Software Engineering COMP 201

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Lecture 11 – Formal Specifications

Formal Specification - Techniques for the Unambiguous Specification of Software

Objectives:

- **To explain** why formal specification techniques help discover problems in system requirements
- **To describe the use of:**
  - algebraic techniques (for interface specification) and
  - model-based techniques (for behavioural specification)
- **To introduce** Abstract State Machine Model (ASML)

Formal Methods

- **Formal specification** is part of a more general collection of techniques that are known as 'formal methods'
  - **COMP313** *"Formal Methods"*

These are all based on the mathematical representation and analysis of software

- **Formal methods** include
  - Formal specification
  - Specification analysis and proof
  - Transformational development
  - Program verification

Formal Methods in reality

- When software was first developed
  - Is was done using assembly language
  - No OO, no high level languages
  - limited understanding of software testing
- Modern software development
  - Many ways to make high quality software
- So
  - Mostly formal methods not used
  - The most acceptable techniques are approaches like programming by contract (e.g. Eiffel)

Acceptance of Formal Methods

- Formal methods have not become mainstream software development techniques as was once predicted
  - Other software engineering techniques have been successful at increasing system quality. Hence the need for formal methods has been reduced
  - Market changes have made time-to-market rather than software with a low error count the key factor. Formal methods do not reduce time to market
  - The scope of formal methods is limited. They are not well-suited to specifying and analysing user interfaces and user interaction for example
  - Formal methods are hard to scale up to large systems

Use of Formal Methods

- Their principal benefits are in reducing the number of errors in systems so their main area of applicability is critical systems:
  - Air traffic control information systems,
  - Railway signalling systems
  - Spacecraft systems
  - Medical control systems
- In this area, the use of formal methods is most likely to be cost-effective

Background Reading

- 1) “Formal Methods: Promises and Problems”, Luqi and J. Goguen, IEEE Software, 14 (1), 1997:

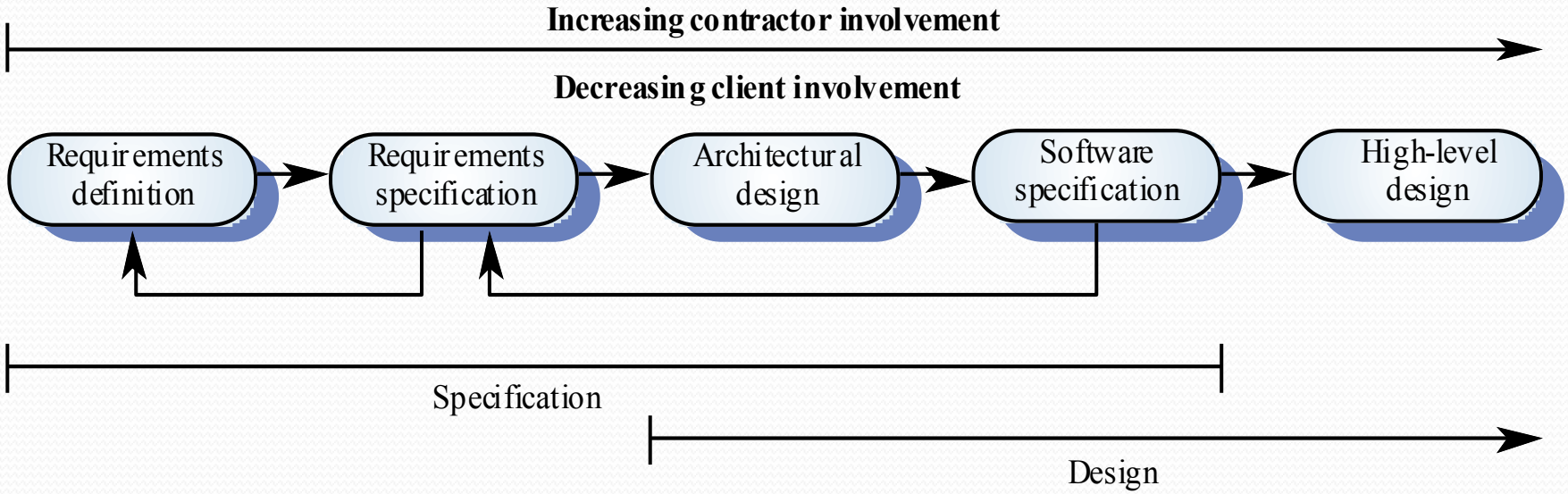
- “Software development failures have reached staggering proportions: an estimated $81 billion was spent on cancelled software projects in 1995 and an estimated $100 billion in 1996.” [1]

- “Experience shows that many of the most vexing problems in software development arise because any computer system is situated in a particular social context..” [1]

Specification in the Software Process

- **Specification** and design are inextricably mixed.
- **Architectural design** is essential to structure a specification.
- **Formal specifications** are expressed in a mathematical notation with precisely defined vocabulary, syntax and semantics.

