GENISYS – A Component Inversion Engine

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Presentation Overview

- Introduction
- Problem Statement
- Background
- Problem Solution
- GENISYS Overview
- Data Path Generator
- Component Inversion Engine
- Test Scenarios
- Related Work
- Conclusion & Future Work

Introduction

- Importance of Testing
- Testing cost in Product Development life-cycle
- Importance of Program Inversion in Testing
- Makes Testing process Complete & Robust
- Reduces cost associated with Failures
- Motivation for Program Inversion

Problem Statement

- Test an Inner-Component of a Structural Component. It is Test Component (TC)
- Structural Component is a **Black-box System**
- Need to find the **Dependence Link** from the System Interfaces (Inputs & Outputs) to the TC
- Invert the components between the TC and System Inputs to derive the required System Inputs to test TC
- Proposed Solution: **GENISYS** – A Component Inversion Engine

Background – Rosetta Specification Language

- Rosetta – System-level Specification Language
- Basic constructs: Facet, Package, Domain
- General Syntax:

package <package_label> :: <domain> is

facet <facet_label> (parameters) :: <domain> is

<optional local variable declarations>

begin

<Terms>

end facet <facet_label>

end packet <package_label>

Rosetta Specification Language…

- Example:

```
package INVERTER_pkg :: static is
facet INVERTER_fct (
        ipt_sig:: input bit; opt_sig:: output bit) :: state_based is
        begin
        L1: opt_sig’ = not(ipt_sig);
  end facet INVERTER_fct;
end packet INVERTER_pkg;
```

Background – XML

- Similar to HTML
- Widely used for Data Storage & Representation
- Flexible – User-defined custom tags
- Strict – Tags are always in pairs. Opening tag has to have a closing tag
- W3C Standard

XML…

- Example:

```xml
<contact_info>
    <address>
        <block>M</block>
        <street>main</street>
        <city>Lawrence</city>
        <state>Kansas</state>
    </address>
    <phone>
        <office>1234567</office>
        <home>7654321</home>
    </phone>
</contact_info>
```

XML…

- XML Schema
  - Defines elements that appear in an XML Document
  - Defines legal building blocks
  - Schema is an XML Document
  - Provides information regarding attributes of a node
- Document Object Model (DOM) Parser
  - XML Document Parser
  - Hierarchical Tree Representation of the XML Document
  - Provides APIs for parsing/modifying the document
  - Root – Top level element of the Tree
  - Leaf – Child element

Background – Program Inversion

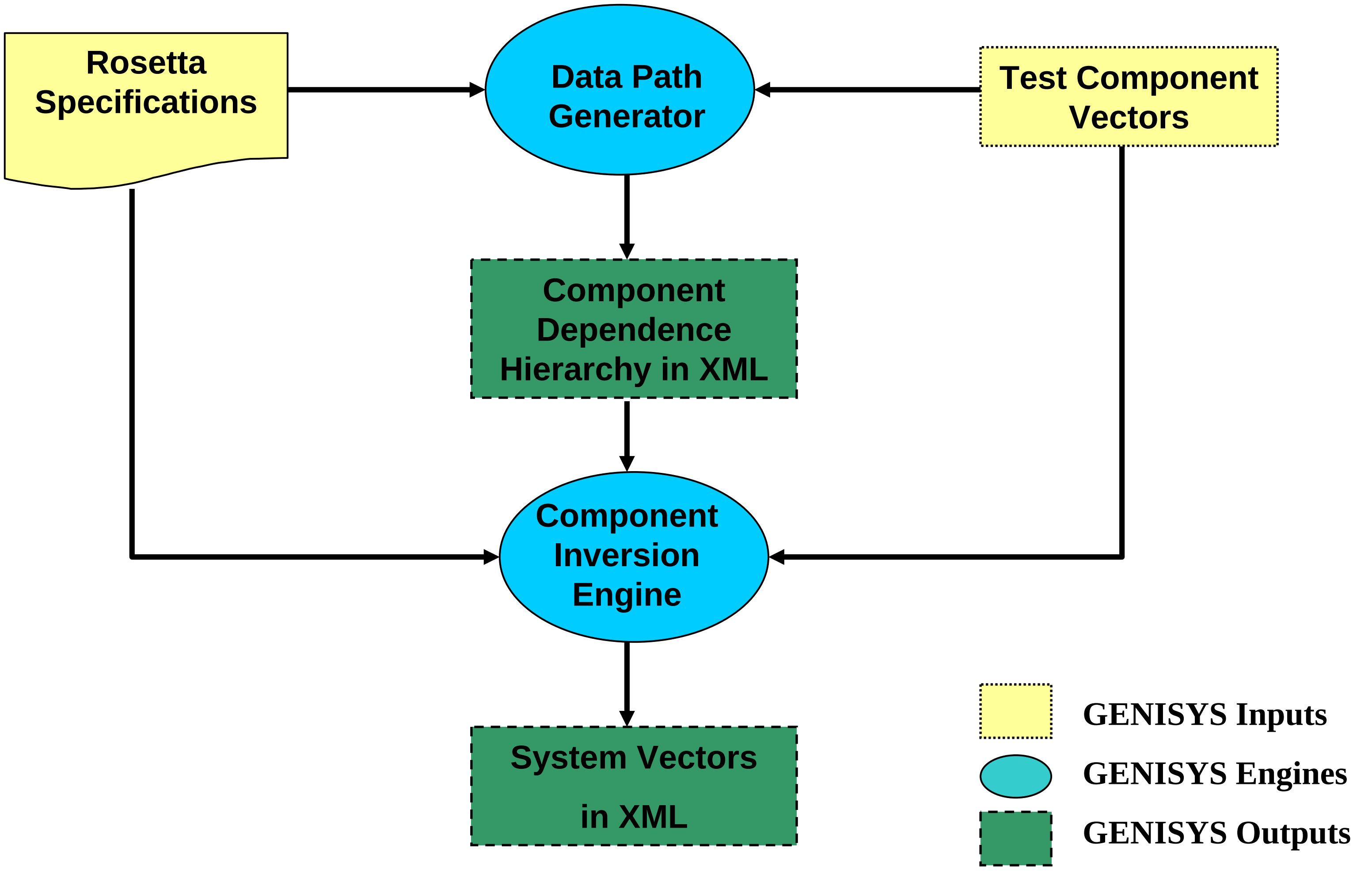
- Program Inversion:
  - is a computational process to derive program input values to generate a given set of output values
  - is a program that computes the inverse computation of another program
  - inverts the terms in the given program from last to first
- Function Inversion – For a given function $F: X \rightarrow Y$, derive inverse function $F^{-1}: Y \rightarrow X$, such that,

