Automated Test Program Generation for an Industrial Optimizing Compiler

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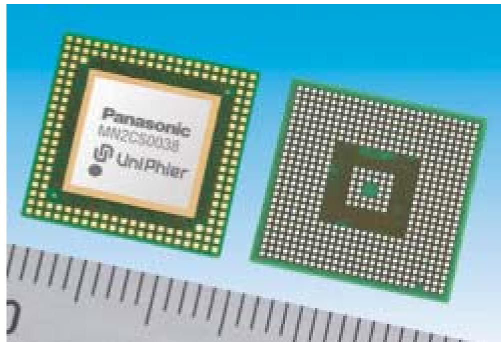
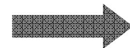
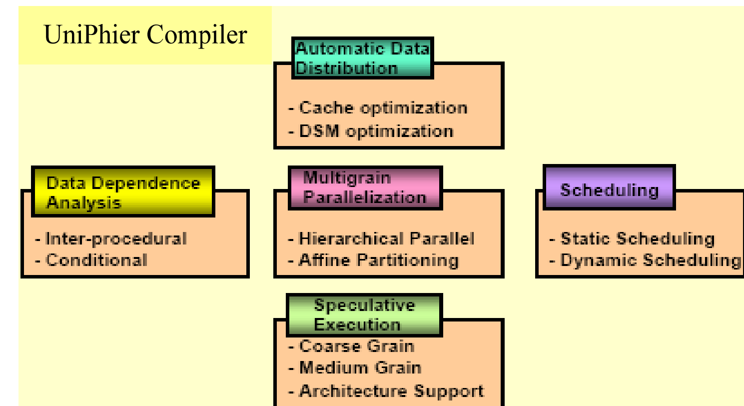
Outline

- Motivation
- Brief Introduction to Compiler Optimizations
- JTT: Automated Tool for Test Program Generation
- Formal Model-based Generation: From Formula to Program
- Evaluation in Testing UniPhier Compiler
- Contributions

Motivation







UniPhier: A popular, high-performance, embedded chip from Panasonic

A collection of compiler optimizations

All optimizations must be TRUSTABLE!

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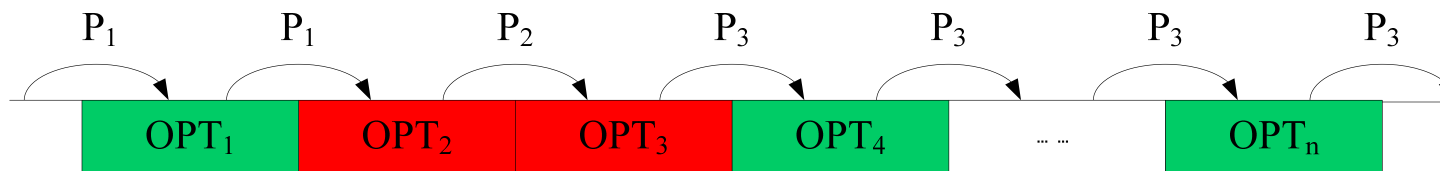
Compiler Optimizations

What is compiler optimization?

"*Compiler optimization is the process of tuning the output of a compiler to minimize or maximize some attribute of an executable computer program.*" ——Wikipedia

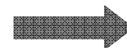


Well-Known Optimizations:

Dead Code Elimination, Common Subexpression Elimination, Loop Interchange, Loop Unrolling…

```
a = b * c + g;

d = b * c * d;
```



```
tmp = b * c;
a = tmp + g;

d = tmp * d;
```

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Compiler Optimizations (Cont'd)

- General Form

$$I \rightarrow I' \ \textit{if} \ \{\textit{Side Conditions}\}$$

- Features
  - Semantic-preserving
  - Many possible prerequisites
  - Dependent to data types