Specification and Design

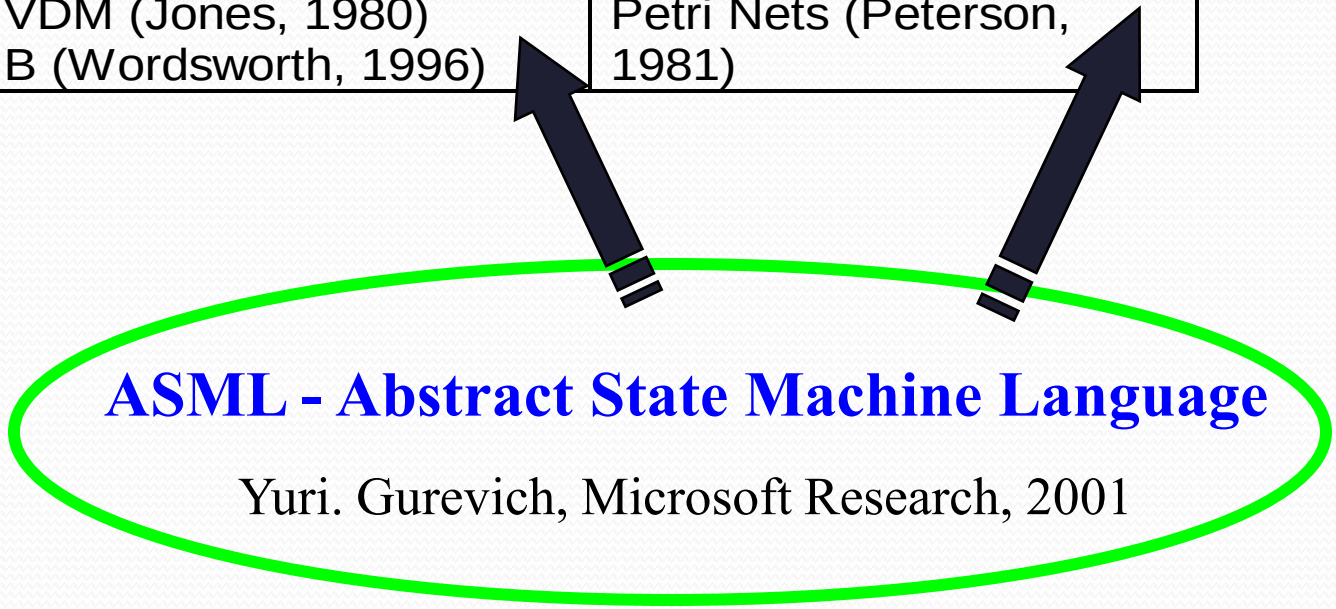


Specification Techniques

- **Algebraic approach**
  - The system is specified in terms of its operations and their relationships
- **Model-based approach**
  - The system is specified in terms of a state model that is constructed using mathematical constructs such as sets and sequences.
  - Operations are defined by modifications to the system's state

Formal Specification Languages

	Sequential	Concurrent
Algebraic	Larch (Guttag, Horning et al., 1985; Guttag, Horning et al., 1993), OBJ (Futatsugi, Goguen et al., 1985)	Lotos (Bolognesi and Brinksma, 1987),
Model-based	Z (Spivey, 1992) VDM (Jones, 1980) B (Wordsworth, 1996)	CSP (Hoare, 1985) Petri Nets (Peterson, 1981)



Use of Formal Specification

- **Formal specification involves investing more effort in the early phases** of software development

  This reduces requirements errors as it forces a detailed analysis of the requirements

- **Incompleteness** and **inconsistencies** can be discovered and resolved.

  Hence, savings are made as the amount of rework due to requirements problems is reduced

Formal Specification

- Critical systems development usually follows a software process based on the waterfall model.
- The system requirements and design are expressed in detail, reducing ambiguity, and carefully analysed and refined before implementation begins
- A large benefit of formal specification is its ability to uncover potential problems and ambiguities in the requirements.
- **Question**: Why does this mean the waterfall model is often used?