  $F(X) = Y \Rightarrow F^{-1}(Y) = X \Rightarrow F^{-1}(F(X)) = X$

Problem Solution

- GENISYS Tool
- Generate the Dependence Links from the System Interface to Test Component
- Determine the *Component Dependence Hierarchies* along the inner-components in the Structural Component
- Invert the components along the Hierarchy to derive *System Vectors*

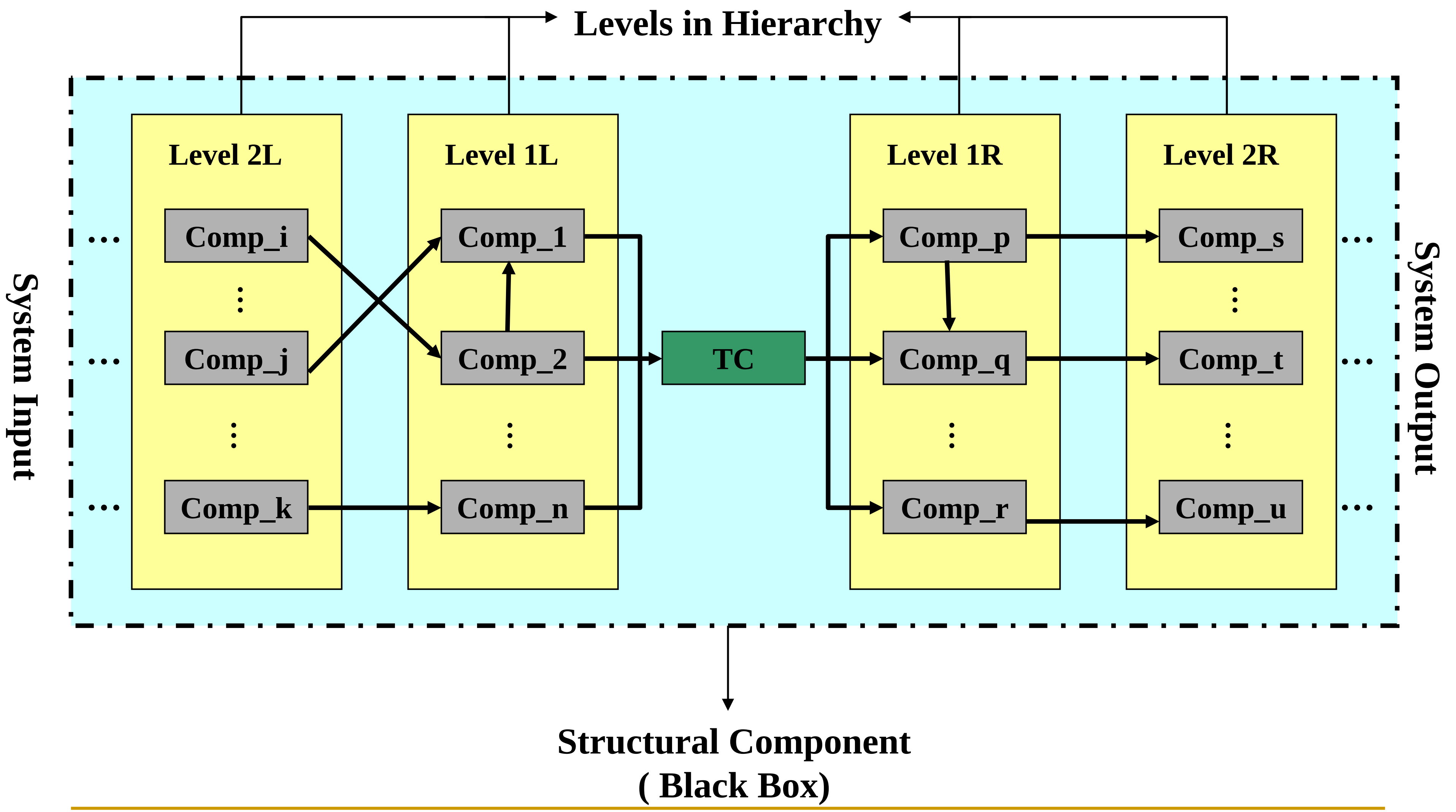
GENISYS Overview



GENISYS - Introduction

- GENISYS - A Component Inversion Engine
- Two Phase Approach
- Data-Path Determination Phase
