable to retain, assess, and validate other software assets such as architectures, test cases, specifications, designs, and design rationales.

- **Exchange/Brokerage** – current intellectual property rights and government acquisition regulations are stifling a software component industry. It is desirable to populate certain application domains (via DSSA) and to support the creation of an electronic software component commerce by defining mechanisms for access control, authentication/certification and establishing composition conventions.

The megaprogramming component interchange expects intially to draw software components from the reuse libraries in STARS and DSSA with future support derived from POB, and CPS/CPL (MIF).

3.0 Conceptual Model for Software Components

"*Before components can be reused, there needs to be components to reuse.*"

As discussed in the previous section, megaprogramming requires the definition of proven, well-defined components that are implemented according to software composition principles. This section presents a formal framework for developing reusable software components that leverage the compositional capabilities of the megaprogramming language LILEANNA (covered in the next section of this paper). A conceptual model[24] is described that distinguishes between three distinct aspects of a software component:

1. the **concept** or abstraction the component represents,
2. the **content** of the component or its implementation, and
3. the **context** that component is defined under, or what is needed to complete the definition of a concept or content within a certain environment.

These three aspects of a software component make the following assumptions about their environment:

1. There is a problem space (application domain) that can be decomposed into a set of concepts (or objects if one prefers using an object-oriented paradigm).
2. There is a solution space that is characterized by the contents (implementations) of the concepts.

3. The solution space is populated by several different implementations, or "parameterized[4]" implementations that can be instantiated by different contexts within the solution space.

Before proceeding further into the material in this section, it is important for one to realize the subtle implications that "dynamic binding" has on one's approach to programming. The conceptual model described in this section assumes a programming language and environment with all binding of parameters done prior to run time (with the exception of actual parameters passed to subprogram operations). The model recognizes that binding can occur at or before compile time, and at load/link edit time. This view of binding, to some readers, may appear limiting (which, in some sense, it is), but this limitation, in reality, is a trade-off for early error detection (strong typing), which, in some application areas, is considered to be of greater importance.

The rest of this section defines the terms context, content, and concept, in more detail and describes their relationships to modularization, specification, interface design and parameterization.

3.1 Three Aspects of a Software Component

This conceptual model for software components is motivated by the need to develop **useful**, **adaptable**, and **reliable** software modules with which to build new applications. These three needs are addressed individually by the model.

1. A **useful** component meets the high-level requirements of at least one concept necessary to design and implement a new software application.
2. An **adaptable** component provides a mechanism such that modules can be easily tailored to the unique requirements of an application.
3. A **reliable** component is one that accurately implements the concept that it defines.

This conceptual model for software components, referred to as the **3-C model**, is based on three aspects of a software component: concept, context, and content. These three terms are addressed individually in the subsections that follow.

3.1.1 Concept

"Domain analysis is the building up of a conceptual framework, informal ideas and relations; the formalization of common concepts." – Ted Biggerstaff, MCC.

The **concept** represented by a reusable software component is an abstract description of "what" the component does. Concepts are identified through requirement analysis or domain modeling as providing the desired functionality for some aspect of a system. A concept is realized by an interface specification and an (optionally formal) description of the semantics (as a minimum, the pre- and post-conditions) associated with each operation. An Ada package specification (operations, type and exception declarations) for a stack abstract data type, with its behavioral semantics described in Anna[14], is an example of a reusable software concept.

3.1.2 Content

"The ability to convert ideas to things is the secret of outward success." – Henry Ward Beecher.

The **content** of a reusable software component is an implementation of the concept, or "how" a component does "what" it is supposed to do. The software component conceptual module assumes that each reusable software component may have several implementations that obey the semantics of it's concept (e.g., operational specifications are the same, but the behavioral specifications are different). The collection of (28) stack packages found among Grady Booch's[3] components is an example of a family of implementations for the same concept (stack).

[4] Perhaps "generalized" is a better word.

3.1.3 Context

"Understanding depends on expectations based on familiarity with previous implementations." – Mary Shaw, SEI.

One of the failures of software reuse is that user's expectations of a reusable software component do not meet the designer's expectations of the reusable software component (the square-peg-in-the-round-hole syndrome). By explicitly defining the context of a reusable software component at the concept and content level, and formally specifying its "domain of applicability", the user can better select and adapt the component for reuse.

The context of a reusable software component takes on three dimensions:

1. the **conceptual context** of a reusable software component – how the interface and semantics of the module relate to the interface and semantics of other modules,
2. the **operational context** of a reusable software component – what the characteristics of the data being manipulated are, and
3. the **implementation context** of a reusable software component – how the module depends on other modules for its implementation.

Parameterization, inheritance and importation of scope through the use of abstract machine interfaces are all language mechanisms that assist in separating context from content. Within the framework of the 3-C model, one uses these language constructs as follows:

1. one specifies the **conceptual context** of a software component by using inheritance to express relationships between concepts (module interfaces). This occurs when two concepts share the same syntax and semantics.
2. one defines the **operational context** of a software component by using genericity to specify data and operations on the data being manipulated by a module (at the conceptual or implementation level).
3. one decides on the **implementation context** of a software component by selecting the operations to be used for and by the implementation of a module. These operations are external to the component. Inheritance or importation of scope are the two languages mechanisms that support the definition of a module's implementation context.

One should note the explicit separation of the roles of code and type inheritance in the model. Type inheritance is used to express the conceptual context of a module. The conceptual context of a software module forms a true partial order in that the concept inheriting another concept "is a" subtype of the latter concept. Code inheritance is used as an implementation mechanism and may or may not be the same as the type inheritance used to express the conceptual context of the concept associated with the software component for which the implementation is being created.

An example of conceptual context is a stack that can be used to describe the interface of a deque (double ended queue). The operational context for a deque is the type of the element being stored. The implementation context of a particular deque implementation might be a sequence abstraction. That is, the implementation would be designed to refer to operations in an abstract machine interface found in a sequence concept, which could have several implementations (e.g., array or linked list). Alternatively, the deque could be indirectly implemented (i.e., generated in the megaprogramming sense) by simply

1. renaming some of the operations in an implementation of the stack (i.e., Push and Pop would become Push_Right and Pop_Right),
2. adding some new operations (Push_Left and Pop_Left), and
3. inheriting the rest (e.g. Print, Length, Is_Empty, etc.).

Using the syntax of LILEANNA, the following megaprogram would generate the (parameterized module) deque described above:

```
make Deque[ Triv ] is
   Stack [ Triv ] * (rename ( Push => Push_Right )
                            ( Pop => Pop_Right )
                            ( Stack => Deque )
                    * ( add Push_Left, Push_Right )
end;
```

The selection of an implementation, or the content of the concept is determined by trade-offs in context. Clearly, knowing the characteristics of the type of data structure being manipulated will lead to more efficient implementations. This can result in the population of a reuse library with several efficient implementations of the same (parameterized) concept, each tailored to a particular context. At design time, a programmer could identify the concept and define the context it is being manipulated under based on requirements or operating constraints. At implementation time, the programmer could instantiate an implementation of the concept with the conceptual contextual information plus any other contentual contextual information necessary.

Separating context from concept and content complements the work of Parnas[19] in suggesting that the quality of software can be improved by isolating change. It has been demonstrated that software is more reusable, or more easily maintained, if the types of possible modifications to the software are taken into consideration at design time.

4.0 LILEANNA

LILEANNA (LIL Extended with ANNA (Annotated Ada) [14]) is an implementation of LIL (Library Interconnect Language), proposed by Joseph Goguen [9] as a MCL (Module Composition Language) for the programming language Ada[25]. LIL is a language for designing, structuring, composing, and generating software systems. It is based on the work of Goguen and Burstall on the language CLEAR[4] and Goguen on OBJ[8]. LIL was first introduced at the Ada Program Libraries Workshop in Monetary California. It was later refined for publication in IEEE COMPUTER[10]. Since then it has been the interest of several researchers[7, 12, 13, 24].

The primary design goals of LIL were:

1. to make it easier to reuse software written in Ada,
2. to facilitate the composition of Ada packages,
3. to support an object-oriented style of design and documentation for Ada,
4. to rapidly prototype new applications by integrating executable specifications with the controlled manipulation of source code,
5. to avoid recompilation, and
6. to support maintenance of Ada programs and families of programs.

The power of megaprogramming in LILEANNA centers on the ability to compose new packages with package and subprogram expressions via the **make** statement. Existing packages may be manipulated through package expressions to specify the instantiation, aggregation, renaming, addition, elimination or replacement of operations, types or exceptions.

LILEANNA supports the structuring and composition of software modules from existing modules. One can

1. instantiate a parameterized module to create
   a. implementations of operations,
   b. a simple package/module, or
   c. a parameterized package/module (generic).
2. Compose/structure modules by
   a. combining other modules (inheritance and multiple inheritance) (e.g., merging two module's operations and types),
   b. adding something[5] to an existing (inherited or instantiated) module (e.g., adding an operation),
   c. removing something from the interface of an existing module (e.g., hiding an operation),
   d. renaming something (e.g., purely textual changing the name of operation in an interface),
   e. selecting from a family of implementations, or
   f. replacing something in an existing module (i.e., a pure swap — a remove and add combination).

The result of evaluating a LILEANNA composition/megaprogramming statement (i.e., a **make** statement) is an executable Ada package specification and body that either is

1. a "stand-alone" flat module (nothing imported), or
2. a hierarchy, with selected functionality imported and perhaps repackaged.

Note that since there is no inheritance in Ada, composition that uses inheritance will need to either import all modules in the inheritance hierarchy (being careful to rename those which might result in ambiguity), or include

[5] Where "something" is a sort/type, operation, exception, or in some cases, an axiom.

all necessary functionality directly in the implementation (package body). In either case, the resulting user interface (package specification) should not be cluttered by such details.

4.1 Formal Foundations of LILEANNA

LILEANNA has its formal foundations in category theory[6] and in initial and order-sorted algebras. These concepts form the basis for advances in algebraic specifications and type theory. Many type systems are based on the concept of an algebra. An algebra defines a set of values and the operations on them just as an abstract data type defines the data of the type and provides operations on them.

Program semantics in LILEANNA are expressed in first order predicate calculus rather than using re-write rules (a la OBJ) as a way of implementing conditional order-sorted equational logic.

4.2 LILEANNA Language Constructs and Examples

LILEANNA is a language for formally specifying and generating Ada packages. LILEANNA extends Ada by introducing two entities: theories and views, and enhancing a third, package specifications. A LILEANNA package, with semantics specified either formally or informally, represents a template for actual Ada package specifications. It is used as the common parent for families of implementations and for version control. A theory is a higher level abstraction, a concept (or a context), that describes a module's syntactical and semantic interface. A view is a mapping between types, operations and exceptions.

