Global Optimization for Compositional Systems

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Outline

Overview of embedded systems

- Composition of hardware and software IP modules
  - Communicate with dedicated hardware devices
- Heterogeneous by nature
  - Application specific integrated circuits (ASICs)
  - Field programmable gate arrays (FPGAs)
  - Embedded software running on one or more processors
- Applications: communications, image processing, and automotive electronics

Co-optimization of embedded systems

- Techniques exist to optimize each IP module and the underlying network (Ch+-DAC-95,HwSwCoDesign-02)
- Integrating computing components introduce new opportunities for optimizations
- Need for co-optimization techniques
  - Work across components
  - Work across hardware and software boundaries

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Important questions

- Can software be developed before hardware is committed?

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Important questions

- Can software be developed before hardware is committed?
- What if new versions of software used hardware that was optimized away?

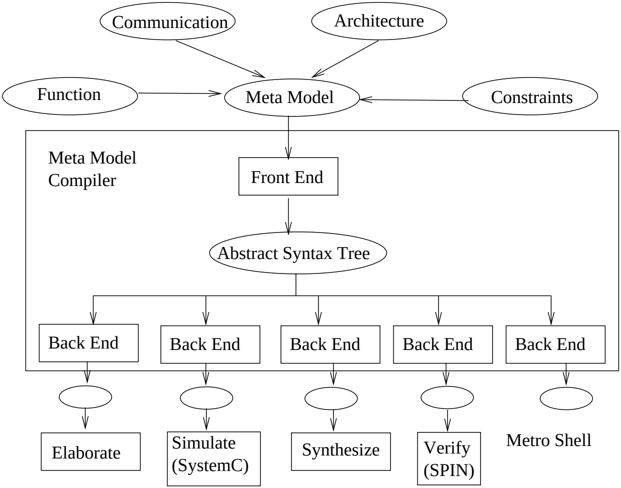
Outline

1. Co-design of embedded systems
   - The Metropolis framework
   - Motivation for co-optimization
2. Co-optimization using symbolic execution
   - Symbolic execution by example
   - Constraint detection and propagation
3. Case Studies
   - Switch fabric
   - Vision system

THE METROPOLIS DESIGN FRAMEWORK [BA+-COMPUTER-03]

- Express embedded systems in Metropolis Meta Model (MMM) netlists
  - MMM extends a subset of the Java programming language
- Separate computation and communication
  - Processes: computing elements
  - Media: communication elements
- Independent of the model of computation (MoC)
  - Similar to the tagged signal model (Ed+-IEEE-97)

ARCHITECTURE OF METROPOLIS



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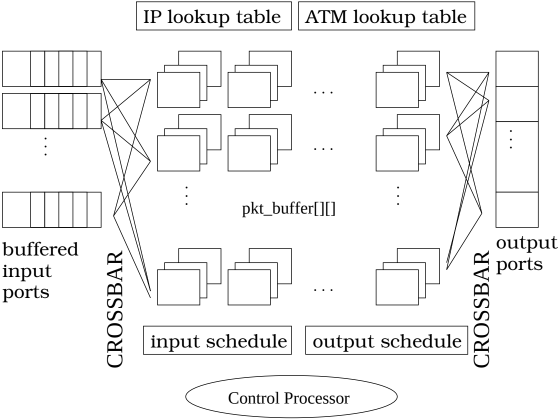
SWITCH FABRIC EXAMPLE



- Optimization opportunities: IP traffic only, dedicated ports
- Need for co-optimization techniques

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2. **Co-optimization using symbolic execution**
   - Symbolic execution by example
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SYMBOLIC EXECUTION BY EXAMPLE

