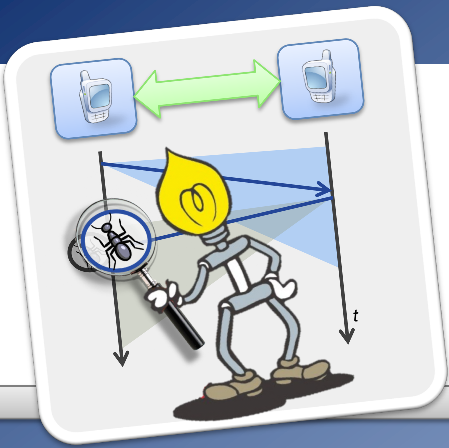

Symbolic Analysis of Networked Systems

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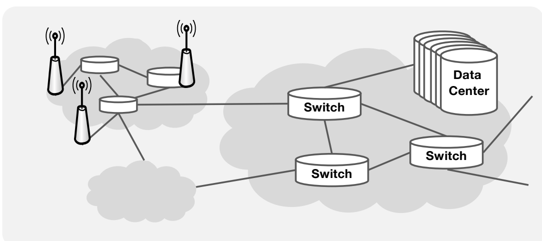
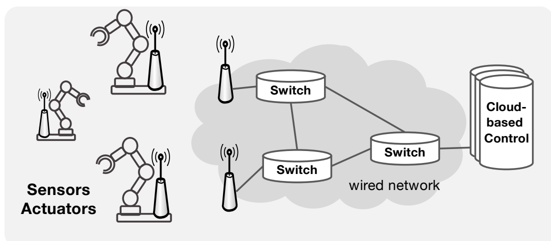
Challenges in Softwarized Communication Systems

- **Software plays an increasingly important role in networking**
  - Protocols, billions of apps, etc.
  - Network elements become flexible (SDN, NFV, In-network processing)
- **Important: Analysis of real code – not models**



Networked Systems (protocols, apps)



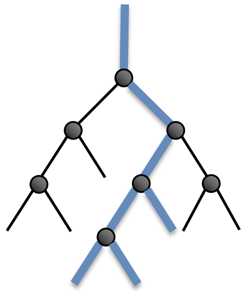
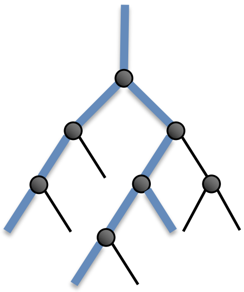
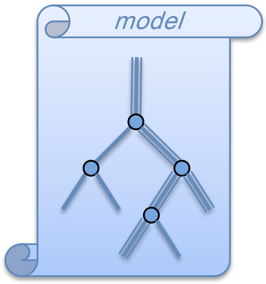
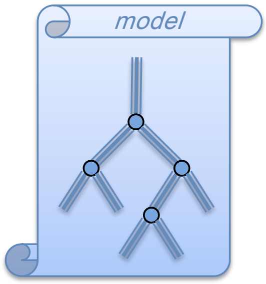
Latency-critical networked control

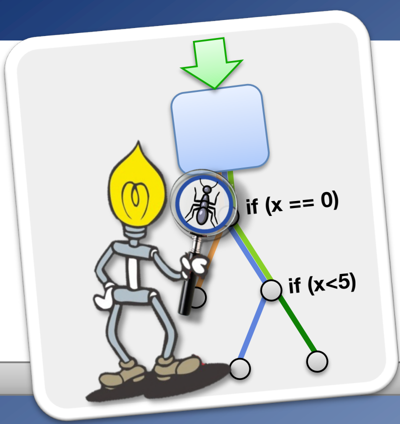
Goal: devise a new methodology for

Software Analysis of Interacting Systems?

Rigorous, automated and effective!