Programs can be structured/composed using two types of hierarchies:

1. **vertical**: levels of abstraction/stratification, and
2. **horizontal**: aggregation and inheritance (type and code).

LILEANNA supports this with two language mechanisms

1. **needs**: import dependencies, and
2. **import, protect**, or **extend**: three forms of inheritance, and **includes**, a subtyping construct.

Theories are an encapsulation mechanism used to express the requirements on generic module parameters. Theories also play a role in building horizontal and vertical hierarchies by defining the interface requirements for modules that later can be instantiated with a more concrete implementation. Views map theories to theories, or theories to packages, or pieces of packages. One powerful feature of LILEANNA is the encapsulation of parameters in theories. With this capability, the semantics of parameters can be formally specified and the domain of applicability of a module can be explicitly qualified.

The generative capability of the LILEANNA is provided by package expressions, a "super make"[7] feature for creating new packages from existing packages through horizontal, vertical and generic instantiation. Package expressions manipulate Ada packages and their contents based on their relationships to LILEANNA packages, theories and views. The basic operations supported are importation in the form of inheritance, specialization in the form of instantiation, generalization, and aggregation. Finally, the contents of modules can be manipulated through * *package operators* by indicating what entities are being added, hidden, renamed, or replaced.

LILEANNA goes beyond the Ada instantiation capability in that generic packages can be composed to create new generic packages without themselves being instantiated. Partial instantiations are also possible. A **view** is used to instantiate a generic package. Default views can be computed if only package name is supplied. Alternatively, mappings of formal to actual parameters may form an in-line view as part of a package expression.

The following example illustrates several LILEANNA language constructs. In the example, the package *Integer_Set* is made from a parameterized LILEANNA package, *LIL_Set*. This example is very similar to the instantiation of an Ada generic, except that in Ada, the instantiation process is done at compile time. In LILEANNA, the generic instantiation is done prior to compile time. This results in Ada source code which is ready to be compiled, composed or further instantiated.

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[6] Goguen has suggested that LILEANNA is based on another 3-C model — Category theory, Colimits, and Comma Categories.

[7] Make is a UNIX term and command for the process of selectively compiling and linking compiled outputs to make an executable module.

```
make Integer_Set is LIL_Set[Integer_View] end;
```

Attention should be paid to the view (shown below), *Integer_View* (from theory *Triv* to the Ada package *Standard*), used in the make statement above. There is an explicit mapping between the type *Element* and the type *Integer*. The point to be emphasized is that this mapping can be given a name and reused in other instantiations.

```
view Integer_View :: Triv => Standard is
   types (Element => Integer);
end;
```

Alternatively, as shown below, the instantiation could have been stated as

```
make Integer_Set is
   LIL_Set [ view Triv => Standard is types (Element => Integer); ]
end;
```

In this case, the view does not have a name, but the mapping is explict to this particular instantiation.

The following example illustrates the use of horizontal and vertical composition. A generic package (*Short_Stack*) is generated by selecting an array implementation (*List_Array*) of the list interface theory (*List_Theory*) needed by the LILEANNA package (*LIL_Stack*). It is assumed that the LILEANNA package (*LIL_Stack*) has a comparable Ada package (*Stack*) and that an explicit view may or may not exist between them.

```
make Short_Stack is
  LIL_Stack   -- inherit Stack Package (horizontal composition)
  needs (List_Theory => List_Array)
              -- supply array package (vertical composition)
end;
```

The following is an example of a **make** statement that instantiates the generic LILEANNA package *Sort* according to the view *Nat_Default* (not shown), which maps the Natural numbers and the pre-defined linear order relationship onto the theory of partially ordered sets.

```
make Sort_Lists_of_Naturals is
   Sort[Nat_Default]
   needs (ListP => Linked_List)
end;
```

An example of a more involved make statement using multiple inheritance and package operators follows. It is based on an existing set of Ada packages that defines an Ada-Logic Interface[15] package for reasoning.

```
make New_Ada_Logic_Interface is
    Identifier_Package +
    Clause_Package*(hide Copy) +
    Substitution_Package +
    DataBase_Package +
    Query_Package*(add function Query_Fail (C: Clause;
                                            L: List_Of_Clauses)
                                               return Boolean)
                  *(rename ( Query_Answer => Query_Results ))
end;
```

The result is a merged package specification where,

1. the *Copy* operation is not available on *Clauses*,
2. an additional operation, *Query_Fail*, now augments those inherited from the specification, *Query_Package*,
3. the *Query_Answer* operation is not available in the resulting interface, instead, the *Query_Results* operation can be invoked.

5.0 Conclusion

"We should stand on each others shoulders, not on each others feet." – Peter Wegner[26]

Megaprogramming is a new programming paradigm that requires both a critical mass of software components and a disciplined approach to program design and specification. This paper has presented one approach to megaprogramming that is based on a formal model (the 3-C Model) for developing reusable software components. This model gives insight into the relationships between type inheritance, code inheritance, and parameterization that is essential for providing the adaptability and interoperability of software components. The corresponding implementation, LILEANNA, serves as a valuable vehicle for exploring megaprogramming concepts.

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Ada Net

John McBride
Planned Solutions

AdaNET

Presented to
RICIS '90 Software Engineering Symposium

November 8, 1990

Presented by
John McBride
Planned Solutions, Inc.

AdaNET Program

- Five Year R & D Effort to Advance the State of Software Engineering Practice
- National Facility in West Virginia to Increase U.S. Productivity, Economic Growth & Competitiveness
- Enhance Existing AdaNET System to Provide a Life Cycle Repository for Software Engineering Products, Processes, Interface Standards, & Related Information Services

Purpose and Scope

- Transfer Software Engineering Technology Within the Federal Sector & to the Private Sector
  - Reusable Software Components Useful in All Phases of Lifecycle
  - Engineering Process Descriptions for Developing Adaptable & Reliable Systems & Software Worthy of Reuse
  - Interface Standards
    - More Consistency in System Features,
    - Simpler System Integration,
    - Aid in the Use of Metrics as Quality Predictors
  - Related Information & Services
    - Software Engineering Help Desk
    - Conference Listings
    - References
    - Networking to Other Databases
    - E Mail

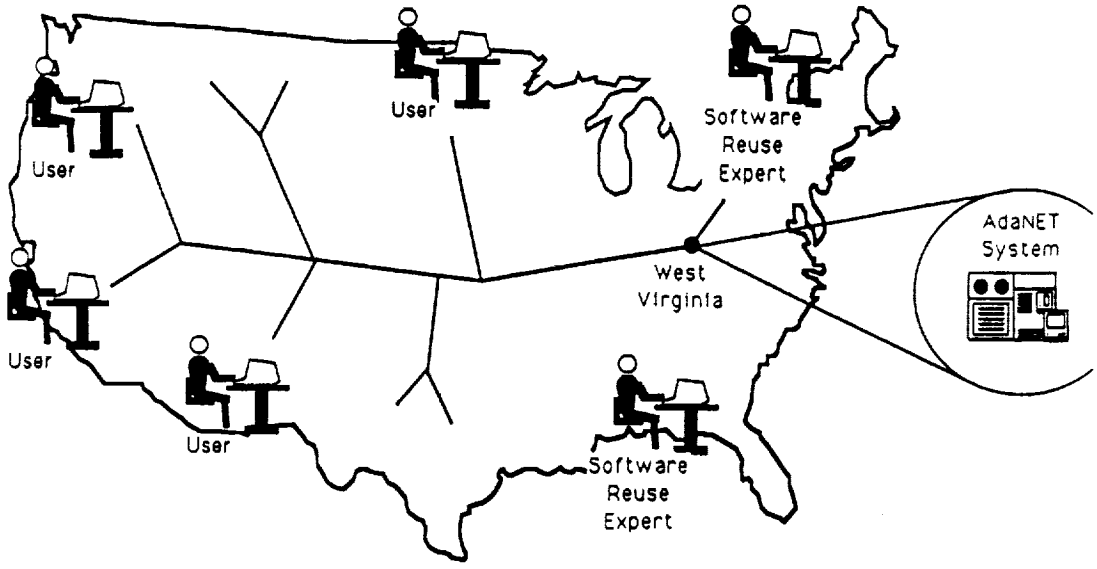
AdaNET Goals

- Establish a National Center for the Collection of Software Engineering Information
- Provide On-Line Life Cycle Repository
- Promote a Cultural Change Necessary to Improved Quality & Efficiency
- Provide a Platform for Research In Technology Transfer

AdaNET Benefits

- Decrease Software Costs
- Improve Quality of Software Systems

AdaNET is a National Resource



Accessible Via InterNET and TeleNET Public Access Dial Up

Users of AdaNET

Small Companies - Reusable Components and Software Engineering Help Desk will Allow These Companies to be More Competitive

Large Companies - Large, Complex Systems can be Built More Reliably and at Lower Cost with Reusable Components

Academia - Facilitates Teaching and Research in Software Engineering With Reusability

U. S. Government - Spinback Benefits to Government Software Developers

Major Research and Technology Issues

Application and Dissemination Policies	Software Reuse Strategies		AdaNET Architecture
• Interagency Agreements	• Domain	• Modification	AdaNET Context
• Customer Licenses	• Type	• Classification	• Operating Modes
• Data Rights	• Granularity	• Retrieval	• Security and Integrity
• Title and Use Guarantees	• Selection	• Assistance	• User Interface
• Liability	• Configuration	• Qualification	AdaNET Services to Access Resources
• Organization Type	.	.	AdaNET Resources
• Charges and Profits	.	.	• Information
• International Clients	.	.	• Products
• Military Restrictions			• Experts
.			
.			
.			

AdaNET Enhancements

AdaNET Service Version Two (ASV2) Current System

- Hosted on Data General
- CEO Office Automation Product Organized Files in Drawers and Folders
- Keyword and Textual Search

ASV3 (late 1991)

- Unix Based
- Integrate JSC/Barrios Developed Autolib & Army/RAPID Derived Technologies
- Natural Language Query, Facets, Keyword Search

ASV4 (late 1994)

- Object Management Support for Full Life Cycle Traceability

AdaNET User Registration

Mountain NET
P.O. Box 370
Dellslow, W.V. 26531
(304) 296-1458
(304) 296-6892 FAX
1-800-444-1458 help desk (Peggy Lacey)

Current AdaNET Products and Services

Reusable Software	
Army Ada Software Repository	(227)*
STARS Repository	(In process)
NASA/JPL Components	(In process)
Products	
• Services	(40)**
• Software	(141)
E-Mail	
Training	
• Guided Study	(102)
• Self Study	(21)
Publications	
• Citations	(678)
• Newsletters	(19)
• Standards	(92)
Conferences	
• Announcements	(112)
• Paper Calls	(20)
News	
• Abstracts	(129)
• User Contributions	(21)
Contracts	
• Awards	(161)
• RFPs	(177)

* - Functional Areas
** - Unique Files

Summary

- Life Cycle Approach to Reuse Can Provide a Significant Impact on Software Productivity
- Software Engineering Information Provides Knowledge Transfer
- AdaNET is an Operational Program with a Prototype Development and Evaluation Cycle

POSIX and Ada Integration in the Space Station Freedom Program

Robert A. Brown
The Charles Stark Draper Laboratory, Inc.