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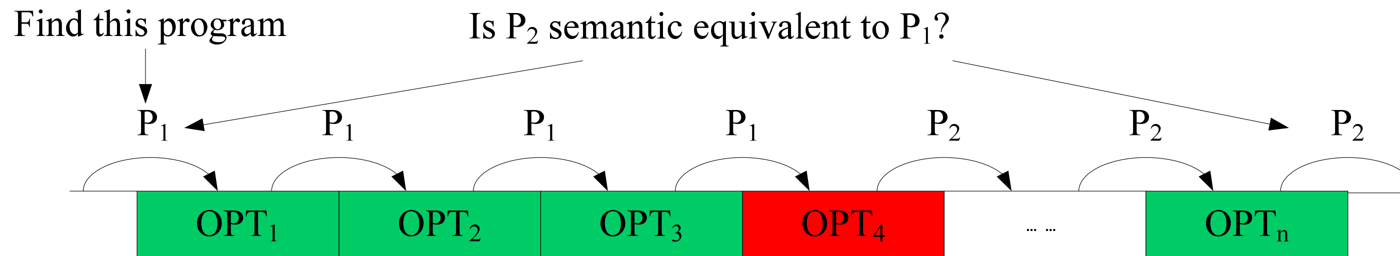
How to Test An Optimization

- Basic approach

  Find a program to active the optimization



- Requirements for test programs
  - Definitely active specific optimization
  - Cover as many prerequisites as possible
  - Use various data types
  - Interleave optimizations and data types

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Extra Difficulties in Testing UniPhier Compiler

Architecture-dependent optimizations
→ not common optimizations
→ special program to active such optimizations

Architecture-dependent data types
→ not common data types
→ special program to use such data types

Especially when such optimizations and data types are interleaving with each other!

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Possible Solutions

Solution	What's it?	Advantage	Disadvantage
Benchmark	SPEC Benchmarks, EEMBC, etc	Popular, public	Performance-oriented, not optimization-oriented; without UniPhier-related features
Public Test Suite	GCC Test Suite and so on	Public available	Language-oriented, not optimization-oriented; without UniPhier-related features
Internal Test Suite by Panasonic	Legacy of past testing in Panasonic	Optimization-oriented, Concerning both common and UniPhier-dependent optimizations	Not available for new architecture features, new optimizations and new data types
Manual Programming	Test program written by test engineers	Optimization-oriented, concerning all optimizations, be aware for evolution of UniPhier and its compiler	Labor-intensive, test efficiency and quality are difficult to achieve

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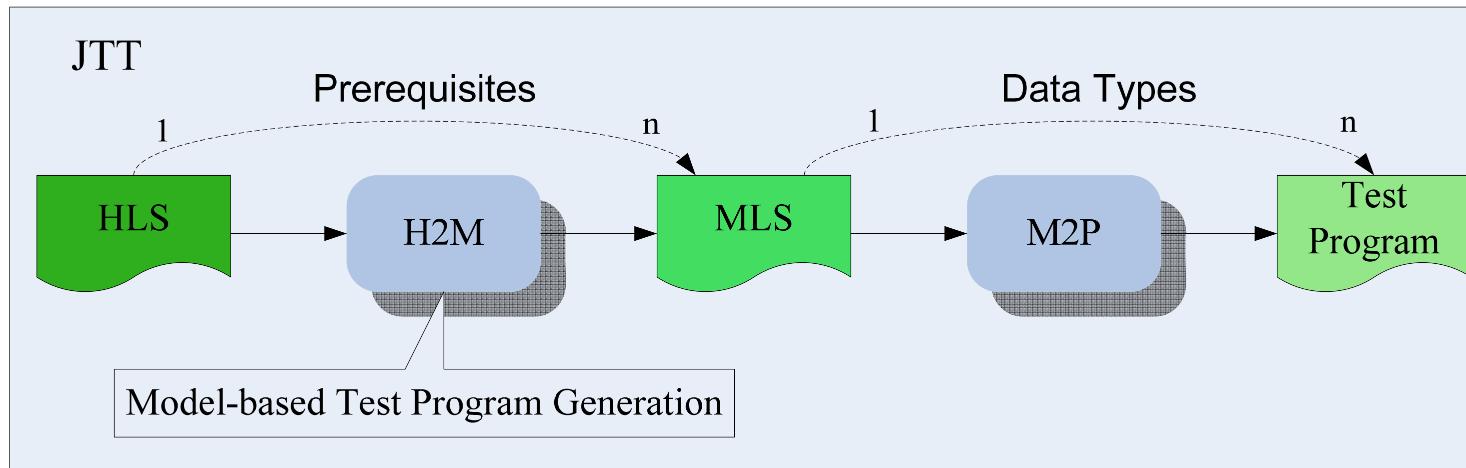
JTT: An Automated Tool for Test Program Generation



HLS (High Level Script): specify test requirements, including optimizations, data types used, statement types, operators and so on. Readable for test engineers.