Interface Specification

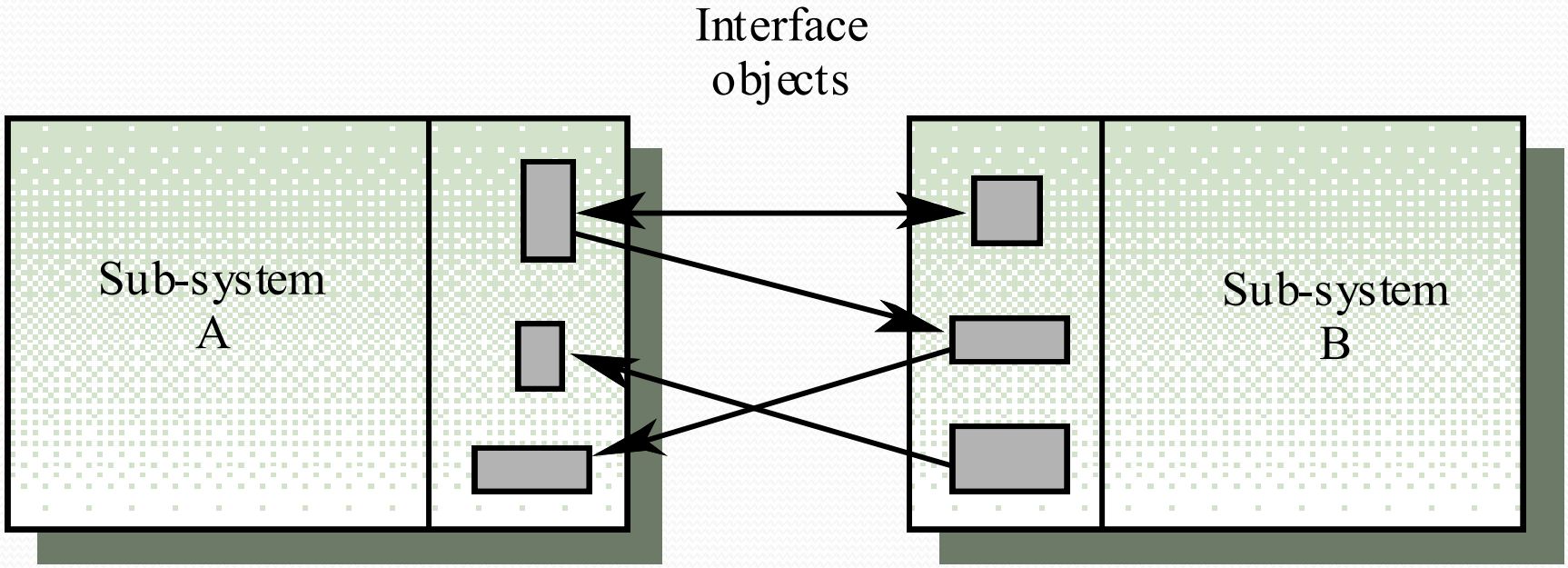
- Large systems are decomposed into subsystems with well-defined interfaces between these subsystems
- Specification of subsystem interfaces allows independent development of the different subsystems
- Interfaces may be defined as abstract data types or object classes

The algebraic approach to formal specification is particularly well-suited to interface specification