Overview

- POSIX Overview
- POSIX Execution Model
- Ada Execution Model
- SSFP Flight Software Ada Requirements
- POSIX/Ada Integration

POSIX Overview

- Portable Operating System Interface for Computer Environments
- IEEE sponsored standards development effort
  - Voluntary participation
  - Concensus standard (75% required for approval)
- Purpose
  - Define standard OS interface and environment
  - Based on UNIX
  - Support application portability at source code level
- Family of open system standards

POSIX Working Groups

- P1003.0: Guide to POSIX Open Systems Environment
- P1003.1: System Interface
- P1003.2: Shell & Tools
- P1003.3: Testing & Verification
- P1003.4: Realtime
- P1003.5: Ada Language Bindings
- P1003.6: Security Extensions
- P1003.7: System Administration
- P1003.8: Networking
- P1003.9: Fortran Language Bindings
- P1003.10: Supercomputing
- P1003.11: Transaction Processing

POSIX Execution Model
P1003.1

- POSIX process
  - Address space
  - Single thread of control executing in address space
  - Required system resources
- Process management
  - Process creation -- fork() and exec()
  - Process group and session
  - Process termination -- exit(), abort()
- Process synchronization
  - Signals -- sigsuspend(), pause()
  - Wait for child termination -- wait(), waitpid()
- Process delay
  - alarm() and sleep()

POSIX Execution Model
Realtime Extensions

- Priority scheduling
- Binary semaphores
- Shared memory
- Message queues
- Asynchronous event notification
- Clocks and timers
  - High resolution sleep
  - Per-process timers

Ada Execution Model
Language Definition

- Ada program
  - Single address space
  - Multiple threads of control
  - Required system resources
- Task management
  - Task creation -- elaboration, allocator evaluation
  - Organization -- task master
  - Task termination -- normal completion, exception
- Task synchronization
  - Rendezvous
- Task delay
  - Ada delay statement

SSFP Flight Software Requirements

- Multiple real-time programs sharing same processor
- Fixed priority, preemptive scheduler
- Single level dispatcher
- Non-blocking i/o and system calls
- Ability to schedule tasks for periodic execution
- Ability to schedule tasks to respond to specific events

Ada Execution Model Realtime Extensions

- Scheduling
  - CIFO cyclic scheduler
- Binary semaphores
- Shared data template
- Precision time services
- Event notification
  - CIFO event management

POSIX/Ada Integration
The Problem

- POSIX looks from program outward
  - Semantics defined for processes only
  - Single thread assumption
- Ada looks from program inward
  - Semantics defined for tasks within a program only
  - Single program assumption
- Integration of POSIX and Ada
  - Extend POSIX semantics to multi-threaded processes
  - Extend Ada semantics to multiple programs

POSIX/Ada Integration
A Solution

- Extension of POSIX semantics to multiple threads
  - Define system interface for threads
  - Redefine existing services for multiple threads
    - Signals
    - Fork() and exec()
    - Per process static data
    - Semaphores, events and timers
- Extension of Ada semantics to multiple programs
  - Global task scheduling
  - Definition of shared package semantics
  - Ada interfaces to multiprogramming services
    - Process control -- start, stop
    - Interprocess communication

Session 4

Software Engineering: Issues for Ada's Future

Chair: **Rod L. Bown** , *University of Houston-Clear Lake*

Assessment of Formal Methods for Trustworthy Computer Systems

Susan Gerhart
Microelectronics and Computer Technology Corp. (MCC)

An Assessment of Formal Methods for Trustworthy Systems

Susan Gerhart
MCC Formal Methods / Software Technology
gerhart@mcc.com 512-338-3492

- What are Formal Methods?
- Standards for Trustworthy Systems
- Assessment of FM via SAFEIT

"Applied Mathematics of Software Engineering"
college sophomore through Ph.D. level

Use

logic, set and sequence notation,
finite state machines, other formalisms

Induction arguments, Symbolic reasoning

In

- system models
- specifications
- designs and implementations

For

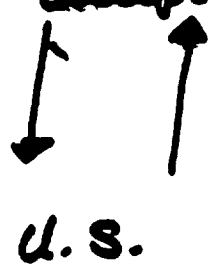
- highly reliable, secure, safe systems — NSA Comp. Sec. U.K. MoD
- more effective production methods — Tek, AICS
- software engineering education — SEI

In levels of use

guidance: structuring what to say

rigorous, formal:
generated and worked proof obligations

mechanized: using proof assistants



A NonExecutable Spec Language: ASLAN

- State-transition based
- First order logic with equality
- Sections
  - » Types (builtin and user constructed)
  - » Constants & Variables
  - » Definitions & Axioms
  - » Initial Condition
  - » Invariant
  - » Constraint
  - » Transitions (pre/post conditions)
- Generates verification conditions
  - » IC => INV
  - » For each t , INV' & PRE'(t) & POST(t) => INV & CON
- Limited type checking
- PASCAL-like syntax
- Levels (of refinement)
  - » Additional VCs
- Derived from Ina Jo research (R. Kemmerer at UCSB)

Portion of an ASLAN Spec

State

```
TYPE ...
        book is structure of (
            title : string,
            author : string,
            subject : string),
        copy,
        copies is set of copy
VARIABLE ...
        db: library,
        staff: users,
        borrower(copy): user,
        next_id: pos_int
```

Properties

```
INITIAL
        db = empty & staff = empty & next_id = 1
INVARIANT
        forall c:copy
        (c isin db -> available(c) xor borrower(c)~=noone)
        &
        cardinality(db,next_id-1)
```

Steps

```
TRANSITION check_out(c:copy, u:user, s:user)
ENTRY   c isin db & available(c) & s isin staff &
         under_lim(u)
EXIT    borrower(c) becomes u

...
```

An ASLAN-generated Verification Condition

consistency conjecture for check_out(c:copy, u:user, s:user):

(forall c:copy
c isin db' -> c[available] xor c[borrower] ~= noone
&
c isin db' & c[available] & s isin staff' & under_lim'(u)
&
~c[available] & c[borrower]=u
&
db = db'
&
staff = staff')

Invariant before

Transition Effects

⊃ ->

(forall c:copy
c isin db -> c[available] xor c[borrower] ~= noone
&
true)

Invariant After

e, indicating that no back-
ocess has been selected for exe-
o interrupts are active, the pro-
ile, and the Select operation
n spontaneously. It is specified

---

g = none

rund' = background
ready
' ∈ ready
uller' = θIntHandler

---

ran a part of the interface be-
kernel and an application. Se-
ternal operation of the kernel
appen whenever its precondi-
. The precondition is

none ∧ ready ≠ ∅

ssor must be idle, and at least
ound process must be ready to
rst part of this precondition is
icitly, and the second part is im-
predicate

ready

value of current is selected
but the specification does not
choice is made — it is non-
ic. This nondeterminism lets
cation say exactly what pro-
may rely on the kernel to do:
guarantee that processes will
din a particular order.
nondeterminism is a natural
e of the abstract view I have
specification. Although the
at implements this specifica-
ministic — if started with the
esses in a certain state, it will
the same process — it ap-
ondeterministic if you pay at
to the set of processes that are
e done in the specification.
e kernel selects the new cur-
the specification says that it
because of the static schedul-
ich determines that after the

In Z, the schema *X* is defined by the form

X
declarations
predicates

Z notation

Global functions and constants are defined by the form

declarations
predicates

The declaration gives the type of the function or constant, while the predicate gives its value. Here, I define only the Z symbols used in this article:

Sets:

$S : \mathbb{P} X$	*S* is declared as a set of *X*'s.
$x \in S$	*x* is a member of *S*.
$x \notin S$	*x* is not a member of *S*.
$S \subseteq T$	*S* is a subset of *T*: Every member of *S* is also in *T*.
$S \cup T$	The union of *S* and *T*: It contains every member of *S* or *T* or both.
$S \cap T$	The intersection of *S* and *T*: It contains every member of both *S* and *T*.
$S \setminus T$	The difference of *S* and *T*: It contains every member of *S* except those also in *T*.
$\emptyset$	Empty set: It contains no members.
$\{x\}$	Singleton set: It contains just *x*.
$\mathbb{N}$	The set of natural numbers 0, 1, 2, ...
$S : \mathbb{F} X$	*S* is declared as a finite set of *X*'s.
max(*S*)	The maximum of the nonempty set of numbers *S*.

Functions:

$f : X \rightarrowtail\!\!\!\!\!\!\rightarrow Y$	*f* is declared as a partial injection from *X* to *Y* (described in the handler definition on p. 23).
dom *f*	The domain of *f*: the set of values *x* for which *f*(*x*) is defined.
ran *f*	The range of *f*: the set of values taken by *f*(*x*) as *x* varies over the domain of *f*.
$f \oplus \{x \mapsto y\}$	A function that agrees with *f* except that *x* is mapped to *y*.
$\{x\} \lhd f$	A function like *f*, except that *x* is removed from its domain.

Logic:

$P \wedge Q$	*P* and *Q*: It is true if both *P* and *Q* are true.
$P \Rightarrow Q$	*P* implies *Q*: It is true if either *Q* is true or *P* is false.
$\theta S' = \theta S$	No components of schema *S* change in an operation.