MLS (Middle Level Script): specify test program template, including program statement template, data types, operators and so on

H2M: transform HLS to MLS M2P: transform MLS to test program

H2M is based on formal model of compiler optimizations

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HLS Script & MLS Script

```
Element {
   Var-type: char, pointer(int), struct(char*pointer(int))
   Statement: if, for, switch, goto
   Operator: +, *, <<, &
}
Structure {
   Intra-module: Type = if+loop, Nest = 3, Parallel = 2
   Inter-module: Depth = 2, Width = 3, Recursion = 0
}
Content {
   ScalarOpt: DCE, CSE
   LoopOpt: Skew, Fusion, Interchange
   Pragma: Prefetch, UnrollLength
}
```

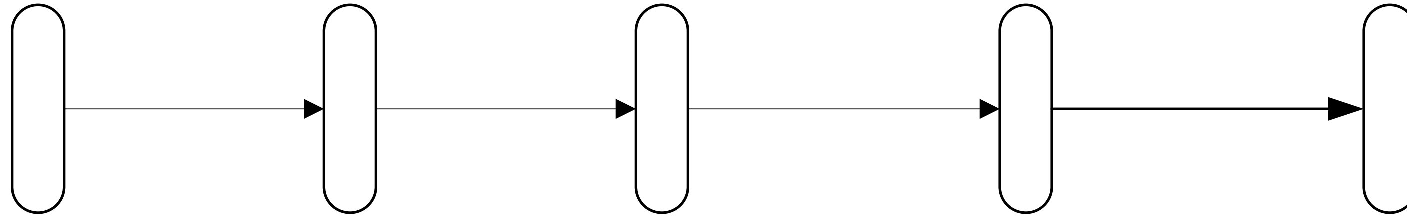
An Example HLS Script

```
Element { ... }
Structure {
   Func1( ){
      IF(||,2;&&,3){
         ASS
      }
      LOOP(Times=20){
         Func2
         ASS
      }
   }
   Func2( ){
      ASS
   }
}
Content { ... }
```

A Possible MLS Script

- Advantage of Two-Level Script
  - Separate test program requirements and test program specification
  - Hide details of test program and architecture in MLS
  - Prerequisites and data types can be interleaved easily
  - Thousands of test programs with respect to HLS can be generated automatically and easily

Model-based Generation: from Formula to Program



CTL Formulas for Optimizations | Node Control Graph | CFG with State and Path Quantifiers | CFG with First-Class Formulas | Program Template in MLS

CTL Formulas for Optimizations: Computation Tree Logic (CTL) Formulas (only name listed in HLS)

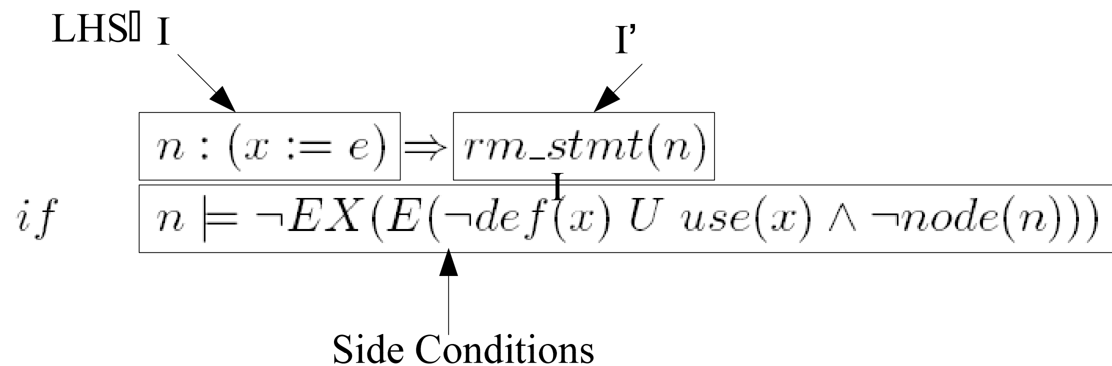
NCG: Node Control Graph, a special CFG

Construction of CFG: enrich complexity of resulting code

Expansion of Temporal Quantifiers: make all nodes in CFG only labeled with first-order formulas