  - Determine Component Dependence Hierarchy
- Component Inversion Phase
  - Invert Components along the Hierarchy

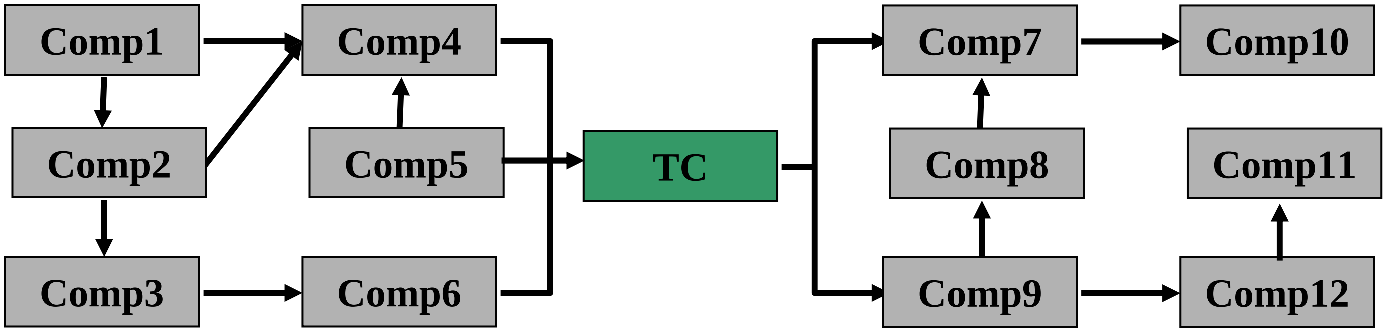
Component Dependence Hierarchy



Level in GENISYS

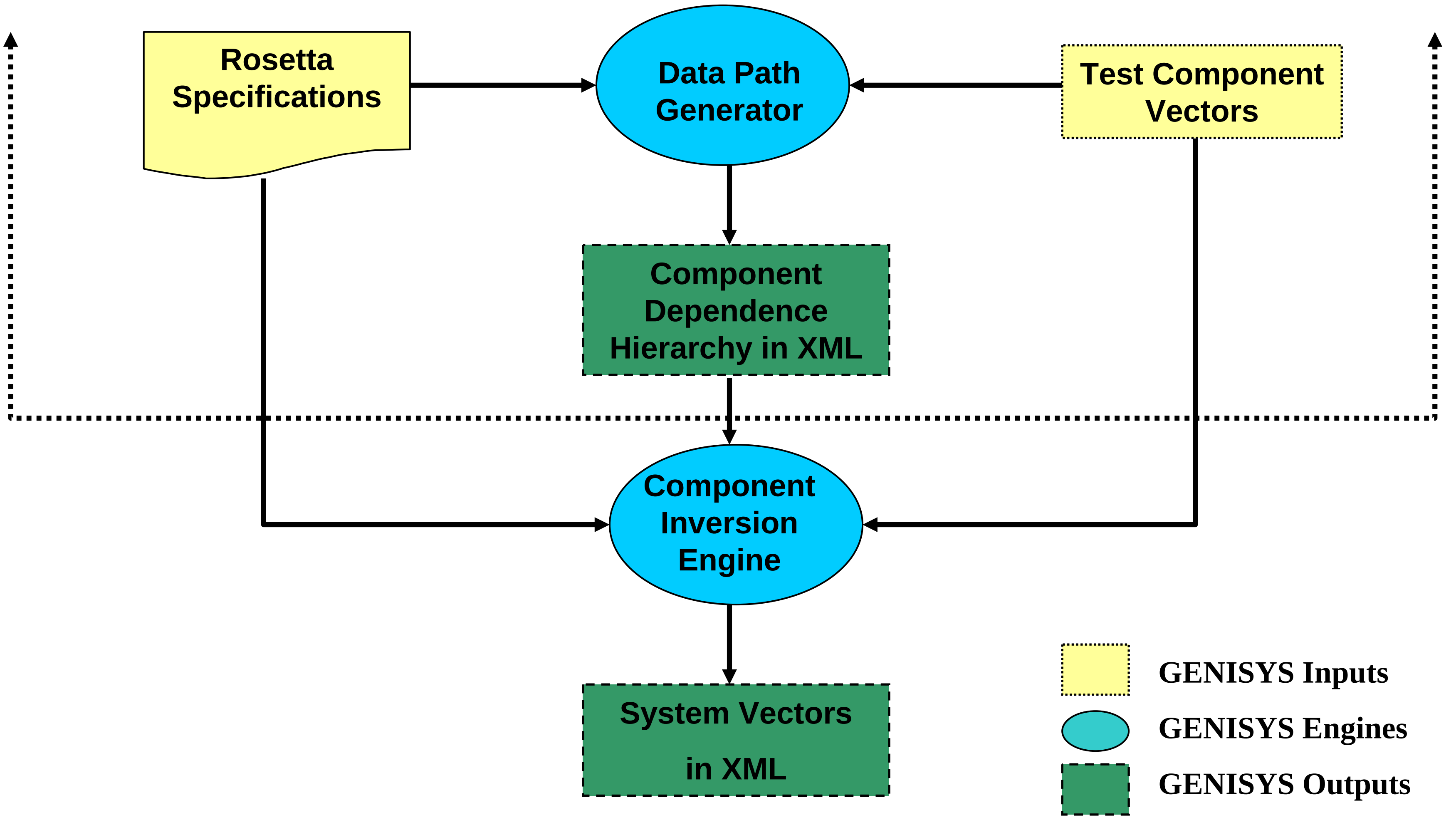
- Level determines the extend of inter-dependence between Component and TC
- Components at the same depth in Hierarchy belong to same Level
- Component can belong to several Levels
- Driving Components:
  - Group Component in highest # Level it belongs to
- Driven Components:
  - Group Component in lowest # Level it belongs to