State of the Art in Distributed Systems Testing

Testbeds, Prototypes Emulation	Random testing	Simulation	Model-based proofs
			
Automatism ✗	Automatism ✓	Automatism ✗	Automatism ✗
Coverage ✗	Coverage ✗	Coverage ✗	Coverage ✓
Effectiveness ✓	Effectiveness ✓	Effectiveness ✓	Effectiveness ✓

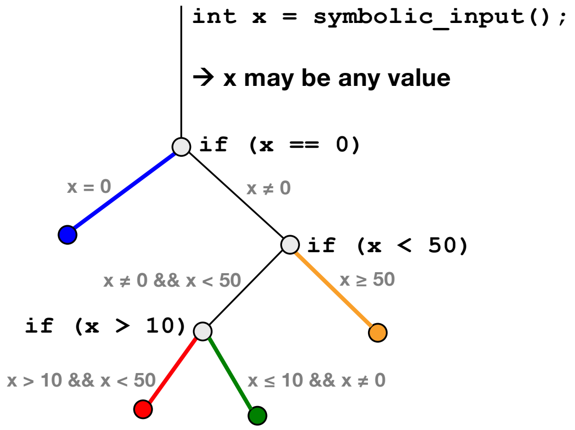


Traditional

Symbolic Execution

Symbolic Execution: A Simple Example

```
int get_range(int x) {
    if (x == 0)
        return blue();
    if (x < 50) {
        if (x > 10)
                return red();
            return green();
        }
    return orange();
}
```

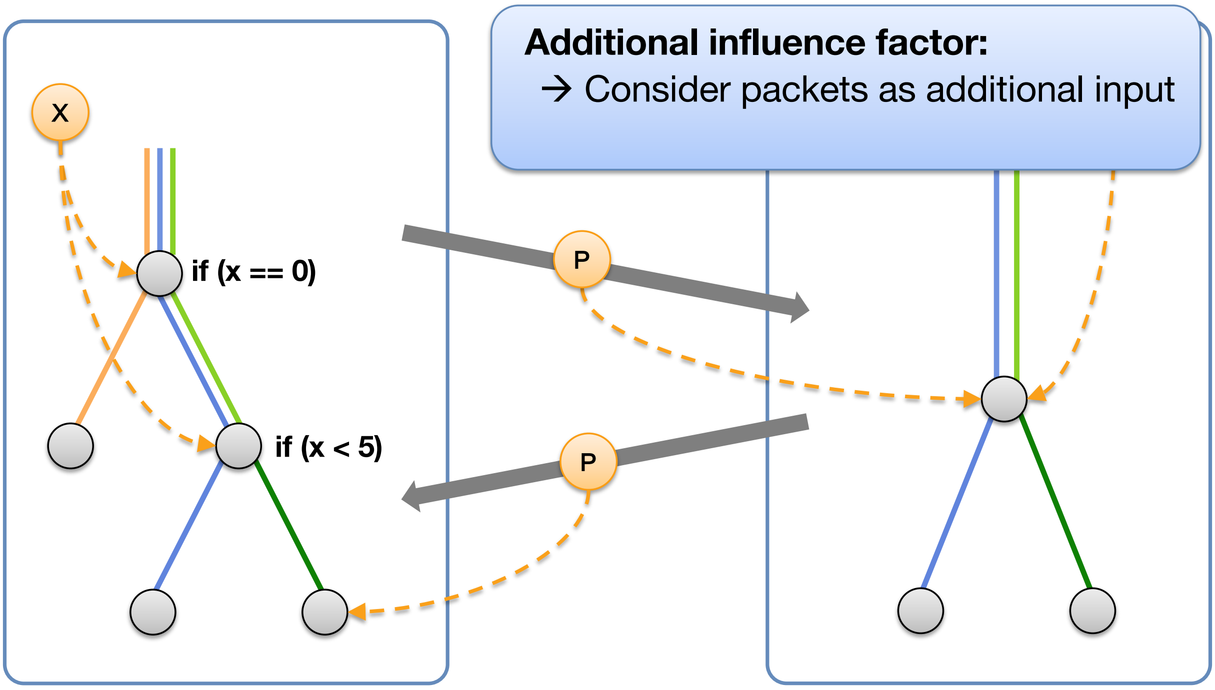


But, is Symbolic Execution able to analyze *networked* systems?

