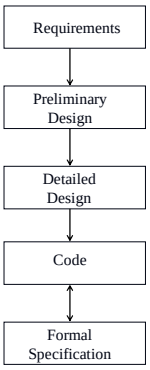
Integrating Formal Specification and Verification Techniques into the Software Engineering Process

After-The-Fact-Verification

- System is built using standard software development approach
- Formal specification is written after the system development is completed
- Properties are proved about the specification and/or code

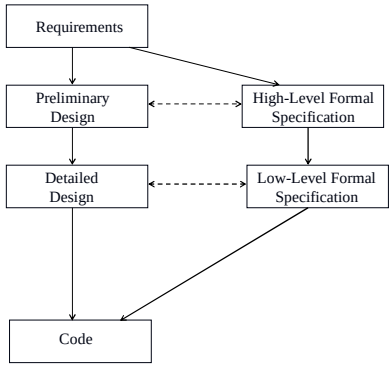


After-The-Fact-Verification

- Disadvantages
  - Additional 30-50% cost for the verification effort
  - Additional time occurs after the product development is completed
  - Errors are more costly to fix because the development cycle is completed

Parallel Verification Effort

- Two teams
  - Software development team
  - Specification and verification team
- Requires constant communication between the two teams
- Developed code is verified to be consistent with the formal specification

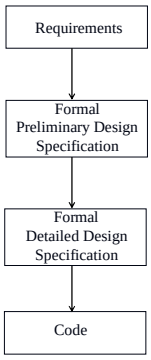


Parallel Verification Effort

- Disadvantages
  - Insufficient communication results in a large gap between the code and the formal specification
  - Costs the same as for the after-the-fact approach

Fully Integrated Approach

- Formal methods integrated into the software development process
- Software development team and the formal verification team are one
- Software developers use formal specifications as their design notation

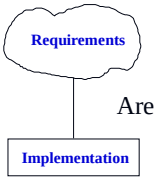


Fully Integrated Approach

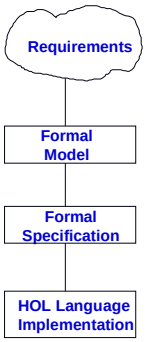
- Advantages
  - Can reason rigorously about the design before writing any code
  - Costs less than with the other two approaches
  - Errors are likely to be found earlier in the software development process

ASLAN

A Formal Specification Language and Formal Verification System



Are these consistent?



Models

Access Control

Considers Subjects and Objects

Requirements:

1) If subject S has read access to object O, then security_level(S) >= security_level(O)

2) If subject S has write access to object O, then security_level(S) <= security_level(O)

Formal Specification

State Machine

Relates values of variables before and after each state transition

e.g.,

Exchange (X,Y)

New_Value(X) = Y

& New_Value(Y) = X

Formal Specifications

Algebraic

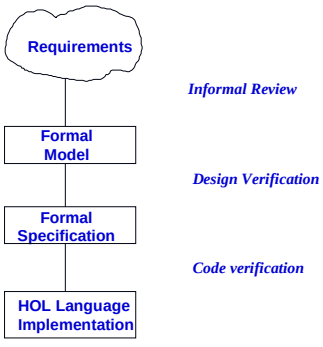
Relates results of sequence of operations

e.g.,

Exchange(Exchange(X,Y)) = (X,Y)

First(Exchange(X,Y)) = Last(X,Y)

Last(Exchange(X,Y)) = First(X,Y)

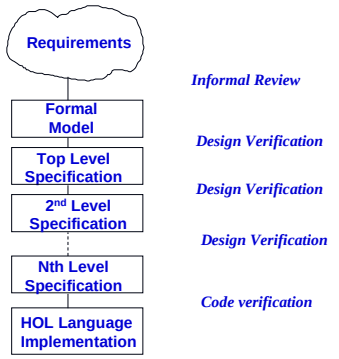


Design Verification

- Consistency between the model and the specification
- Assumes
  - Model is appropriate
  - Specification is complete

Code Verification

- Consistency between the specification and the implementation
- Assumes
  - Specification is complete
  - Implementation language is correctly defined