CTL Formulas for Compiler Optimizations

A conditional rewriting rule containing CTL formulas for Dead Code Elimination

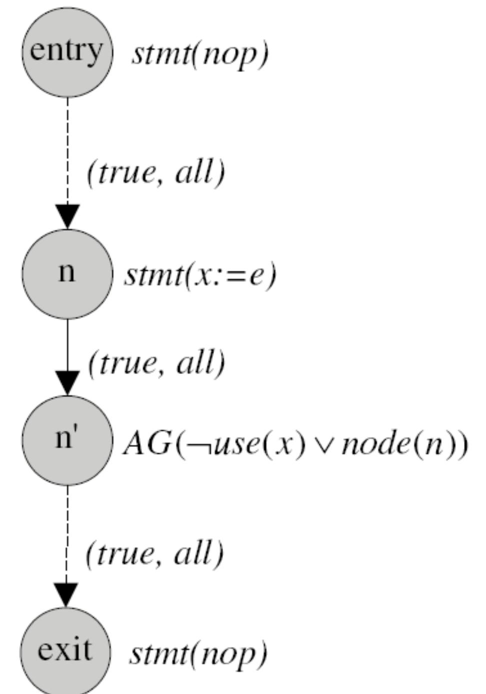


LHS specifies some statements in test program
Side conditions specify why an optimization is semantic-preserving – a relationship between LHS and other statements in test program

LHS + Side Conditions → Test Programs

Node Control Graph

- A special CFG
  - Constructed according to CTL Formula
    - X operator leads to a first-successor node and a solid edge to current node
    - U operator leads to a successor node and a dashed edge to current node
  - Each dashed edge can be replaced by a basic block
  - Each edge is labeled with a formula for all or some paths in the basic block
  - Each node is labeled with a formula for statement at the node



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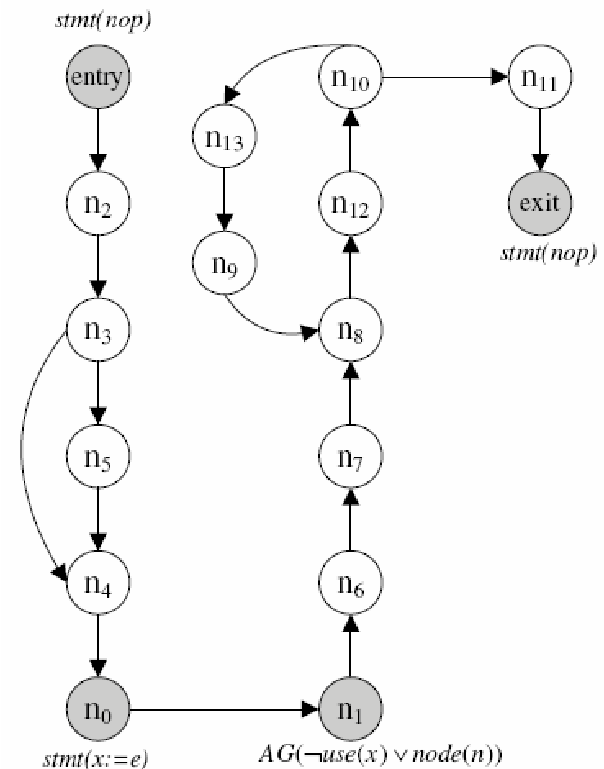
Construction of CFG with State & Path Quantifiers