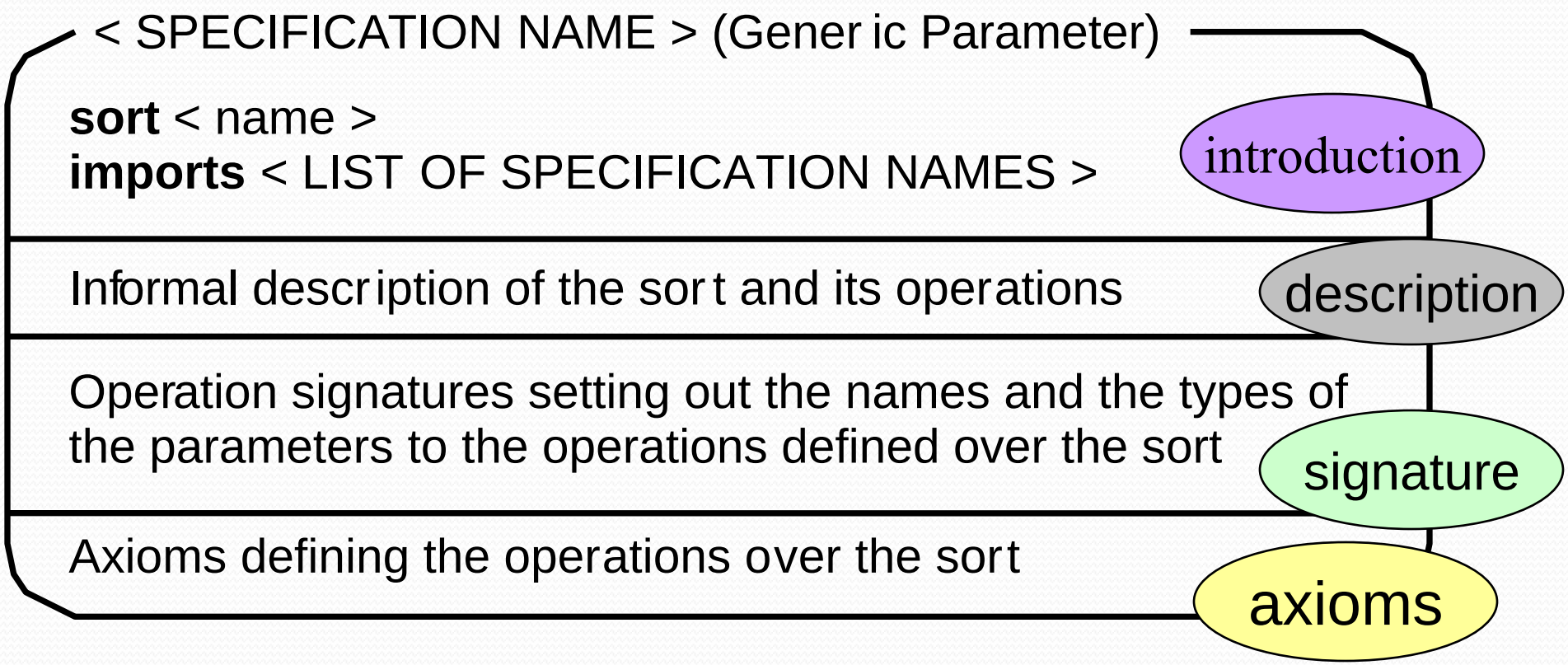
Sub-System Interface Specification

- Clear and unambiguous sub-system interface specifications reduce the chance of misunderstandings between a provider and user of a sub-system.
- The algebraic approach to specification was originally developed for the definition of *abstract data types*.
- This idea was then extended to model complete system specifications.

Sub-System Interfaces



The Structure of an Algebraic Specification



The Structure of an Algebraic Specification

- **Introduction** – Declares the sort (the type name) of the entity being specified, i.e., a set of objects with common characteristics. It also imports other specifications to use.
- **Description** – An informal description of the operations to aid understanding.
- **Signature** – Defines the syntax of the interface to the abstract data type (object), including their names, parameter list and return types.
- **Axioms** – Defines the semantics of the operations by defining axioms characterising the behaviour.

Systematic Algebraic Specification

- **Algebraic specifications** of a system may be developed in a systematic way:
  - Specification structuring;
  - Specification naming;
  - Operation selection;
  - Informal operation specification;
  - Syntax definition;
  - Axiom definition.

Specification Operations

- Constructor operations. Operations which create entities of the type being specified.
- Inspection operations. Operations which evaluate entities of the type being specified.
- To specify behaviour, define the inspector operations for each constructor operation.

Example: Operations on a List ADT

- Let us take an example of a "list" abstract data type.
- A list contains a sequence of elements of some type where elements may be added to the end and removed from the front (this is also called a *queue*, how does this differ from a *stack*?).
- We want operations to Create, Cons (create a new list with an added member), Head (to evaluate the first element), Length and Tail (which creates a list by removing the first (head) element).

Example: Operations on a List ADT

- Constructor operations which evaluate to sort List
  - Create, Cons and Tail.
- Inspection operations which take sort list as a parameter and return some other sort
  - Head and Length.
- Tail can be defined using the simpler constructors Create and Cons. No need to define Head and Length with Tail.