Level in GENISYS…



- Level 1L: Comp4, Comp6
- Level 2L: Comp5, Comp3
- Level 3L: Comp2
- Level 4L: Comp1
- Level 1R: Comp7, Comp9
- Level 2R: Comp8, Comp10, Comp12
- Level 3R: Comp11

Data-Path Determination Phase



Data-Path Generator

- Data-path Engines Inputs:
  - Rosetta Specifications of the Structural Component
  - Test Component Vectors
- Generates two Component Dependence Hierarchies in XML:
  - Driving Hierarchy – Components directly/indirectly driving the TC
  - Driven Hierarchy – Components directly/indirectly driven by the TC

Component Dependence Hierarchy…

```
<COMPONENT_HIERARCHY file="foo.sld">
 <TEST_COMPONENT component_name="inverter">
  <DRIVING_COMPONENT component_name="amplifier1" driving_variable="volt_out1">
   < DRIVING_COMPONENT component_name="FET1" driving_variable="out_bit1">
   </DRIVING_COMPONENT>
  </DRIVING_COMPONENT>
 </TEST_COMPONENT>
</COMPONENT_HIERARCHY>
```

Driving Comp Hierarchy

Driven Comp Hierarchy

```
<COMPONENT_HIERARCHY file="foo.sld">
 <TEST_COMPONENT component_name="inverter">
  <DRIVEN_COMPONENT component_name="amplifier2" driving_variable="volt_out2">
   < DRIVEN_COMPONENT component_name="FET2" driving_variable="out_bit2">
   </DRIVEN_COMPONENT>
  </DRIVEN_COMPONENT>
 </TEST_COMPONENT>
</COMPONENT_HIERARCHY>
```

Feedback Loops

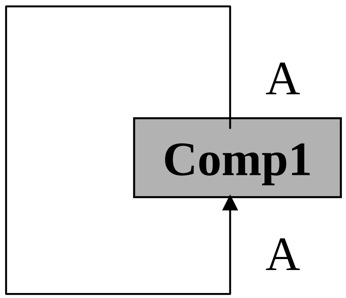
- Loop formed in Component Dependence Hierarchy
- Driven component directly or indirectly drives the driving component
- Solution - ***Break*** the last link that forms the feedback loop
- Simple & Efficient

Types of Feedback Loops

- Self-Feedback Loop

  Loop involving a single Component

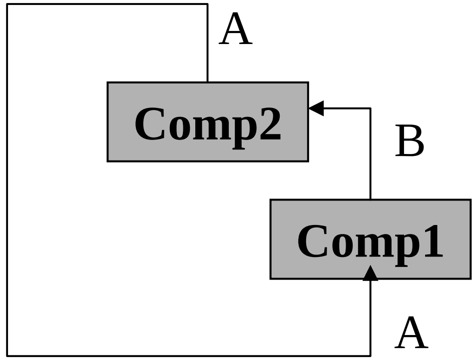
  facet Comp1(A :: input bit; A :: output bit) :: logic is
  …
  end facet Comp1;



- Primary Feedback Loop

  Loop involving two Components

  facet Comp1(A :: input bit; B :: output bit) :: logic is
  …
  end facet Comp1;
  facet Comp2(B :: input bit; A :: output bit) :: logic is
  …
  end facet Comp2;