Z structure - schema

Stop
ΔState
running ∈ *background*
background' = *background* \ {*current*}
ready' = *ready* \ {*current*}
current' = *none*
θ*IntHandler'* = θ*IntHandler*

For this operation to be permissible, the processor must be running a background process. This process is removed from background and ready, and the current

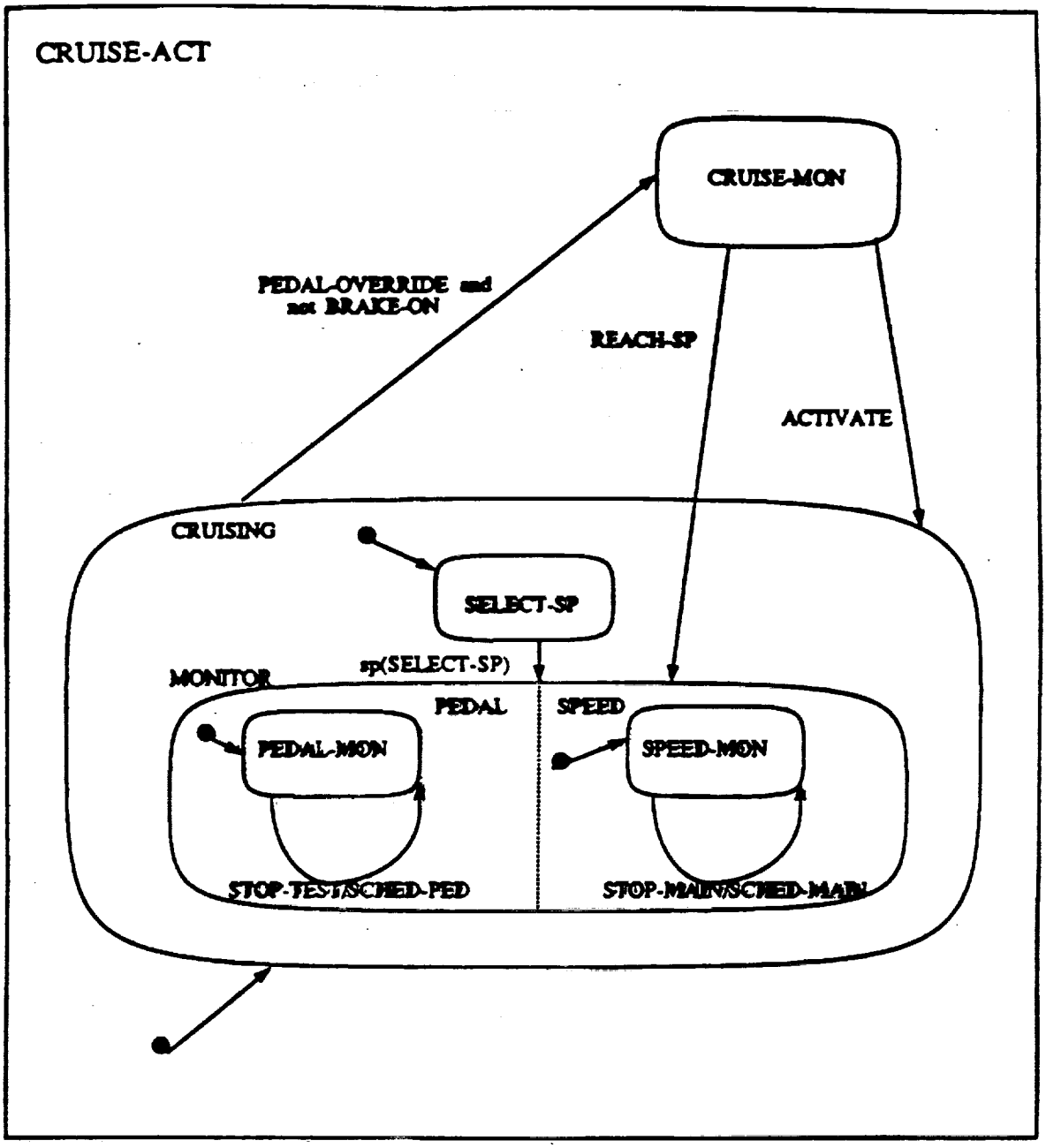
puts, the process identifier and a flag, which takes one of the values set or clear:

FLAG ::= set | clear

The SetReady operation is:

SetReady
ΔState
p?: *PID*
flag?: *FLAG*
p? ∈ *background*
flag? = *set* ⇒ *ready'* = *ready* ∪ {*p?*}

Statecharts



throughout PEDAL-MON - TEST-PED-DEF
throughout SPEED-MON - MAINTAIN-SP
throughout SELECT-SP SELECT-SP
throughout CRUISE-MON - TEST-PED-DEF and CHECK-SP

STOP-TEST - stopped(TEST-PED-DEF)
STOP-MAIN - stopped(MAINTAIN-SP)
SCHED-PED - schedule!(start!(TEST-PED-DEF),n seconds)
SCHED-MAIN - schedule!(start!(MAINTAIN-SP),n seconds)

Cruise-Act State

STATEMATE, I-Logix, Inc

Figure 4: Cruise State Zoom-in

MCC FM Testbed

Tools Catalogue

Languages

- NonExecutable:
  Z, VDM (at least 2 flavors), ASLAN, Larch, Estelle, ...
- Executable: (prototyping)
  Miranda, OBJ, me too, StateChart, Caliban,D, Prolog

Static Analysis

FUZZ, ASLAN + (all executable systems)

Language-tailored Environments

Raise, Larch, Gist, Statemate

Concurrency-centered

CSP, CCS, Unity, Petri-nets, Spec, Lotos, ...

Temporally focused

L.0, ASLAN-RT, RTL, Timed CSP, Tempura, TempLog,

Theorem Provers

Boyer-Moore, HOL, Clio, m-EVES, B, Isabelle, OBJ, EHDM, Gypsy, uRAL...

Sample Applications in Progress

Project	Parties	Problem	Status
CICS	Oxford PRG IBM Hursley	Transaction Processing	Released, Measured (??)
Cleanroom	IBM FSD NASA SEL	Embedded, Restructurer	Released Evaluated
ZEE	Tektronix	Oscilloscopes	On-going
Avalon/C++	C-MU	Atomicity	Preliminary
GKS, OA Doc.	British Standards Institute	Graphical, Documents	Published
Hypertext Ref. Model	Dexter Group Denmark	Hypertext Concepts	Report VDM90
SXL	GTE Labs	Protocols	In use
L.0	Bellcore	Protocols	In use
CASE	Praxis	Object Manager	Report, product
Anti-MacEnroe Device	Sydney Inst. Technology	Tennis Line Fault Detector	Report (Occam,CSP)
Security VIPER	Honeywell Ford Aero. Digital TIS RSRE, Cambridge	LOCK Multi-net Gateway Secure VMS Trusted Mach Microprocessor Tools	In progress " " " Reports Newsletter
Verified Stack	CLinc	Microp, assembler, O.S.	Reports
Oncology	U. Wash.	Cyclotron	Starting
Reactor Control	Parnas, Ontario Hydro	Shutdown Certification	Reports, Certified
Murphy	U.C. Irvine	Safety	Reports
SACEM	French RR	Train Control	ICSE12

Standards

Security "Orange Book" -NSA

Safety

MoD 0055/56 (interim)

Hazard analysis +

Safety-critical development proces

SafeIT - goals (UK DTI)

- technically sound
- generic
  - sector - transportation, medica
  - application
- feasible
- international

[NIST standards]

Motivations

Safe systems

High integrity industry competitio

Trade advantage (1992)

SOFT NEWS

How software affects the world. How the world affects software.

Editor: Galen Gruman
IEEE Software
10662 Los Vaqueros Cir.
Los Alamitos, CA 90720
Compmail: soft.one
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Software safety focus of new British standard

Galen Gruman, Soft News Editor

The British Defence Ministry expects to issue a new software-safety standard this spring that will require the use of formal methods and mathematical verification on all safety-critical software. Only developers who prove that their software is not safety-critical will be exempt from the requirements.

The standard, MoD-Std-0055, will ban the use of assembly language, limit the use of high-level languages like Ada to safe subsets, and require the use of static analysis. It also sets standards for project engineers. It will require that an engineer sign off on the software's safety compliance, that the engineer have taken accredited formal-methods instruction within the past two years, and that an independent engineer with similar accreditation also sign off on the system. This is similar to the responsibility and requirements enforced on systems-safety engineers for the overal project.

The 0055 standard will be in effect for two years, during which time the Defence Ministry will revise it on the basis of industry's experience. The intent is to develop a long-term standard, said Kevin Geary, a software consultant for the British navy's procurement department who is working on the 0055 standard. The ministry is also working on MoD-Std-0056, a hazard-analysis standard that will help software developers determine where to apply formal methods and mathematical verification, Geary said. "Both mathematical verification and hazard analysis must be performed to provide software with acceptable risk. Neither is adequate alone," said Nancy Leveson, a software-safety expert and a computer-science professor at the University of California at Irvine.

Pros of formal methods. The 0055 standard has been called a "landmark" by those in the software-safety and formal-methods communities, who argue that assigning responsibility to software engineers, as has been tradition in hardware engineering, will help encourage changes in development methods that will help assure safe systems. Safety is increasingly important because software is becoming a greater part of critical systems like aircraft controls, medical devices, nuclear-power plants, early-warning defense systems, and missile controls, they said.

Most software-engineering standards depend on testing, which is not always reliable, Geary said. "The problem with software is that you must test against specifications. If you didn't get the specifications right, you might not get the software right," he said. However, mathematical analysis of formal specifications notations can be used to find errors in the specifications, Leveson said.

The forthcoming UK Defence Ministry standard will require the use of formal methods and mathematical verification for safety-critical software.

The increasing number of tools like Zed, Vienna Development Method, Spade, and Malpas will help make the implementation of formal methods possible because these tools can perform static analyses of information flow and semantics quickly, rather than in the years required with manual techniques, Geary said.

Formal methods and mathematical verification are often considered too difficult to apply, Geary conceded. "There is a lot of unease, but it's quite surprising that there are a lot of key people who've come around after looking at it," he said. Geary cited IBM's British development center, which decided for commercial reasons — not for government or other outside requirements — to use the Zed formal method on CICS development. "People's resistance is based on ignorance," Geary said.

Another source of resistance is the confusion between formal, mathematical methods and mathematical correctness. "Correctness is a meaningless goal for real systems. For example, do you have a 'correct' airplane?" Leveson said. "A more realistic and useful goal is to build a system that satisfies agiven set of functional and mission requirements while at the same time trying to satisfy constraints of safety, security, and cost," she said. Many of these goals involve trade-offs in setting priorities, she said.

Leveson compared formal methods to traditional hardware engineering: "Engineers build formal mathematical models and then use analysis methods to determine whether the model has certain desired properties," she said, "which should be the role of formal methods in software engineering." (Leveson's "Safety as a Software Quality" essay in this issue's QualityTime, on pp. 88-89, gives more details about this process.)

"Both software engineers and hardware engineers specify design," Geary said. "The only difference is how tangible [the product] is," he said.