est 1: x = 0
est 2: x = 22
est 3: x = 5
est 4: x = 99

Symbolic Execution and Networked Systems

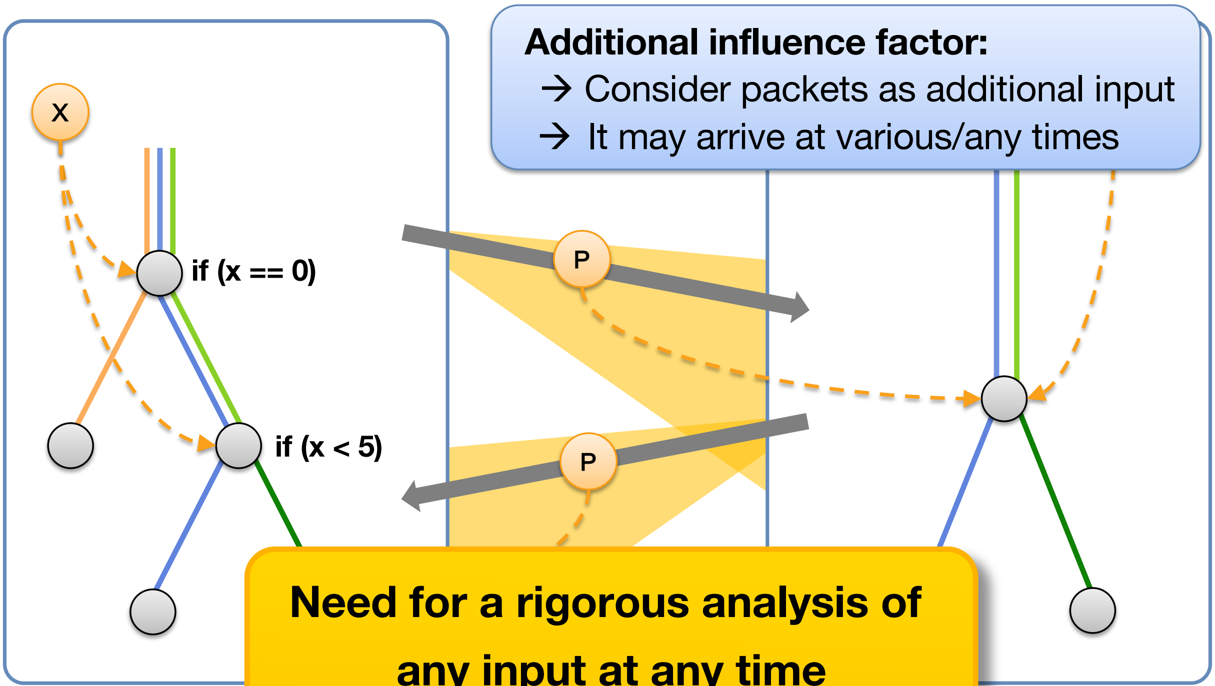
- **Symbolic analysis of networked systems?**



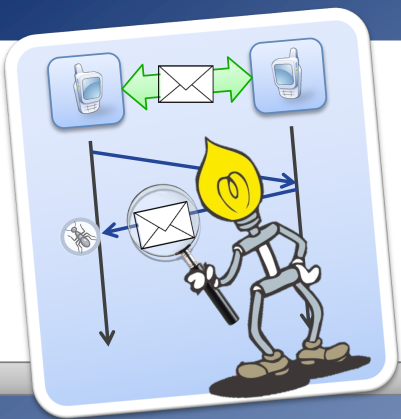
Symbolic Execution and Networked Systems

- **Symbolic analysis of networked systems?**

Additional influence factor:
→ Consider packets as additional input
→ It may arrive at various/any times