Types of Feedback Loops…

- Secondary Feedback Loop

Loop involving more than two Components

facet Comp1(A :: input bit; B :: output bit) :: logic is

…

end facet Comp1;

facet Comp2(A :: input bit; C :: output bit) :: logic is

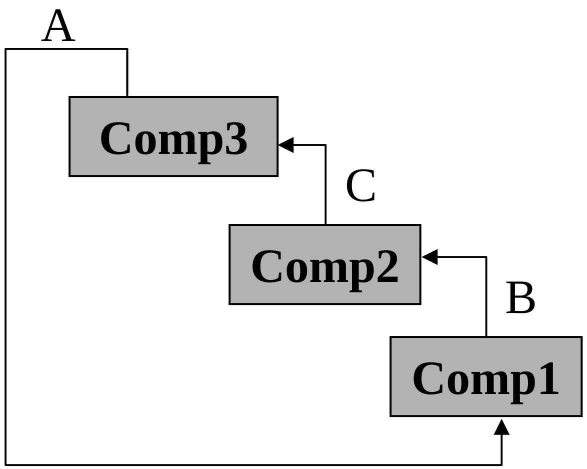
…

end facet Comp2;

facet Comp3(C :: input bit; A :: output bit) :: logic is

…

end facet Comp3;



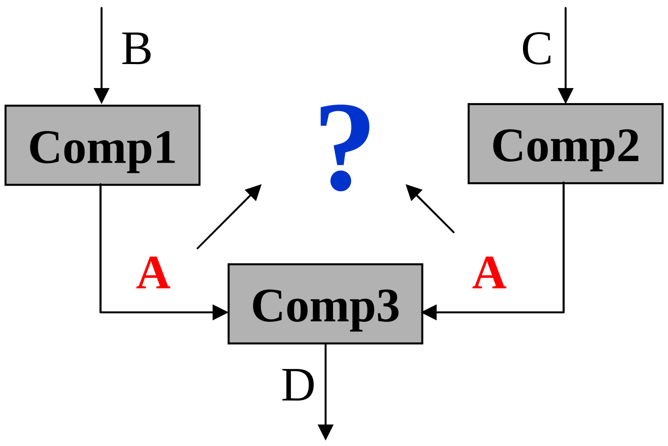
Non-Determinacy in Hierarchy

Non-Determinacy – A Parameter driven by more than one component

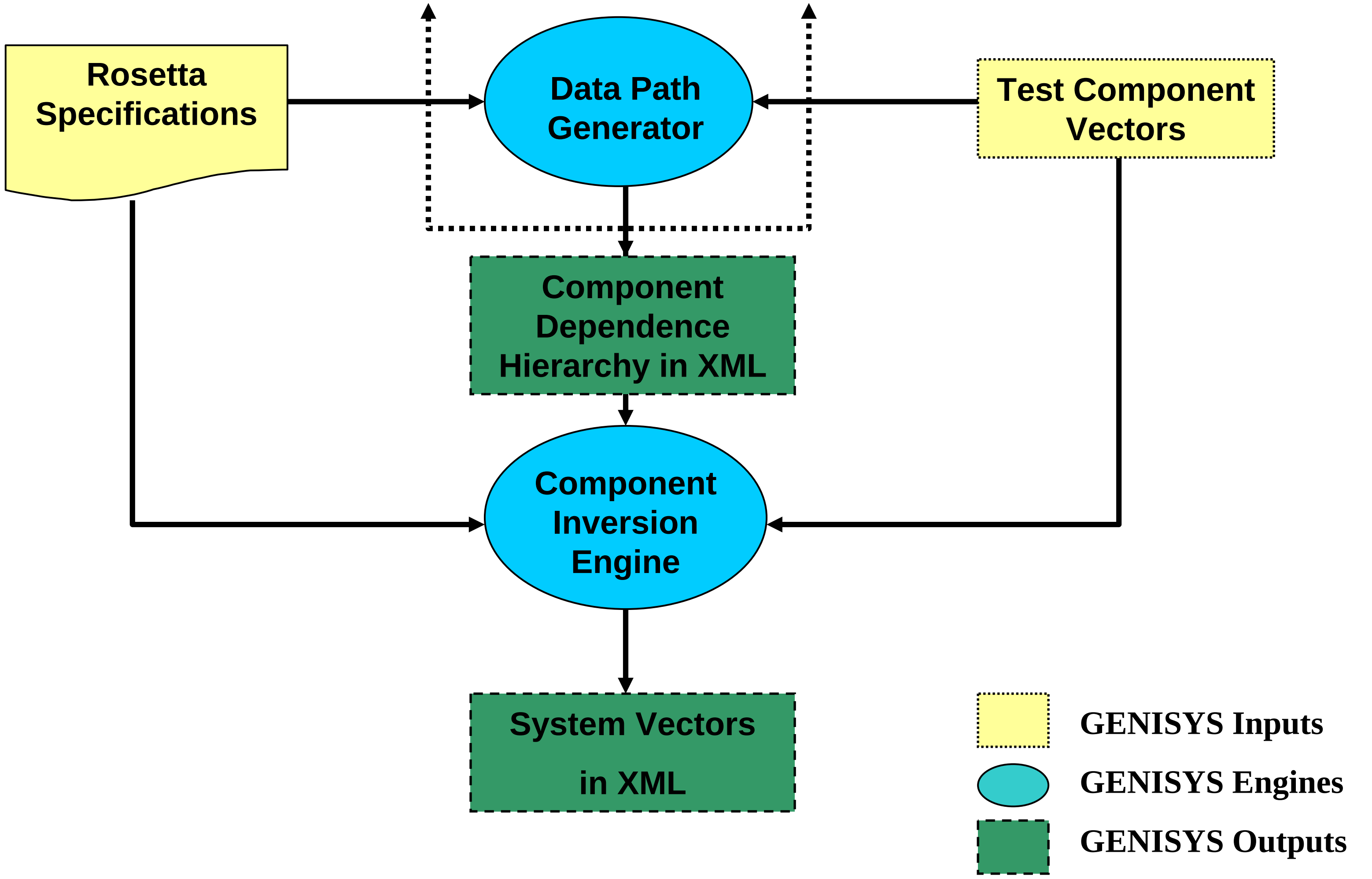
facet Comp1(B:: input real; **A :: output real**) :: logic is
…
end facet Comp1;