- Replace each dashed edge with a basic block

The basic blocks are generated randomly



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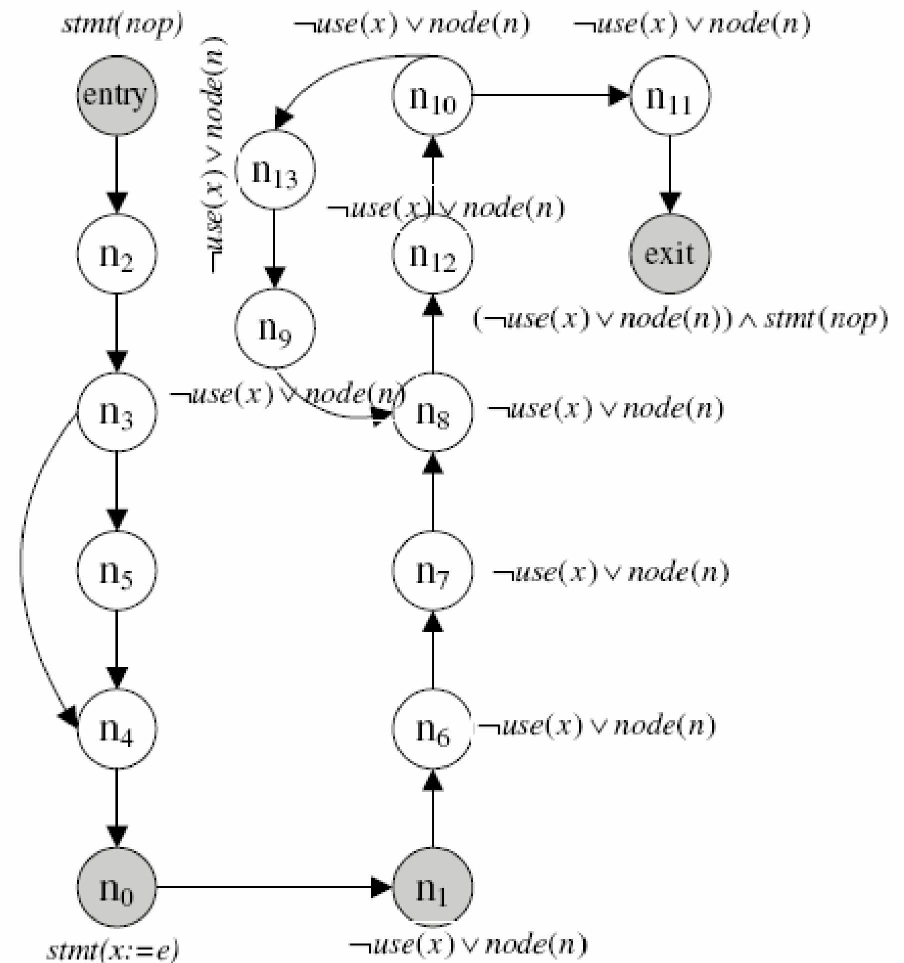
CFG with first-order Formulas

Expand temporal quantifiers to all involved nodes

Make all nodes only labeled with first-order formulas for convenience of generation

Different expansion for A/E path quantifiers and G/F state quantifiers



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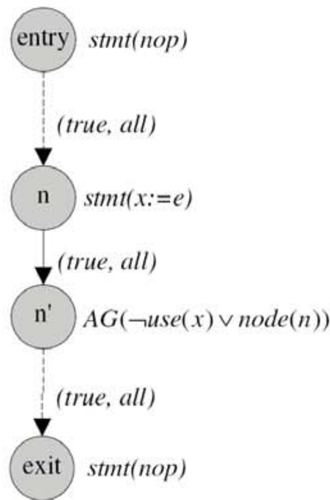
Example Generation

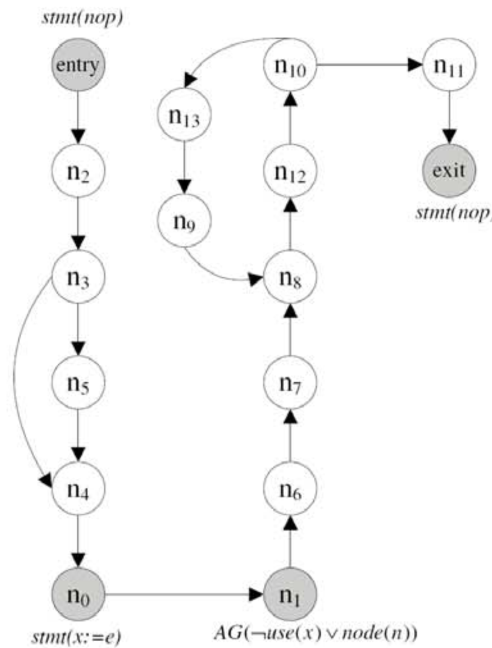
$n : (x := e) \Rightarrow remove\ statement\ n$