Need for a rigorous analysis of any input at any time



Symbolic Analysis of Network Input

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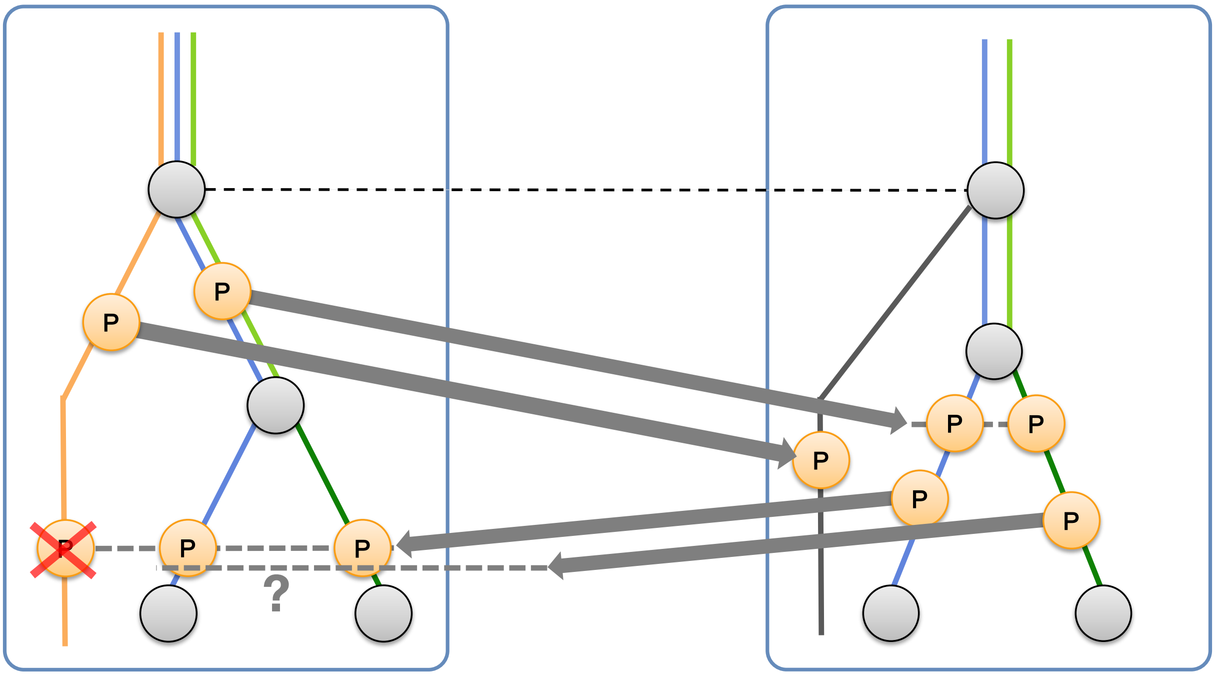
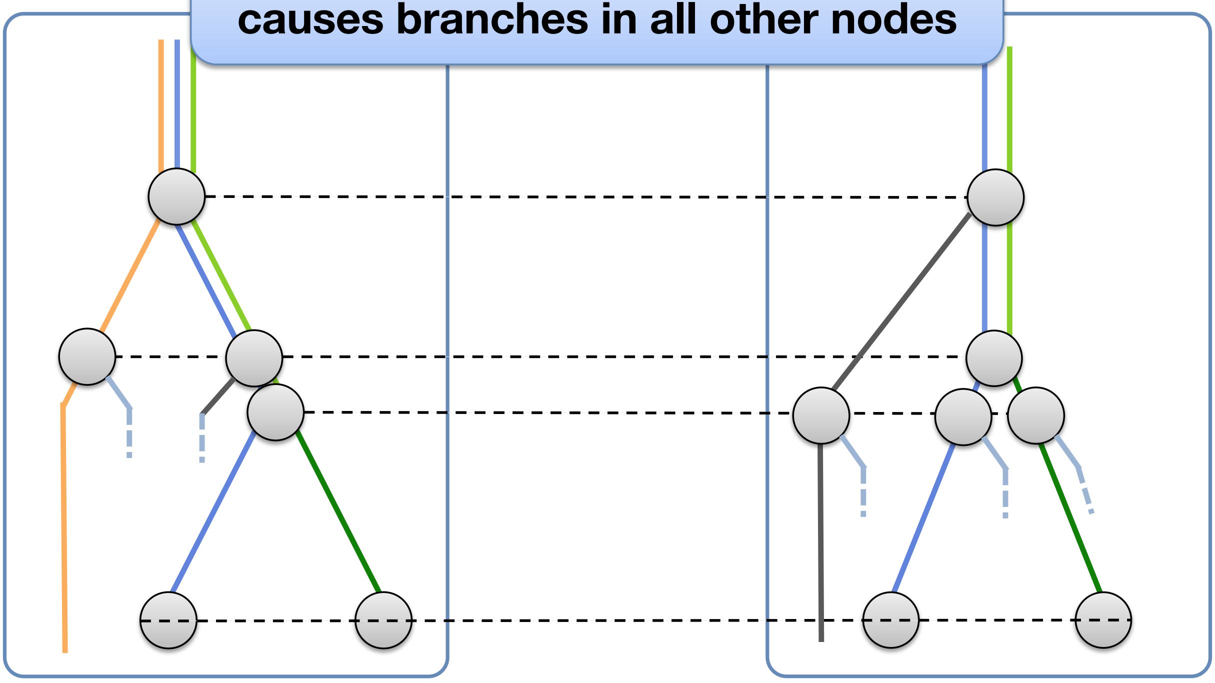
Symbolic Execution of Networked Systems