JUZI/CVC-LITE [KH+-TACAS-03]

```
int x, y;
if (x > y) {
    x = x + y;
    y = x - y;
    x = x - y;
    if (x - y > 0)
        assert(false)
}
```

$$\boxed{x = A, y = B}$$

Symbolic execution by example

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$\boxed{x = A, y = B}$

$\boxed{A >? B}$

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$x = A, y = B$

$A > ?B$

$\langle A \leq B \rangle$ **end**

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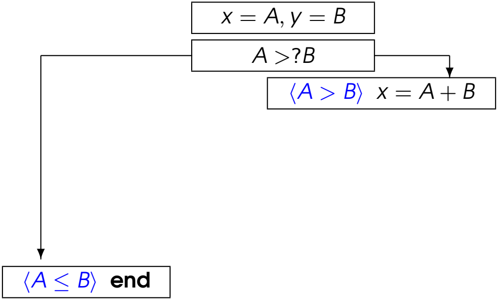

Symbolic execution by example

Juzi/CVC-Lite [Kh+-TACAS-03]

COSE
FMCAD 07
Co-design
Metropolis
Motivation
COSE
SE example
Constraints
Cases
Fabric
Vision

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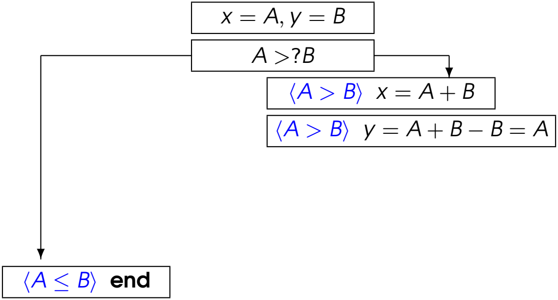

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$\langle A > B \rangle \quad x = A + B$

$\langle A > B \rangle \quad y = A + B - B = A$

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Symbolic execution by example

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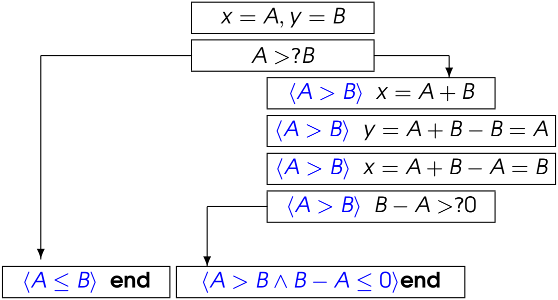

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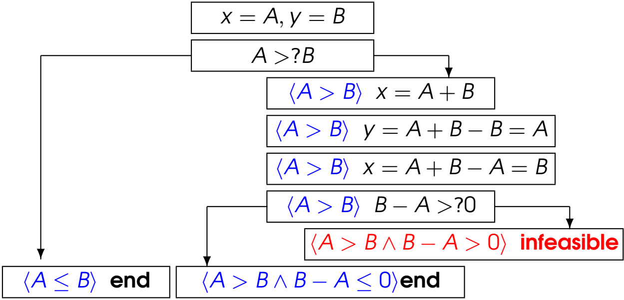

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$\langle A > B \rangle \quad y = A + B - B = A$

$\langle A > B \rangle \quad x = A + B - A = B$

$\langle A > B \rangle \quad B - A >? 0$

$\langle A > B \wedge B - A > 0 \rangle$ **infeasible**

$\langle A \leq B \rangle$ **end**

$\langle A > B \wedge B - A \leq 0 \rangle$ **end**

- COSE instruments MMM code to perform symbolic execution

UT ECE

Outline

CONSTRAINT DETECTION

- Use symbolic execution on component level
  - Detect local invariants—constraints
  - Accumulate path conditions
- Annotate ports with detected constraints
- Quality of detected invariants
  - Designer may not know them
  - Designer may not recognize them as useful to optimize other components

Constraint propagation

- Build dependency map between components
- Propagate constraints to other components
  - Start with detected constraints as initial path conditions
  - Use symbolic execution to propagate constraints