Still, software engineers do face a burden that their hardware counterparts generally do not: the complexity of their product, said Martyn Thomas, chairman of Praxis Systems, a software-engineering consulting firm in Bath, England, that does much work in safety engineering. Traditional engineers like bridge builders "never had techniques for design, which is more important for software because that's where the complexity comes in. It's not a software problem but a design-complexity problem," he said. Whether overtly or covertly, the profes-

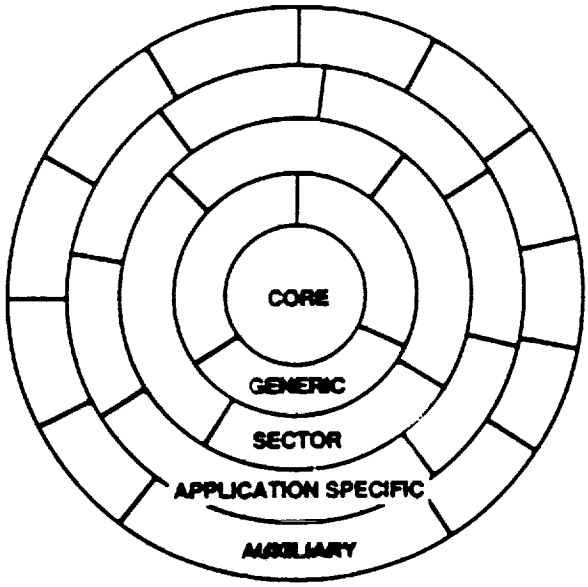
"17. Specification

17.1 Safety Critical Software shall be specified using formal mathematical techniques. A specification of the Safety Critical Software shall also be produced in clear English. Both specifications shall be included as part of the Procurement Specification. A list of formal mathematical specification techniques is given in Annex L."

- VDM, Z, OBJ, HOL, CCS, CSP, Temporal Logic, Lotos

Figure 1 Structure of the Framework

Components



Hierarchy

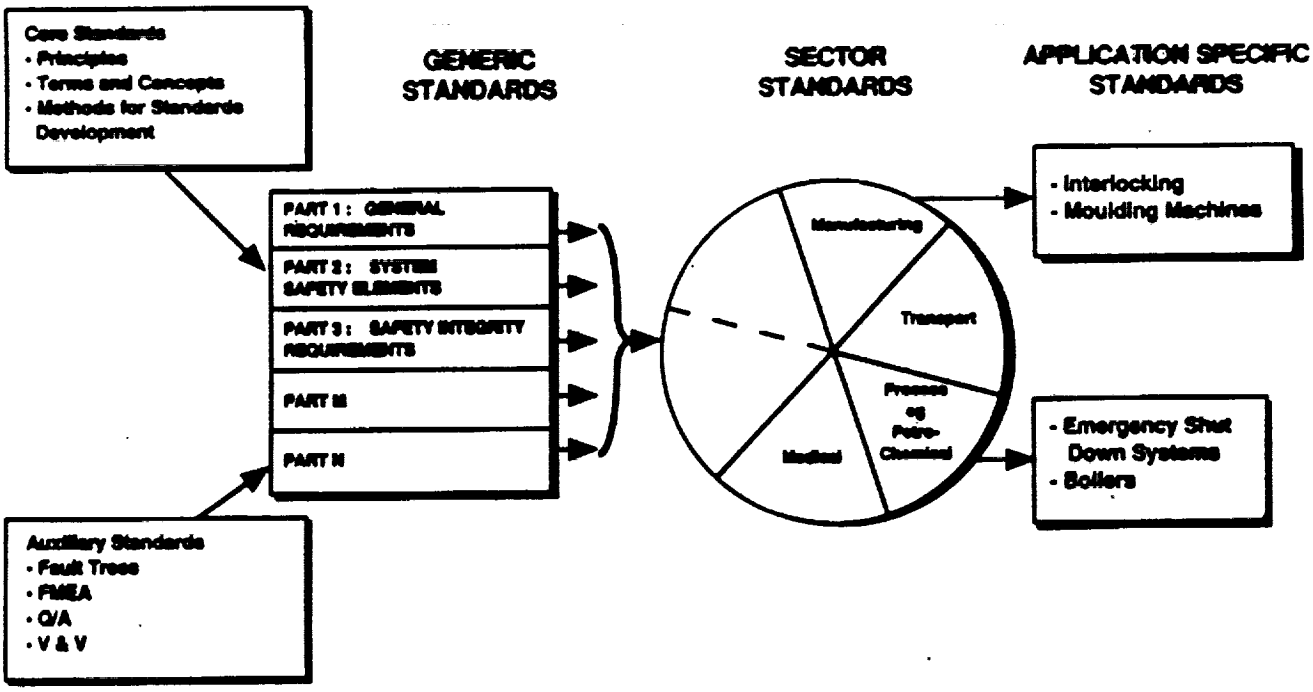


Table 1: Summary of Objectives
Overall Objective: Assured Integrity

Main Objectives	Sub-Objectives
adequate specification of safety features Adequate Spec	clarity and precision management of complexity self consistency
validity Validity	valid translation of PES specification to software defined and valid specification of other PES components defined and valid specification of external systems eg physical, software, human and maintenance systems fault detection, toleration and management defined
implementation (code) satisfies specification Satisfies Spec	clarity and precision management of complexity self consistency adequate refinement
integrity of management and development process Process Integrity	commitment of senior management motivated and competent staff active and effective management controls
integrity maintained during operation Integrity maintained	maintenance specified during design integrity of maintenance process integrity of modifications security of software code
assurance Assurance	comprehension empirical and analytical evidence recognition of residual doubt and fallibility demonstration to second and third parties valid reasoning system

SafeIT: A Framework for safety Standards, June 1990
ICSE Secretariat, Dept. of Trade & Industry,
ITD2a - Rm. 840, Kingsgate House
66/74 Victoria Street London SW1E 6SW

Objective: adequate specification		
Sub-Objectives	**Techniques**	**IEC techniques**
clarity and precision	formal specification language with defined syntax and semantics; graphical representation; application specific language/engineering notations — block diagrams, Process and Instrumentation diagrams, algebra, z transforms, discrete equations; natural language annotations; structured natural language; subsets of languages	formal mathematical modelling; data flow diagrams; finite state machines/state transition diagrams; structure diagrams
management of complexity	abstraction; modularity; information hiding; structured design technique	formal mathematical modelling; data flow diagrams; finite state machines/state transition diagrams; structure diagrams
self consistency of specification	animation — proof of invariants and theories; semantics for notations; review and inspection; execution of properties — prototyping of selected properties; testing	prototyping/animation; simulation; functional testing; formal mathematical modelling; Fagan inspections; formal design reviews
validity	*see next table*	

Formal Spec. Lang./Methods

ASLAN - state transition

Z - set-based

Larch - theories

CCS, UNITY - concurrency

Statechar - finite state

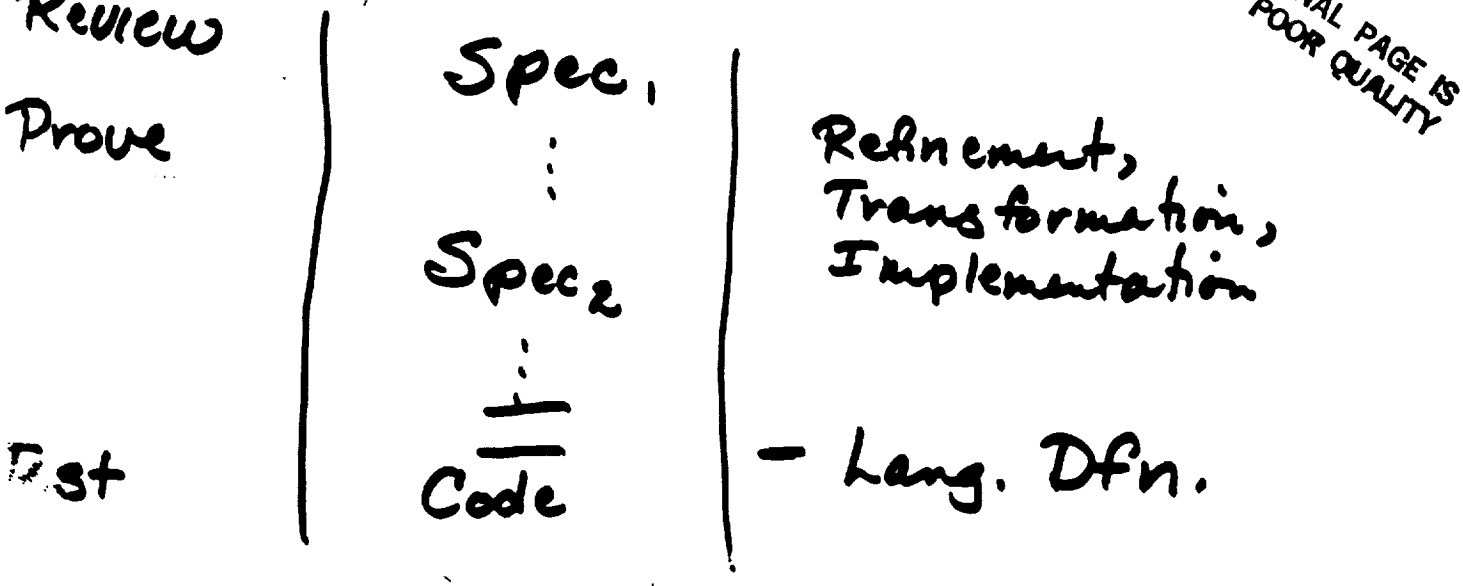
graphics + formal text + informal text

Tools

Provers ← Symbolic analysis → Tests

Usable..

Sub-Objectives	Techniques	IEC techniques
clarity and precision	formal specification language with defined syntax and semantics; graphical representation; application specific language; engineering notations — block diagrams, Process and Instrumentation diagrams, algebra, z transforms, discrete equations; natural language annotations; structured natural language; subsets of languages	formal mathematical modelling; data flow diagrams; finite state machines/state transition diagrams; structure diagrams
management of complexity	abstraction; modularity; information hiding; structured design technique	formal mathematical modelling; data flow diagrams; finite state machines/state transition diagrams; structure diagrams
self consistency of specification	animation — proof of invariants and theories; semantics for notations; review and inspection; execution of properties — prototyping of selected properties; testing	prototyping/animation; simulation; functional testing; formal mathematical modelling; Fagan inspections; formal design reviews
adequate refinement	logical reasoning; review/inspection; testing; static analysis; experimentation; experience in the field; diversity of tools and people; use of subset of programming language; languages that can cope with different levels of abstraction	Fagan inspections; formal design reviews; formal proof of program; sneak circuit analysis; walkthroughs; functional testing



K.4 Integrity of process

106 As in any engineering endeavour, the integrity of the development and management process is essential to the achievement and assurance of integrity. There is a requirement that the system is what it seems, that documentation is adequate and under configuration control and that the claims made about the system are valid.