$if \quad n \models \neg EX(E(\neg def(x)\ U\ use(x) \wedge \neg node(n)))$

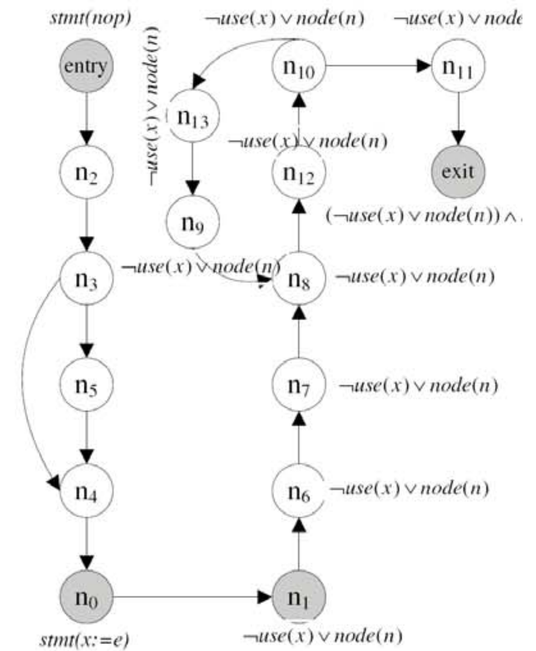
(a) DCE Formula



(b) NCG of A Possible DCE Instance



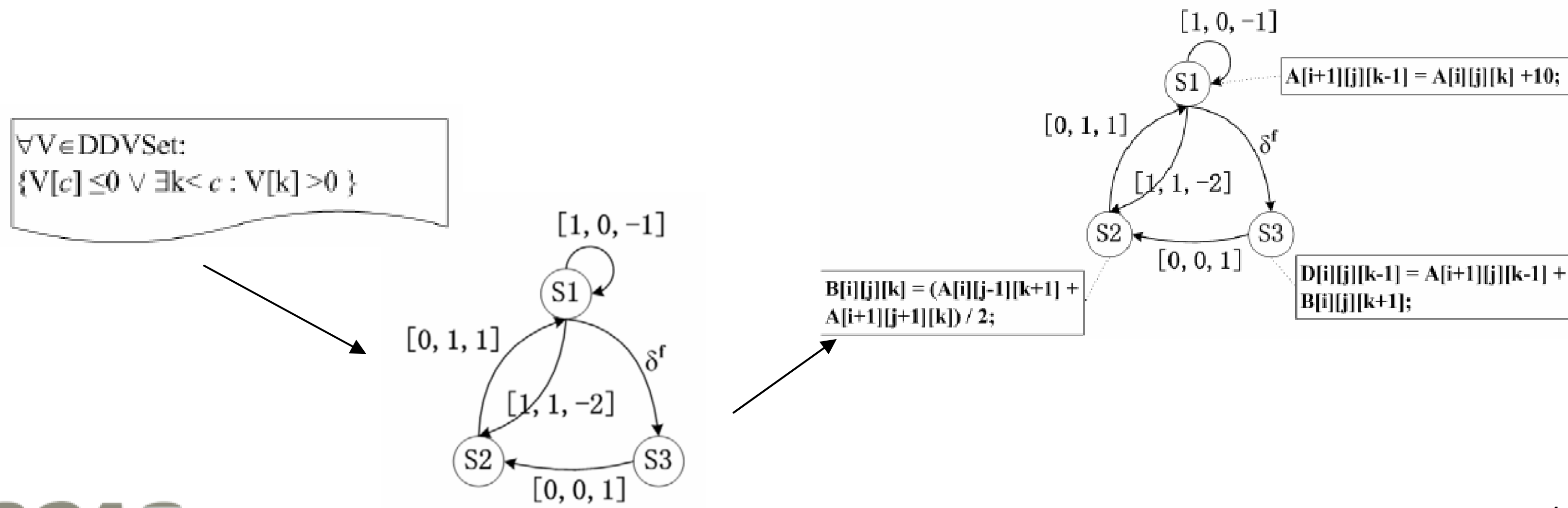
(c) CFG Labeled with Temporal-Logic Formula



(d) Program Template

Data Dependence Generation for Loop Optimizations

- Assign flow-, anti-, and output-dependence to statements within loop nests
  - Steps:
    1. Assign valid types of data dependence to statements
    2. generate proper subscription function according to data dependence (Linear Integer Programming)



Evaluation in UniPhier Compiler

- JTT v.s. Benchmark & Public Test Suite

	M1	M2	M3	M4	M5	M6	M7
Benchmark & Public Test Suite	85%	18%	79%	0%	0%	1%	1%
With JTT	88%	54%	80%	63%	49%	68%	56%

Statement Coverage of 7 Optimizing Modules in UniPhier Compiler

- JTT v.s. Manual Programming

6,000+ test programs v.s. 1,000+ test programs

- Bugs Found
  - 6 new serious bugs found by JTT
  - Found 21% bugs by JTT during testing

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Contributions

- Model-based test program generation for optimizing modules
- Automated script-driven test case generation for a large system with complex inputs
- Application of formal methods in a large complex system

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Thanks for Your Attention!
Any Questions?

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