facet Comp2(C:: input real; **A :: output real**) :: logic is
…
end facet Comp2;

facet Comp3(**A:: input real**; D :: output real) :: logic is
…
end facet Comp3;



Component Inversion Phase



Component Inversion Algorithm

- Identify Invertible Components
- Assign Components to Hierarchy Levels
- Use Abstract Test Vectors of TC to perform Component Inversion for each Vector
- Invert all Components in each Level starting from Level 1L to Left-most Level in Hierarchy
- This will generate System Input parameters

Algorithm to Identify Invertible Components

- If a Component belongs to the Hierarchy,
  - it is Invertible
  - It is directly or indirectly related to TC
- If a Component doesn't belong to the Hierarchy,
  - it is Non-Invertible
  - it is independent of TC
- Component Inversion Engine processes Invertible Components *only*

Algorithm to Invert a Component

- Populate the local information storage from Global information storage
- Invert all expression in order from last to first
- Populate local information storage with values computed after each expression inversion
- Populate Global information storage from local at the end

Conjunctive Normal Form (CNF)

- A common form of representing Boolean Expressions
- Logical AND of one or more Clauses
- A Clause consists of logical OR of one or more literals
- CNF comprises of conjunction of disjunctions of literals
- Literals comprises of variables or their complements
- Eg: $(A \lor B) \land (B \lor \neg C) \land D$

Boolean Expression → CNF Conversion

- Eliminate the arrows

  $(A \rightarrow B) \Rightarrow \neg A \vee B$

- Drive the negations in using De Morgan's Law

  $\neg(A \vee B) \Rightarrow \neg A \wedge \neg B$

  $\neg(A \wedge B) \Rightarrow \neg A \vee \neg B$

- Distribute OR over AND

  $(A \vee (B \wedge C)) \Rightarrow (A \vee B) \wedge (A \vee C)$

zChaff SAT Solver

- Implementation of the Chaff Solver
- Won the SAT 2002 Competition as the Best Complete Solver in both industrial and handmade benchmarks categories
- Tested on Solaris/Linux/Cygwin machines with g++ as the compiler
- Can be compiled with Visual Studio .Net under Windows
- Maintained by Zhaohui Fu, Princeton University
- Implemented in C++

zChaff SAT Solver – File Format

- CNF file name must end with .cnf extension
- Comment starts with a ‘c’ in the file
- Prelude Format

  p cnf $\boldsymbol{Num_{var}}$ $\boldsymbol{Num_{clause}}$
- Num_{var} & Num_{clause} are # variables and # clauses in the expression
- Variables are numbers from 1 to Num_{var}
- A literal can either be a variable or its complement.
- A complement is expressed as the negation of the number representing a variable.
- Eg: if 6 → x6 ➔ -6 → ¬x6

zChaff SAT Solver – File Format…

- A clause is a line of literals separated by spaces and ends with 0.
- Eg: (1 -2 3 0) → (x1 V ¬x2 V x3)
- A line with a single 0 terminates the CNF file.
- Eg:

```
c CNF for: (x1  V  ¬x2)  Λ  (¬x2  V  ¬x3)
p cnf 3 2
1 -2 0
-2 -3 0
0
```

Component Inversion & SAT Solver

- All Rosetta expressions are Boolean
- Rosetta Expression → Boolean Expression
- Boolean Expression → CNF
- CNF expression fed to SAT Solver
- E.g.,
  - F(*x*) = *y* is a Rosetta expression, where F() is some function over unknown parameter *x* & value of *y* is V
  - Find *x*, such that F*(x)* = V
  - If *x* is found ➔ Expression is Satisfiable
  - Otherwise the expression is not Satisfiable

Algorithm to invert If-Then-Else Expression

- An if-then-else expression is a boolean expression:

  if(A) then B else C ➔ $(A \land B) \lor (\neg A \land C)$
- Ensure the validity of the expression
- Traverse to the inner-most if-then-else expression
- Transform the expression to its boolean equivalent and pass it to its parent expression
- Recursively transform the if-then-else expression to its boolean till the whole expression is converted to its boolean equivalent

Algorithm to invert If-Then-Else Expression…

- Use the zChaff SAT Solver to solve the boolean equivalent of the if-then-else expression
- The result will be valid assignments for the sub-expressions of the if-then-else expression