Objective: integrity of process		
Sub-Objectives	**Techniques**	**IEC techniques**
active and effective management controls	QMS to ISO 9000; independent QA; automated configuration management; manual configuration management; clear delineation of authority and responsibility for safety; adequate project planning, cost estimation and monitoring tools and procedures	checklists; Fagan inspections; formal design reviews
commitment of senior management to safety and quality	awareness campaigns; certification approval schemes; demonstration of economic benefits; regulatory inspection; liability; standards; safety culture	
motivated and competent staff	competency of key staff (eg to BCS Safety Critical Curricula); experience in application domain and of software techniques used in project; qualification to Chartered Engineer status; status and pay; professional development; certification; safety culture	

107 Note: Within this technical framework only recommendations concerning management controls and competency of staff can be made. Other factors are important and should be addressed during the project (eg safety culture considered in the selection of contractors). Similarly, broad security issues have not been considered. It may be possible in future versions of the Framework to reference out these objectives to a QMS standard.

operational phase. The integrity can be compromised in three ways:

(i) Maintenance and modification activities are inadequate. It should be appreciated that maintenance can be a dominant source of common mode failures in redundant systems. Also, maintenance will be particularly important in long lifetime systems or systems which are expected to evolve.

(ii) Security of the embedded code is violated. General consideration of security are outside the scope of this framework, for further discussion see the publications from the DTI Commercial Security Centre [9].

(iii) Failures in the system violate the stated conditions under which the integrity is ensured. The detection, toleration and management of such changes are addressed in the section on validity (K.2) and are not considered further in this section.

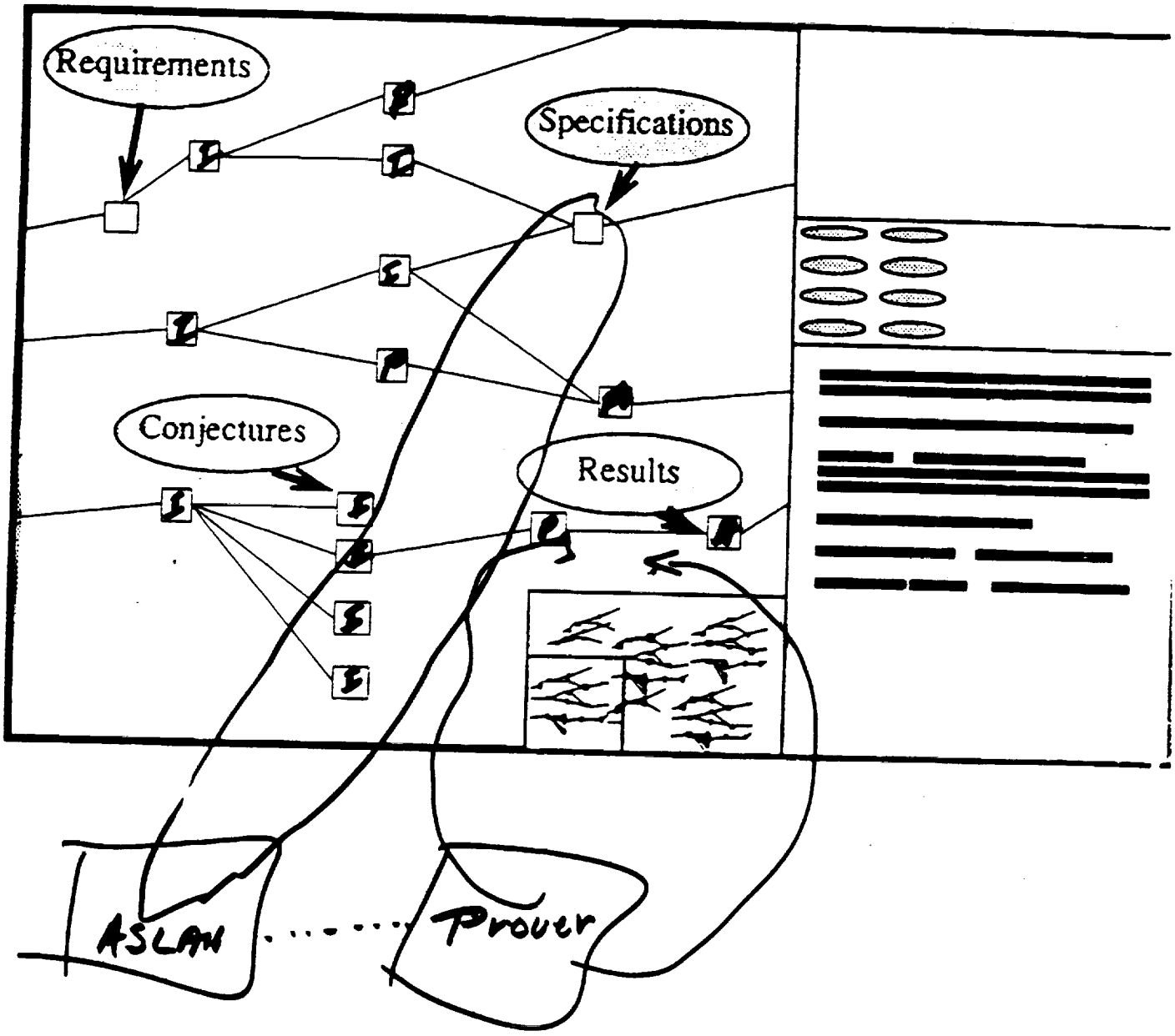
109 The need for maintenance of the hardware and software will affect the design of the software structure and fault handling, reporting and recovery mechanisms. This is addressed in section K.2.

Objective: integrity of software maintained during operation		
Sub-Objectives	Techniques	IEC techniques
integrity of maintenance process	maintenance planning and standards; manual configuration management; automated configuration management; authorisation procedures; availability of qualified staff; development facilities; Quality Management Systems	
integrity of modifications	application of design standards and development standards to modifications; regression testing; procedures for assessing impact and importance of change; modularity and structuring	
security: software code unchanged	robust storage media; security; administrative access controls; passwords; safety critical data not changed by operational staff; encryption and other fault tolerant techniques	error correcting codes

Objective: Assurance

comprehension	timely provision of documentation; visible lifecycle; satisfaction of other framework objectives	
empirical and analytic evidence	*See 'satisfaction of specification'. In addition require:* proof deliverable; appropriate V&V techniques — dynamic testing, logical reasoning, documented reviews; evaluation of operating experience of identical and similar systems; use of proven or certificated components	formal proof of program; checklists; Fagan inspections; formal design reviews; boundary value analysis; error guessing; error seeding; performance modelling; simulation; test coverage; functional testing
recognition of residual doubt	claim limits; design guidance (e.g. 'no single failure criterion') on system level diversity	
recognition of fallibility	diversity of tools, techniques, people and organisations — IV&V, ISA; diverse proof checker; diversity of other tools; robust design — fault detection and containment; QA and technical review	checklists; Fagan inspections; formal design reviews; fault detection and diagnosis
demonstration to second or third parties	involvement of customer; QA within a QMS; liason with customer QMS; compliance with Health and Safety at Work Act and other relevant legislation and standards; safety record log or accomplishment summary; certification of people, procedures and components	checklists; Fagan inspections; formal design reviews
valid system of reasoning	accepted mathematical inference system or calculus; empirical evidence; common language	formal mathematical modelling

MCC SpecTra Screen Mock-up



See: RICIS hypermedia conf., Dec. GERM

MCC Extensions: Hypertext Issue Model

```
label:: books
type:: declaration
date:: Jun 14 10:05 1990
author:: greene
Contents:: books is set of book
```

Figure 7 *Contents of the* `Decl` *node labeled* `books`

Besides the `one-of` links (denoting the set membership relation), there are `is-of-type` and `depends-upon` links (*v* `is-of-type` *t* when *v* is a state variable and *t* is its type and `Decl` *d1* `depends-on` `Decl` *d2* when the declaration *d2* mentions the formal entity declared in *d1*). These links are by default invisible (to cut down on the clutter) but can be displayed at the user's request. For example, a user can click on a transition node (a node containing the entry and exit conditions of an ASLAN transition) and ask for all of the nodes in the specification on which this transition depends. SpecTra then highlights all of the nodes in the specification which can be reached by starting at the clicked upon node and following `depends-upon` links. Thus the graphical representation of an ASLAN specification is easier to browse than the textual representation. SpecTra is also able to highlight all the nodes which depend upon a user specified node. This eases the task of specification modification as users can be pointed to all the parts of the specification which will be affected by a change.

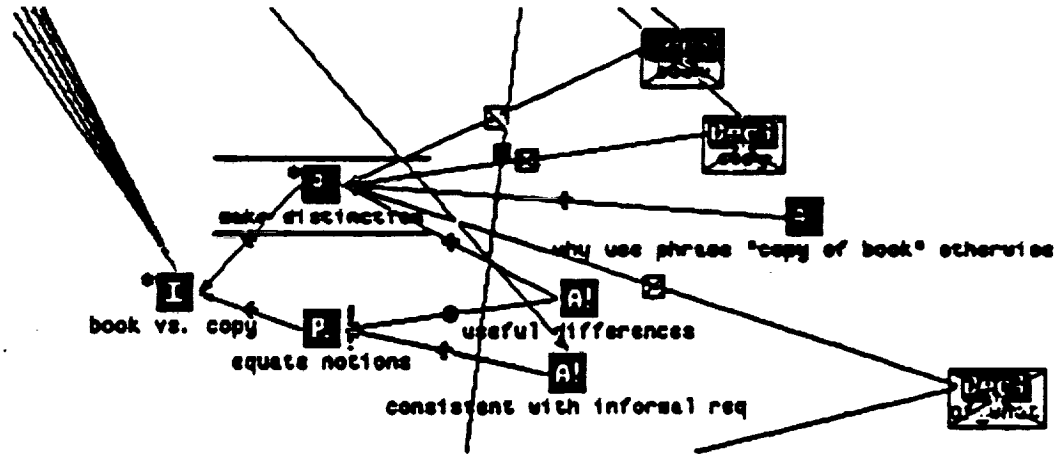
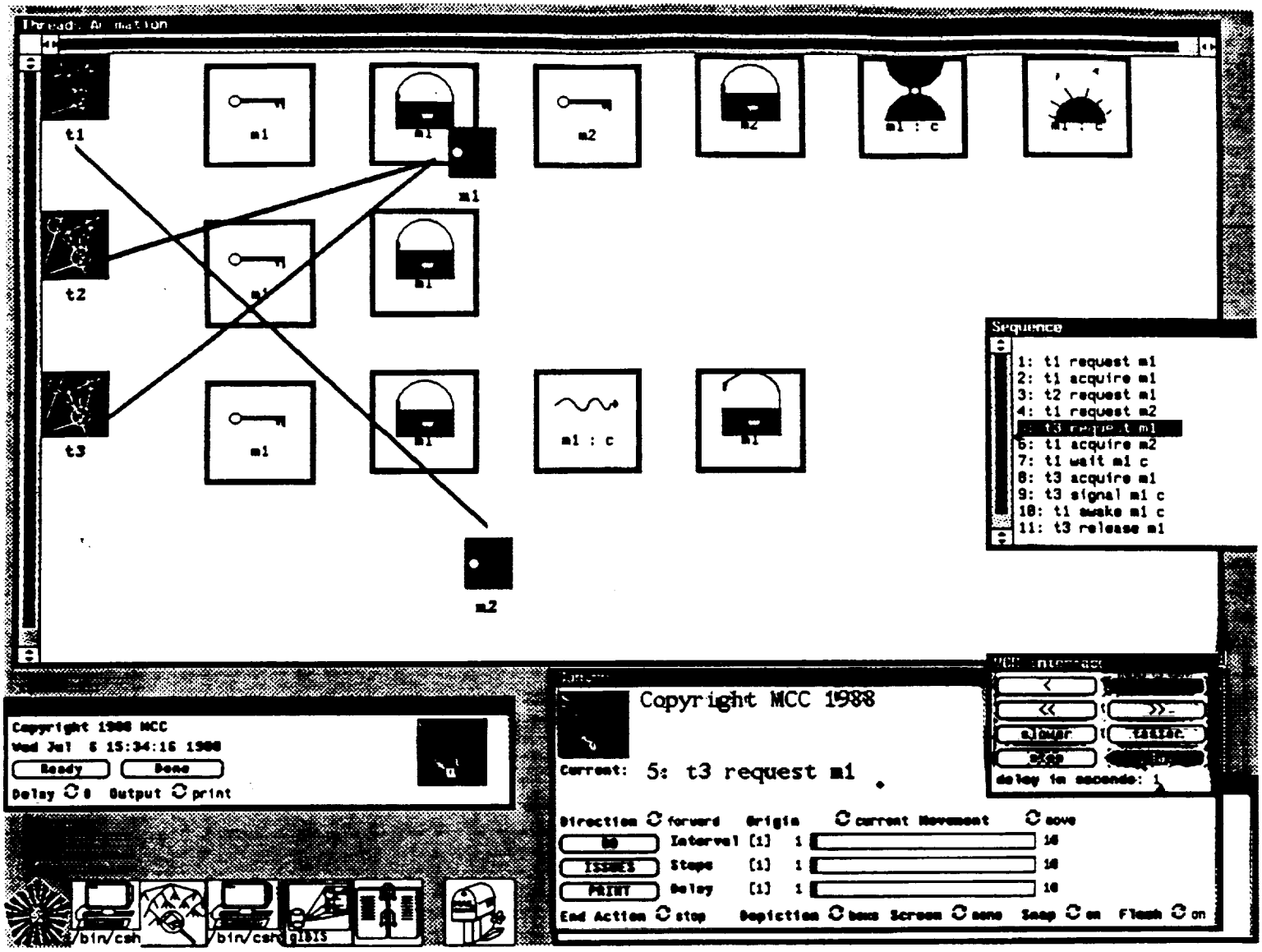