Aslan

- An integrated methodology for design, specification, implementation, and verification of software
- Enforces the establishment of rigorous connections between successive stages of development
  - Identification and modeling of critical requirements
  - Design specifications
  - Verification of specifications
  - Program design specifications
  - Verification of implementations

Components of Aslan

- Aslan specification language
- Aslan specification processor
- Interactive theorem prover
- Verification condition generator (vcg)

Aslan Language

- State machine representation
- Non-procedural
- Assertion language: extension of first-order predicate calculus
- Language elements
  - Types
  - Constants
  - Variables
  - Definitions
  - Initial conditions
  - Invariants
  - Constraints
  - Transitions
  - Levels
  - Implementations (Mappings)

Type User,
Book,
Mystery Subtype Book

Type Status is (In, Out, Lost),
Book_Collection is set of Book

Type Pos_Integer is Typedef i:Integer (i>0)

```
Constant   Book_Limit: Pos_Integer,
           Title(Book): Book_Title

Variable   Library:Book_Collection,
           Checked_Out(Book): Boolean

Define     Copy_Of(b1,b2:Book): Boolean ==
                Author(b1) = Author(b2)
             & Title(b1) = Title(b2)
```



```
Constant   Book_Limit: Pos_Integer,
           Title(Book): Book_Title
Variable   Checked_Out(Book): Boolean
Define     Copy_Of(b1,b2:Book): Boolean ==
                Author(b1) = Author(b2)
             & Title(b1) = Title(b2)

Axiom  Forall b1,b2,b3:Book(
           Left_Of(b1,b2) & Left_Of(b2,b3)
                → Left_Of(b1,b3))
```



```
Initial
     Library = Empty
  & Forall u:User (Number_Books(u) = 0)
  & Forall b:Book (~Checked_Out(b))
```


Critical Requirements

Invariant is about a single state

Constraint is across successive states


```
Invariant
     Forall u:User(
          Number_Books(u) <= Book_Limit)
  & Forall u:User,b1,b2:book(
          Checked_Out_To(u,b1)
        & Checked_Out_To(u,b2)
        & Copy_Of(b1,b2)
     →    b1 = b2)
```



```
Constraint
  Time > Time′  | (Time=0  &  Time′> 0)
```

```
Transition Return(b:Book)
Entry
  Checked_Out(b)
Exit
  Forall b1:Book(
    if b1=b then ~Checked_Out(b1)
            else Nochange(Checked_Out(b1))
    fi)
```


Aslan Procedural Operators

- Becomes Operator
- Conditional Statements
- Alternative Statements


```
Transition Return(b:Book)
Entry
  Checked_Out(b)
Exit
  Checked_Out(b) Becomes false
```



```
Transition Check_Out(u:User, b:Book)
Entry
    Available(b)
  & Number_Books(u) < Book_Limit
  & Forall b1:Book (
      Checked_Out_To(u,b1) → ~Copy_Of(b,b1))
Exit
    Number_Books(u) Becomes Number_Books'(u) +1
  & Checked_Out(b) Becomes True
  & Responsible(b) Becomes u
  & Never_Out(b) Becomes False
```



```
Transition Login(u:user, p:password)
Exit
  if Password_OK(u,p)
     then
        Logged_In(u) Becomes true
      & Nochange(Failed_Logins)
     else
        Failed_Logins = Failed_Logins' + 1
      & Nochange(Logged_In)
  fi
```


Conditional Treated Like a Procedural Statement

```
Transition Login(u:user, p:password)
Exit
  if Password_OK(u,p)
     then Logged_In(u) Becomes true
     else Failed_Logins = Failed_Logins' + 1
  fi
```

```
Transition Login(u:user, p:password)
Exit
      Password_OK(u,p)
   & Logged_In(u) Becomes true
   & Nochange(Failed_Logins)
|
      ~Password_OK(u,p)
   & Failed_Logins = Failed_Logins' + 1
   & Nochange(Logged_In)
```


Alternative Treated Like a Procedural Statement

```
Transition Login(u:user, p:password)
Exit
         Password_OK(u,p)
      & Logged_In(u) Becomes true
   ALT
         ~Password_OK(u,p)
      & Failed_Logins = Failed_Logins' + 1
```