Example: List Specification

List(Elem) **sort** List **Imports** INTEGER
Defines a list where elements are added at the end and removed from the front. The operations are Create, which brings an empty list into existence, Cons, which creates a new list with an added member, Length, which evaluates the list size, Head, which evaluates the list size, Head, which evaluates the front element of the list and Tail, which creates a list by removing the head from its input list.
Create -> List Cons(List, Elem) -> List Head (List) -> Elem Length (List) -> Integer Tail (List) -> List
Head(Create) = Undefined **exception** (empty List) Head(Cons(L,v)) = **if** L = Create **then** v **else** Head (L) Length(Create) = 0 Length(Cons(L,v)) = Length (L) + 1 Tail(Create) = Create Tail(Cons(L,v)) = **if** L = Create **then** Create **else** Cons(Tail(L), v)

Interface Specification in Critical Systems

- Let us consider another example: an *air traffic control system* where aircraft fly through managed sectors of airspace.
- Each sector may include a number of aircraft but, for safety reasons, **these must be separated**.
- In this example, a simple vertical separation of 300m is proposed.
- The system should warn the controller if aircraft are instructed to move so that the separation rule is breached.

A Sector Object

- Critical operations on an object representing a controlled sector are
  - Enter - Add an aircraft to the controlled airspace;
  - Leave - Remove an aircraft from the controlled airspace;
  - Move - Move an aircraft from one height to another;
  - Lookup - Given an aircraft identifier, return its current height;

Primitive Operations

- It is sometimes necessary to introduce additional operations to simplify the specification.
- The other operations can then be defined using these more primitive operations.
- Primitive operations
  - Create - Bring an instance of a sector into existence;
  - Put - Add an aircraft without safety checks;
  - In-space - Determine if a given aircraft is in the sector;
  - Occupied - Given a height, determine if there is an aircraft within 300m of that height.

Sector Specification (1)

SECTOR

sor t Sector
impor ts INTEGER, BOOLEAN

Enter - adds an aircraft to the sector if safety conditions are satisfed
Leave - removes an aircraft from the sector
Move - moves an aircraft from one height to another if safe to do so
Lookup - Finds the height of an aircraft in the sector

Create - creates an empty sector
Put - adds an aircraft to a sector with no constraint checks
In-space - checks if an aircraft is already in a sector
Occupied - checks if a specified height is available

Enter (Sector , Call-sign, Height) → Sector
Leave (Sector , Call-sign) → Sector
Move (Sector , Call-sign, Height) → Sector
Lookup (Sector , Call-sign) → Height

Create → Sector
Put (Sector , Call-sign, Height) → Sector
In-space (Sector , Call-sign) → Boolean
Occupied (Sector , Height) → Boolean

Sector Specification (2)

```
Enter (S, CS, H) =
   if       In-space (S, CS )     then   S exception   (Aircraft already in sector)
   elsif    Occupied (S, H)   then   S exception   (Height conflict)
    else    Put (S, CS, H)

Leave (Create, CS) = Create   exception   (Aircraft not in sector)
Leave (Put (S, CS1, H1), CS) =
     if CS = CS1   then   S else   Put (Leave (S, CS), CS1, H1)

Move (S, CS, H) =
     if       S = Create   then   Create   exception   (No aircraft in sector)
    elsif     not  In-space (S, CS)   then   S  exception   (Aircraft not in sector)
    elsif    Occupied (S, H)   then   S  exception   (Height conflict)
    else    Put (Leave (S, CS), CS, H)

-- NO-HEIGHT is a constant indicating that a valid height cannot be returned

Lookup (Create, CS) =  NO   -HEIGHT exception   (Aircraft not in sector)
Lookup (Put (S, CS1, H1), CS) =
     if CS = CS1    then   H1 else   Lookup (S, CS)

Occupied (Create, H) = false
Occupied (Put (S, CS1, H1), H) =
     if       (H1 > H  and  H1 - H Š 3  00)  or (H > H1  and   H - H1 Š 3  00)   then   true
     else     Occupied (S, H)

In-space (Create, CS) = false
In-space (Put (S, CS1, H1), CS ) =
     if CS = CS1   then   true  else  In-space (S, CS)
```

Specification Commentary for Sector

- Use the basic constructors Create and Put to specify other operations.
- Define Occupied and In-space using Create and Put and use them to make checks in other operation definitions.
- All operations that result in changes to the sector must check that the safety criterion holds.

Lecture Key Points

- Formal system specification complements informal specification techniques.
- Formal specifications are precise and unambiguous. They remove areas of doubt in a specification.
- Formal specification forces an analysis of the system requirements at an early stage. Correcting errors at this stage is cheaper than modifying a delivered system.
- Formal specification techniques are most applicable in the development of critical systems and standards.