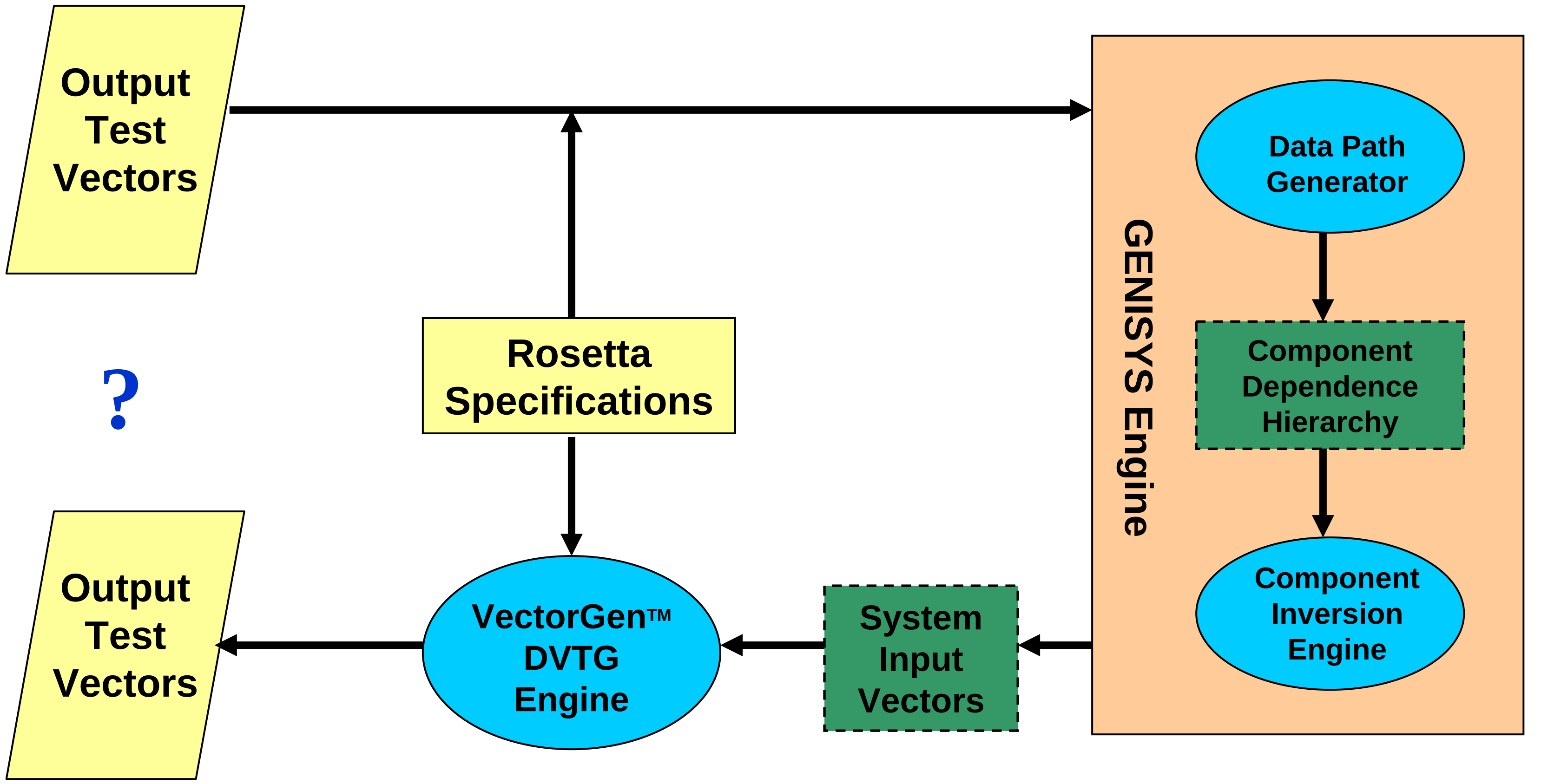
Algorithm to invert If-Then-Else Expression…

- *If (A) then*
  if (B) then C else D end if
  else if(E) then
  F else G end if end if;
- If(B) then C else D ➔ (B ∧ C) ∨ (¬B ∧ D)
- If(E) then F else G ➔ (E ∧ F) ∨ (¬E ∧ G)
- (A ∧ ((B ∧ C) ∨ (¬B ∧ D))) ∨
  (A ∧ ((E ∧ F) ∨ (¬E ∧ G)))
- DNF: (A ∧ B ∧ C) ∨ (A ∧ ¬B ∧ D) ∨
  (¬A ∧ E ∧ F) ∨ (¬A ∧ ¬E ∧ G)

System Test Vectors

```xml
<TestData>
 <Config>
  <DataConfig>
     <Name>input_par1</Name>
      <Index>1</Index>
      <InputType/>
  </DataConfig>
  …
 </Config>
 <TestSet>
  <TestVector>
     <Input>
       <Name>input_par1</Name>
       <Value>0</Value>
     </Input>
     <LocalVar>
       <Name>var1</Name>
       <Value>1.5</Value>
     </LocalVar>
     <Output>
       <Name>output_par2</Name>
       <Value>0.99</Value>
     </Output>
  </TestVector>
  …
 </TestSet>
</TestData>
```