MMM AND SYMBOLIC EXECUTION

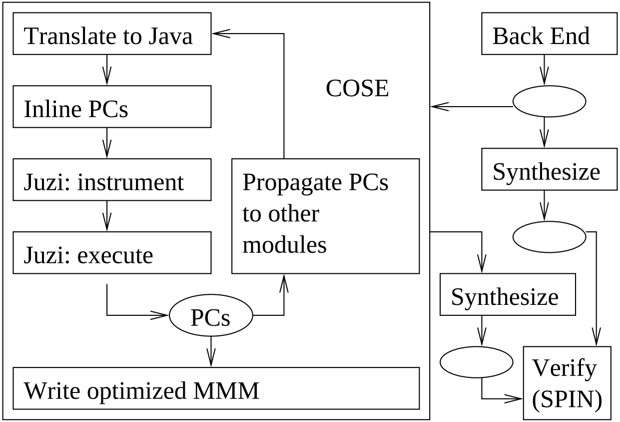
- Translate MMM into inlined Java
  - MMM is an extension of a Java subset
  - Process, medium, and netlist: class
- Juzi instruments Java code
- CVC-Lite solves and simplifies path conditions

COSE optimizations

Qualitatively different than those detected by local compiler optimizations

- Eliminate dead code — infeasible path conditions
- Detect range restrictions and re-encode variables
- Detect mutually exclusive executions
  - Target resources sharing and multiplexing
- Annotate MMM with constraints and pass to synthesis tools
  - Apply constant propagation, redundancy removal, and observability don't care reductions

COSE ARCHITECTURE



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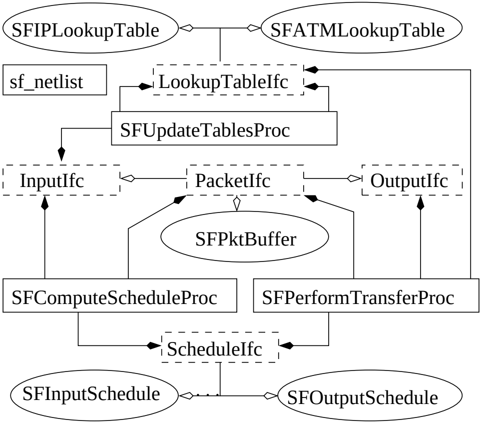
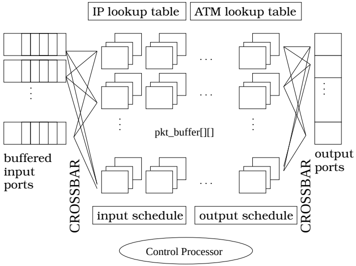
MMM for Switch fabric example

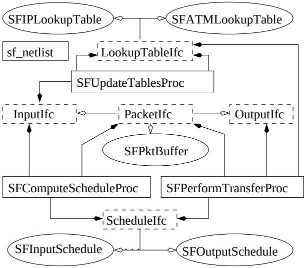
Opportunities: IP traffic only, dedicated ports



Processes: compute schedule, perform transfer, update

Case study: switch fabric
Mixed traffic, multiport, 755 lines of MMM code



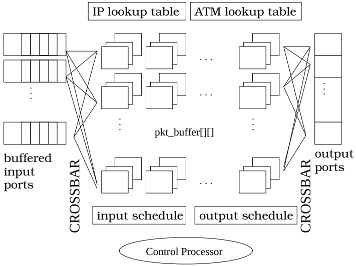


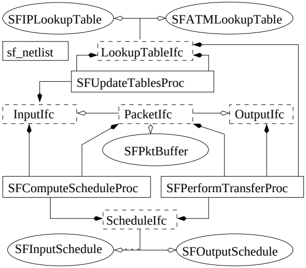
IP traffic only

- 4 input ports, 4 output ports, and 8×16 packet buffers
- 192 minutes and 37K symbolic variables

Case study: switch fabric

Mixed traffic, multiport, 755 lines of MMM code





Limited output ports

- 4 input ports, 8 output ports, and 8×16 packet buffers
- Enabled dropping 4 output ports
- 247 minutes and 61K symbolic variables