Figure 8 *Informal requirements linked to formal specification*

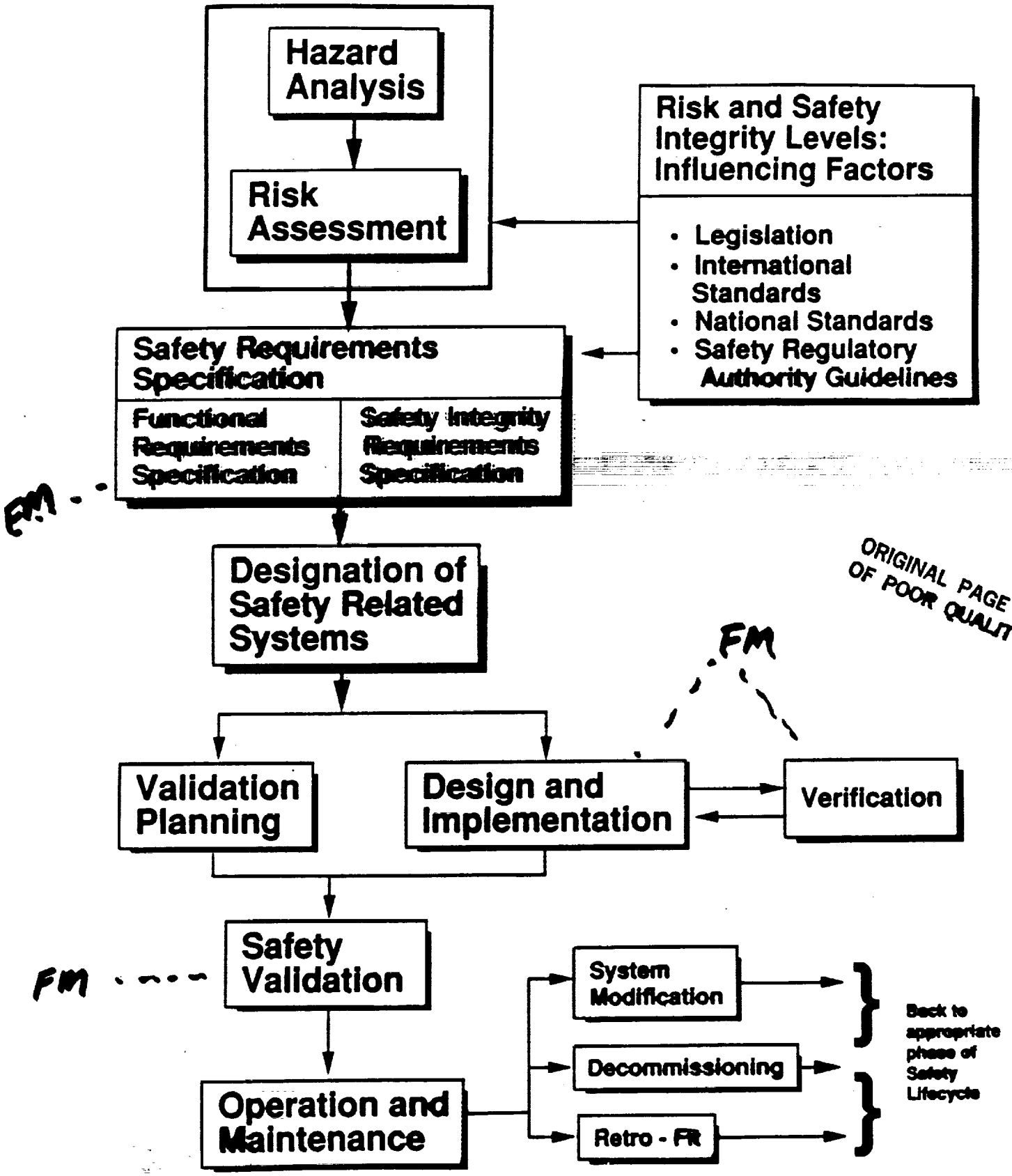
Using these new node and links types, formal ASLAN specifications can be entered and browsed within Gem. Additionally, I/P/A structured informal requirements may coexist in the database and these informal notions may be linked to the portion of the formal specification which is their formalization. For example, in the process of coming up with requirements for the library database, the following issue arose. Should the concepts *book* and *copy* be identified? Arguments (pro and con) were given and it was decided that these two notions should be distinguished. The position taken was that a book was something abstract and that a copy was an instance of that abstraction. The links between this posi-

MCC Extensions: Animation



Animation of Process (threads) Spec

Figure 2 Relationship of the risk and safety integrity levels to the Safety Lifecycle Model



Conclusions

SafeIT could be used to define support needed for trustworthy system development, e.g. Space Station

Techiques	×	Sector, Application	×	Ada
Formal Meth. Safety Eng. Software Eng.				≡

Preliminary Assessment – FM

- Evidence for effectiveness
  - IEEE Sw, Computer, TSE Sept. '90
  - FM89 ... Springer Verlag 1991
- Education basis
  - SEI MSE, texts, network groups
- Tool environments weak
  - Proven Interfaces --?--> Formal CASE

MCC Formal Methods Project

1) Transition Study

Survey, assess
Experiments
Education

14 organizations, incl. NASA, MITRE, Rockwell

2) SpecTra

Hypertext platform

Nodes - specs.
Links - process, dependencies

"Executable specs"

Logic & functional prog.

Hybrid methods
Integrating tools

MCC

Formal Methods Transition Study

Call for Participation
April, 1990

Interest is growing worldwide in the application of precise mathematical techniques to the specification and design of hardware and software systems. In fact, European successes in this area, commonly called *Formal Methods*, have already led governments to require that the techniques be used for safety critical systems.

MCC's Software Technology Program proposes a one-year in-depth study of Formal Methods techniques and the tools that support them. Drawing upon significant research experience at MCC, we will assess the state of the art worldwide and determine the implications for a variety of North American industries.

This proposal describes the background, rationale, and contents of the funded study, including its timeline and deliverables. Our goal is to provide executives with the information they need to ascertain their own companies' requirements in the Formal Methods area. For those whose interest calls for further technology development, this study will also establish a plan for appropriate research and development work.

Background, Rationale: Formal Methods, a body of techniques supported by powerful reasoning tools, offer rigorous and effective ways to model, design, and analyze systems. Several research groups, primarily in Europe, have generated specification, implementation, and verification techniques for a broad class of systems, and have cast the techniques into industrially usable forms. Their affiliated companies have already employed several of these techniques in the development of real-world hardware and software applications. Attention by governments and industry is increasing as well, due in large part to a growing concern with the high risks of faulty computer control in systems critical to life and property. Indeed, certain combinations of Formal Methods are now seen as necessary for ensuring that these systems meet existing regulations and standards, or that they avoid legal liability repercussions. And there are other, broader applications for these techniques as well; in particular, they can help circumvent many of the expensive problems of general software development practices, such as late discovery of errors and poor communication among end users, designers, specifiers, and implementors.

MCC is in a unique position to build on the progress in Formal Methods. Even today, a number of tools and techniques developed in MCC research laboratories can be brought to bear. For example, Software's issue-based design methodology can be integrated with Advanced Computing Technology's declarative language technology and with externally developed Formal Methods-based toolsets. MCC researchers have proposed several novel ways in which to exploit MCC-developed techniques to advance Formal Methods research. Moreover, researchers in the Software Technology and Computer-aided Design programs are investigating CoDesign—design and analysis techniques spanning both hardware and software. So that we may capitalize on worthwhile outside developments as they occur, MCC's International Liaison Office closely monitors the maturation of Formal Methods techniques in Europe and gauges industrial and government interest in both Europe and the U.S. At the same time, MCC's experiences with technology transfer continue to give us bountiful insights into the problems and operations of MCC's sponsoring organizations.

Content of Study: We propose to study Formal Methods issues as they directly relate to North American companies. First, we will determine how Formal Methods can help these companies meet demands for higher quality, possibly regulated software-intensive systems. Second, we will pinpoint how the companies can exploit Formal Methods in current environments for more productive software development processes.