Implementation Mappings

All types, constants, variables and transitions are mapped to the next lower level

Aslan Specification Processor

- Reads Aslan specifications including the critical requirements and implementation mappings
- Generates proof obligations

Critical Requirements are Invariants and Constraints

Invariants must hold in every reachable state

Constraints must hold between two successive states

Top Level Proof Obligations

- Initial conditions satisfy the invariants
- Each transition preserves the invariants and satisfies the constraints

Initial Conditions Satisfy the Invariants

Initial_Assertion → Invariant

Each Transition Preserves the Invariants and Satisfies the Constraints

For the Normal Case:

Invariant′ & Entry′ & Exit → Invariant & Constraint

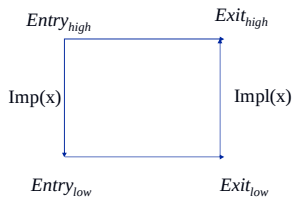
For Each Exception:

Invariant′ & Except′ & Exit → Invariant & Constraint

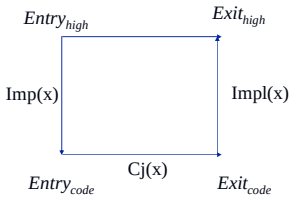
Refinement Proof Obligations

- Lower level initial conditions implement the higher level initial conditions
- Lower level transitions correctly implement the corresponding higher level transitions with respect to the implementation mapping
- Lower level transitions that do not correspond to a higher level transition preserve a refinement of the higher level invariants and satisfy a refinement of the higher level constraints

Implementation Mapping



Implementation Mapping



Lower level initial conditions imply a mapping of the higher level initial conditions and the lower level invariants

Initial_Low →
IMPL(Initial_High) & Invariant_Low

Unmapped lower level transitions preserve invariants and satisfy the constraints

For the normal case:

IMPL(Invariant_High') & Invariant_Low'
& Entry' & Exit
→
IMPL(Invariant_High) & Invariant_Low
& IMPL(Constraint_High)
& Constraint_Low

For each exception:

IMPL(Invariant_High') & Invariant_Low'
& Except-i' & Exit-i
→
IMPL(Invariant_High) & Invariant_Low
& IMPL(Constraint_High)
& Constraint_Low

For each refined transition

Assuming the mapping
T_High == T_Low

For the normal case

Correct application:

IMPL(Entry_High) & IMPL(Invariant_High)
& Invariant_Low
→
Entry_Low

Correct refinement:

IMPL(Entry_High') & IMPL(Invariant_High')
& Invariant_Low' & Exit_Low
→
IMPL(Exit_High) & Invariant_Low
& Constraint_Low

For each exception

Correct application:

IMPL(Except-i_High) & IMPL(Invariant_High)
& Invariant_Low
→
Except-i_Low

For each exception

Correct refinement:

IMPL(Except-i_High') & IMPL(Invariant_High')
& Invariant_Low' & Exit-i_Low
→
IMPL(Exit-i_High) & Invariant_Low
& Constraint_Low

Each Entry(Except)/Exit pair can have its own mapping and the mapping expressions may be arbitrarily complex

Consider T_High.i == if expr
then T1.j
else T2.k
fi

This is equivalent to
T_High.i == expr & T1.j
| ~expr & T2.k

Four proof obligations are produced

For correct application:

IMPL(Except-i_High) & IMPL(Invariant_High)
& Invariant_Low & expr
→
Except-j_T1

IMPL(Except-i_High) & IMPL(Invariant_High)
& Invariant_Low & ~expr
→
Except-k_T2

For Correct refinement:

IMPL(Except-i_High') & IMPL(Invariant_High')
& Invariant_Low' & expr' & Exit-j_T1
→
IMPL(Exit-i_High) & Invariant_Low & Constraint_Low

IMPL(Except-i_High') & IMPL(Invariant_High')
& Invariant_Low' & ~expr' & Exit-k_T2
→
IMPL(Exit-i_High) & Invariant_Low & Constraint_Low