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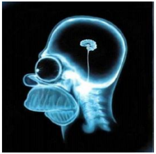
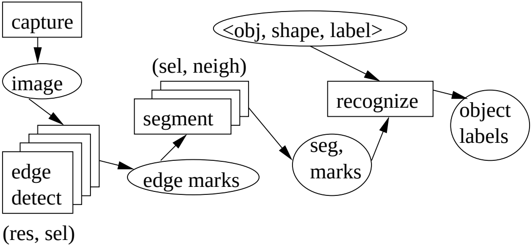
Case study: ObjectID vision system

Flow diagram, 4K lines of C/RTL code

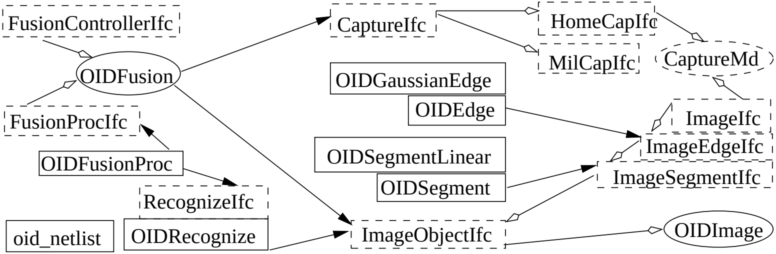




- Labels objects in image with identified names
- Developed for military and medical purposes
  - Deployed for home surveillance applications

Case study: ObjectID vision system

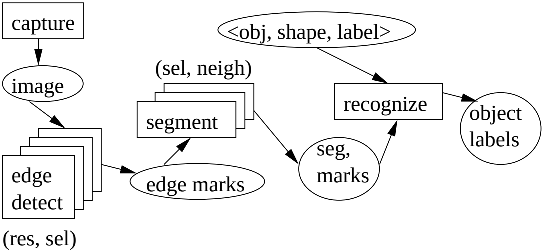
Class diagram, 1255 lines of MMM



- 4 process classes, 3 media classes, and 10 Interfaces

Case study: ObjectID vision system

Results: low resolution capture



Case study: ObjectID vision system
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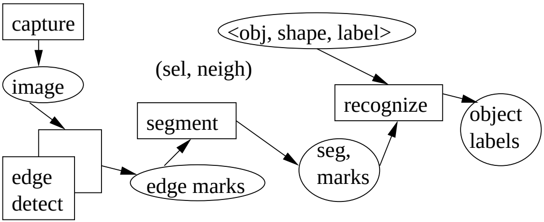


- Dropped 2 edge detectors in the first iteration
- Dropped a segmentation process in the second iteration
- 15 minutes and 13K symbolic variables

FUTURE...

- Use a difference equation solver instead of CVC-Lite
- Use symbolic execution to optimize linking compilable software modules

Thank you!

- Questions?

  - Can software be developed before hardware is committed?
  - What if new versions of software used hardware that was optimized away?
  - ...

Outline

4 Answers

Software latency question

Can software be developed before hardware is committed?

- Metropolis supports different design abstraction and implementation refinement levels
  - At each refinement level discard COSE optimizations and compute again

Flexibility question

What if new versions of software used hardware that was optimized away?

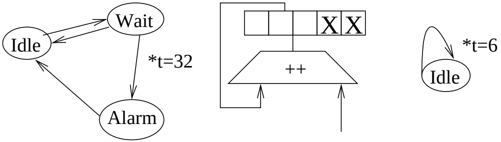
- COSE produces the path conditions it used to optimize the design
  - Can be used as a guide to avoid adding optimized hardware
  - Can be used to undo the optimizations

COSE

FMCAD 07

Answers

CLASSICAL SEAT BELT EXAMPLE...



(a) seat belt controller (b) counter (c) force key off