The study will explore the issues and topics that pertain to a full-scale Formal Methods research effort at MCC, including:

Fundamental concepts of Formal Methods—what is a formal method, and how does it work?

Training and instructional material—sample course outlines, evaluation of course offerings.

Modes of using formal methods—specification, verification, documentation, refinement; integration with object-oriented and other widespread approaches; consistency of artifacts from requirements through code.

Survey of major applications—summaries of Formal Methods projects to date, interpretations of collected project data, evaluation of successes and failures, derived guidelines for applications.

Tools survey—catalog of editors, syntactic/semantic checkers, theorem provers, and other tools; MCC experiments with North American and European toolsets; assessment of state of toolsets.

Models of formal-based software development—injection of techniques into standard productivity, risk, and QA models; scenarios of future development processes.

Regulatory and legal trends in safety and security—the high-integrity market sector; research funding patterns (U.S., Europe, and Japan); forecasts of error and development costs, adoption patterns, optimistic and pessimistic scenarios.

Transitional tips—what to teach, to whom, and follow-through; projects to try; pitfalls, motivation, and so on.

Experimental results—results of using MCC technology and personnel, along with imported tools, instructors, consultants, and other studies, to apply Formal Methods to industrially relevant problems. These experiments will illustrate many of the above topics.

Research needs and strategy.

Timeline and Deliverables: The proposed study will be conducted from September 1, 1990, to September 30, 1991. At the end of this period, participants will receive a comprehensive report covering the topics outlined above, together with video overviews, tool demonstrations, and thorough accounts of experimental protocols and results. Drafts of the report's topics will be available at quarterly intervals; midterm and final reviews and information sessions will occur at the MCC site; and at least one formal interaction will be designed according to the specific interests of each participant (within the domain expertise limits of MCC personnel).

The study in its entirety will be proprietary to participants for one year, after which MCC may distribute it more widely. Selected sections reporting experimental results and new insights of interest to the research community may be published as technical reports and papers during the course of the study, both to further the field and to establish the MCC Formal Methods initiative in the research community.

Costs: Costs for the study will be targeted to ten participants at $60,000 each. Membership is open to all MCC shareholders and associates; non-member companies can opt to participate in MCC for the one-year study period only, paying a special Project Associate fee of $7,500 in addition to the study participation fee. Should there be more than ten participants, additional personnel will be added to increase the study's scope and depth.

A full-scale, multiple-year Formal Methods initiative will be proposed in mid-1991. While the study's report will motivate many of the initiative's activities, it will not constitute a full definition of those activities. Study participants have no commitment beyond September 1, 1991; however, if a participant does elect membership in the initiative, it may deduct $25,000 from the cost of membership over the first two years.

Personnel: The MCC researchers who will conduct the study are broadly experienced in the theory and application of Formal Methods techniques and tools. They are also experts in tracking and forecasting technology trends. The study coordinator, Dr. Susan Gerhart, has led a major U.S. formal verification project and participates in international Formal Methods strategic activities. Other project members are experts in a variety of tools (already assembled at MCC), techniques, and theories and have applied them to industrially interesting problems. This unique group has been cooperating for a year and will be complemented by consulting expertise from outside MCC as well as from related MCC projects.

For more information, contact:

Susan Gerhart
(512) 338-3492
gerhart@mcc.com

Ted Ralston
(512) 338-3547
ralston@mcc.com

Microelectronics and Computer Technology Corporation
3500 W. Balcones Center Drive
Austin, Texas 78759

Issues Related to Ada 9X

John McHugh
Computational Logic, Inc.

Recent Ada 9X Activities

John McHugh

Baldwin / McHugh Associates
Durham, North Carolina

8 November 1990

OVERVIEW

- Ada 9X
- The 9X process
- Issues for Critical Systems

Ada 9X

ISO Standards such as Ada must be reviewed for possible revision every 10 years. The review process can

- Leave the standard unchanged
- Withdraw the standard
- Initiate a revision process

Ada 83 is undergoing a revision. The new language will be known as Ada 9X.

- The current expected value for X is 3.

The Ada 9X Process

The Ada 9X process is being managed by the Air Force out of Eglin AFB, Fla. The project manager is Christine Anderson.

- Revision requests submitted 88-89
- Requirements workshops 89-90
- Distilled to revision issues by IDA
- Requirements document - drafts fall 90
- Inputs still coming from interest groups
- Mapping contractor (Intermetrics) will map requirements into revised language

My Subjective View of Process

The following represent my own , distinctly minority view of the process.

- The ground rule that calls for upward compatibility at all costs does more harm than good as it guarantees a more complex language.
- As Ada tries to be all things to all people, dialects and subsets will become necessary.
- A rational approach is probably not possible. Without it, Ada 9X will not be a substantial improvement over Ada 83 and Ada will eventually collapse under its own weight,

Ada 9 X and Critical Systems

As a part of the revision that Ada is undergoing , the trusted systems community has raised a number of issues. They are summarized in the following slides.

Requirement A

IDENTIFY AND *JUSTIFY ALL* ELEMENTS OF THE STANDARD THAT PERMIT UNPREDICTABLE PROGRAM BEHAVIOR.

e.g., Program blockage

Integer (1.5) $\stackrel{?}{=}$ Integer(1.5)

INTENT IS TO ELIMINATE WHERE POSSIBLE AND FORCE ANALYSIS AND COST BENEFIT DECISION ELSEWHERE.

REQUIREMENT A -continued

1) Eliminate most erroneous cases
2) Eliminate "incorrect order dependency"--define order-dependent semantics
3) Define undesirable implementation dependency (UID)
4) UID has defined effect, not cause for "program error"
5) Implementations shall attempt to detect remaining erroneous and UID cases
6) Specific cases of undefined variables:
   a. Majority - URG position on LHS usage
   b. Minority - catch all usage

REQUIREMENT B

EXPOSE IMPLEMENTATION CHOICES

1) Language choices (LRM alternatives)
2) Implementation strategy (storage management, scheduling, etc.)
   - Static choices
   - Dynamic choices
   - What can user control?
   - How can information be shared with others? With tools?

   Choices include:

   a) Parameter passage
   b) Optimization
   c) Heap vs stack vs ...storage management

REQUIREMENT C

ALLOW USERS TO CONTROL

IMPLEMENTATION TECHNIQUES

Certain implementation choices lead to explosive growth in possible execution behaviors.

Implementations must honor–or reject with warnings–user directives for items such as parameter passing mechanisms, orders of evaluations, etc.

This is analogous to the representation specification for data.

REQUIREMENT D

IMPLEMENTATIONS SHALL ATTEMPT COMPILE OR RUNTIME ANALYSIS FOR KNOWABLE INSTANCES OF UNSOUND PROGRAMMING AND ISSUE WARNINGS/EXCEPTIONS AS APPROPRIATE.

- Aliasing
- Unsynchronized sharing
- Uninitialized variables
- Etc.

REQUIREMENT E

PROGRAM BEHAVIOR TO BE DEFINED OR PREDICTABLE IN THE FACE OF OPTIMIZATION

We call for further study on the following

- Canonical order of evaluation vs radical optimizations
- Exceptions
- Side effects
- Possibility of pragma control

REQUIREMENT F

FORMAL STATIC SEMANTICS AS PART OF ADA 9X STANDARD

The formal definition to be accompanied by tools that facilitate use for answering questions about the legality and meaning of programs.

While this does not necessarily change the language, development of the definition and tools may contribute to language changes.

N.B. Parameterize formal definition for implementation decisions and architecture/environment.

REQUIREMENT G

DYNAMIC SEMANTICS AS ONGOING EFFORT WITH AIM OF INCORPORATIONS IN NEXT STANDARD.

This area has enough uncertainty to keep it off the Ada 9X critical path. On the other hand, development of portions of the dynamic semantics as part of the Ada 9X effort should aid in evaluating and understanding proposed language changes.

N.B. Parameterize formal definition for implementation decisions and architecture/environment.

REQUIREMENT H

ASSERTIONS

MAJORITY
1) Need dynamic semantics for assertions to be useful for proof
2) Suitable form not known
   - Extend Ada expressions
   - Ada vs spec functions
   - Etc.

   ∴ Wait, but work on issue

MINORITY
1) Anna exists
2) Anna is better than nothing

   ∴ Use Anna for now

DON'T PRECLUDE LATER CHOICE/DECISION

Mixed Results

- Requirements A, B, and D are largely reflected in the Requirements Document
- Requirements C and H have been largely ignored.
- Requirement E has resulted in special consideration being given to the critical systems community.
- Requirements F and G have been completely rejected, but ...

Language Precision Team

PRDA issued by Ada 9X project last spring.

- Supports Ada 9X mapping team by providing formal analysis of selected language topics
- "Creeping formalism" approach to demonstrating utility of formal methodology
- May have some influence on Ada 9X language

A team led by ORA was issued a contract during the last days of FY 89.

Research Issues and Efforts

The language precision team will work with Intermetrics to model specific aspects of the Ada language where the application of formal techniques appears to have promise. These include optimization and tasking. While the project is probably worth while, the approach may be less than satisfactory for a number of reasons.

Features Interact

In isolation, most Ada features are innocuous. It is in combination that they cause problems. The LPT approach risks ignoring the interactions

- Overloading
- Separate Compilation
- Private types
- Signals and handlers
- Tasking
- Optimization and code generation

Consider Optimization

Optimization and code generation are difficult to separate. One man's optimization strategy is another's code generation paradigm.

- Ada has no explicit low level parallelism. Most modern architectures do, even if it is *only* a pipeline or a coprocessor.
- Array and vector processors have primitives that are of a *higher* level than the Ada primitives that they implement.
- The ability of the programmer to explicitly handle exceptions from predefined operations makes visible implementation details that are better hidden.

Reconsider Optimization

The interaction of exception handling, global data, and separate compilation with low level parallelism makes code generation difficult.

- Reordering exception raising operations *can* create unexpected program states or even turn a legal program into an *erroneous* one.
- If the exception is unhandled, this may not matter.
- If the exception is handled in another compilation, the dependencies are difficult to track.
- Without global analysis, the wrong choices are sure to be made sometimes.

Meanwhile back at Intermetrics

The first Ada 9X Mapping Issues document produced by Intermetrics addresses no issues that are of specific interest to the critical systems community. The issues addressed include:

- Type extensions and polymorphism
- Pointers to static objects
- Changes in visibility rules for operators
- etc.

What lies Ahead?

The process will inexorably wend its way towards a revised Ada. While some of the warts of the present language may be removed in the process, it is certain that others will spring up to take their place.

The process is under the control of those with a certain vested interest in the status quo.

What is lacking is a long term, radical view of what ought to be. If Ada 9X, like Ada 83 fails to serve the needs of portions of the community, where can they go? What alternatives do they have?