GENISYS Verification



Testing & Example

- Inner Components
  - Trigger-based Circuit
  - Negative Trigger Circuit
  - Positive Trigger Circuit
  - Multiplexer Circuit
  - OR Gate Circuit
  - Inverter Circuit
- Rosetta Specification for all these inner components

Testing & Example…

- Structural Component

Inner-Components

```
package STRUCT_COMPONENT :: logic is
   /* package body begins here */
  use INVERTER, POSITIVE_TRIGGER, NEGATIVE_TRIGGER,
        QUAD_MUX2X1, OR_GATE, TRIGGER_CIRCUIT ;

   facet STRUCT_COMPONENT
      (  /* interface parameters declared */
        a  :: input  bit;     B  :: input  bit;  d  :: input  bit;    h  :: input  bit;
        G   :: input  bit; x  :: input  bit;       z  :: input  bit; W  :: input  bit;
        u  :: input  bit;  Aa :: output bit; BB :: output bit;   eE :: output bit;
        Ff :: output bit; DD :: output bit; Gg :: output bit;  E  :: input  bit;
        Y   :: input  bit;   V  :: input  bit;  HH :: output bit; CC :: output bit;
      zZ:: output bit   ) :: state_based is
```

Interface Parameters

Testing & Example…

Component Inter-Dependence

```
/* locally declared variables */
     C, F, I, J, K, L, M :: bit;
     /* facet body begins here */
     begin
     COMPONENT_1 : INVERTER(A, C);
     COMPONENT_2 : POSITIVE_TRIGGER(C, B, F);
     COMPONENT_3 : NEGATIVE_TRIGGER(F, D, I);
     COMPONENT_4 : OR_GATE(I, F, ZZ);
     COMPONENT_5 : QUAD_MUX2X1(A, B, C, D, E, F, G,
                               H, I, J, K, L, M);
     COMPONENT_6 : TRIGGER_CIRCUIT(U, V, W, X, Y, Z,
                                   J, K, L, M, AA, BB,
                                   CC, DD, EE, FF, gg, HH);
  end facet STRUCT_COMPONENT;
end package STRUCT_COMPONENT;
```

Test Scenarios – 1 *(TRIGGER_CIRCUIT → TC)*

```
<COMPONENT_HIERARCHY file="STRUCT_COMPONENT" >
 <TEST_COMPONENT component_name="COMPONENT_6" >
  <DRIVING_COMPONENT component_name="COMPONENT_5" driving_variable="J" >
   <DRIVING_COMPONENT component_name="COMPONENT_1" driving_variable="C" >
   </DRIVING_COMPONENT>
   <DRIVING_COMPONENT component_name="COMPONENT_2" driving_variable="F" >
    <DRIVING_COMPONENT component_name="COMPONENT_1" driving_variable="C" >
    </DRIVING_COMPONENT>
   </DRIVING_COMPONENT>
   .    .    .
  </DRIVING_COMPONENT>
 </DRIVING_COMPONENT>
 </TEST_COMPONENT>
</COMPONENT_HIERARCHY>
```

Driving Comp Hierarchy

Driven Comp Hierarchy

```
<COMPONENT_HIERARCHY file="STRUCT_COMPONENT" >
 <TEST_COMPONENT component_name="COMPONENT_6">
 </TEST_COMPONENT>
</COMPONENT_HIERARCHY>
```

Test Scenarios – 1…

```
<TestData>
  <Config>
    <DataConfig>
      <Name>A</Name>
      <Index>1</Index>
      <InputType/>
    </DataConfig>
    .   .   .
  </Config>
  <TestSet>
    <TestVector>
      <Input>
        <Name>A</Name>
        <Value>0</Value>
      </Input>
      .   .   .
<LocalVar>
        <Name>C</Name>
        <Value>0</Value>
      </LocalVar>
      .   .   .
      <Output>
        <Name>ZZ</Name>
        <Value>-</Value>
      </Output>
    </TestVector>
    .   .   .
  </TestSet>
  .   .   .
</TestData>
```

System Vectors

Test Scenarios

- INVERTER → TC
  - No Driving Component Hierarchy
  - All Inner-Components are Driven by TC
- NEGATIVE-TRIGGER → TC
  - Has both Driving and Driven Comp. Hierarchies
- Invalid Specification Scenarios
  - Feedback Loop in Hierarchy
  - Non-Determinacy in Hierarchy

Related Work

- Program Inversion – *Edsger W. Dijkstra*
- Running Programs Backwards: The Logical Inversion of Imperative Computation – *Brian J. Ross*
- A Formal Approach to Program Inversion – *Wei Chen*
- Reverse Execution of Programs – *Bitan Biswas & R. Mall*

Conclusion

- Developed GENISYS, a tool for Component Inversion
- GENISYS produces Component Dependence Hierarchies for a given Component Inter-dependence Scenario
- GENISYS processes Invertible Components to derive System Vectors
- zChaff SAT Solver is used for inverting expressions in Rosetta language
- Hierarchy and System Vectors generated in XML format

Future Work

- Allow each inner-component to be structural component itself
- Invert Functions defined in Rosetta language
- Define inner-components in Structural component
- Optimize the Component Inversion algorithm. Keep track of all the valid solutions of the SAT Solver and try the best. Computation-intensive approach

Thank You!!!

Questions?