- **Symbolic analysis of network input**



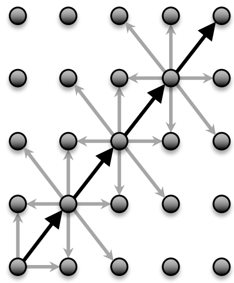
Symbolic Distributed Execution (SDE)

Branching within a node causes branches in all other nodes

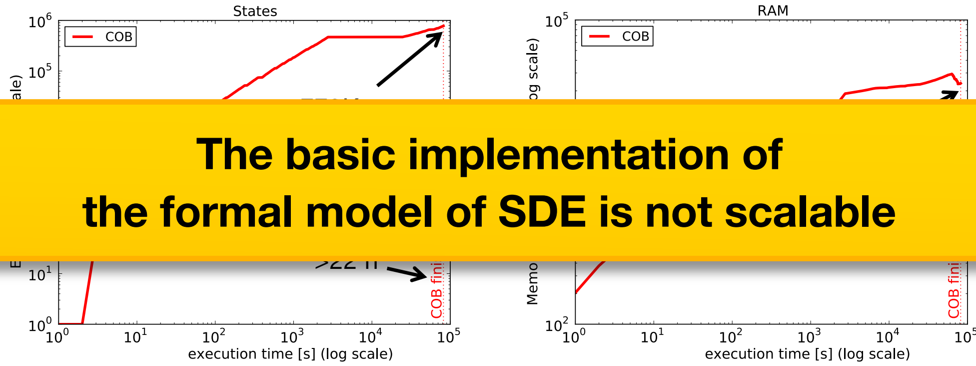


SDE: State Explosion

- **Test scenarios**
  - Grid with n^2 nodes (example: 49)
  - Transmissions via a static path
  - Symbolic network failures
  - 10s simulated time



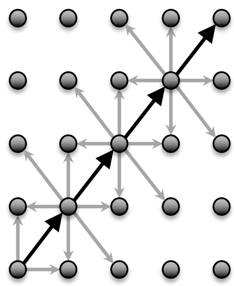
- **Results using the conservative approach (49 nodes)**



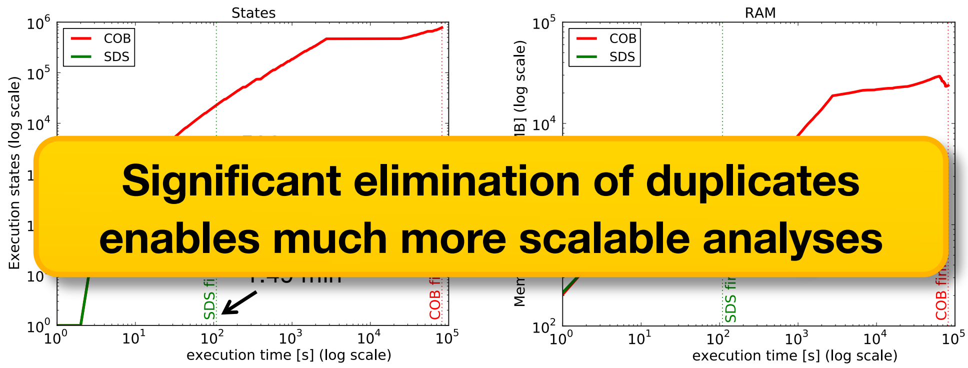
The basic implementation of the formal model of SDE is not scalable

SDE: Elimination of Redundant States

- **Test scenarios**
  - Grid with n^2 nodes (example: 49)
  - Transmissions via static path
  - Symbolic network failures
  - 10s simulated time



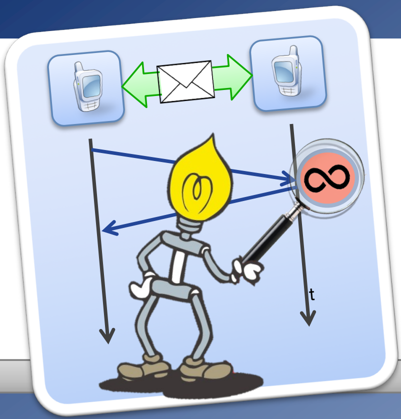
- **Results using conservative and lazy forking algorithms**



Significant elimination of duplicates enables much more scalable analyses

Infinite Loop Detection

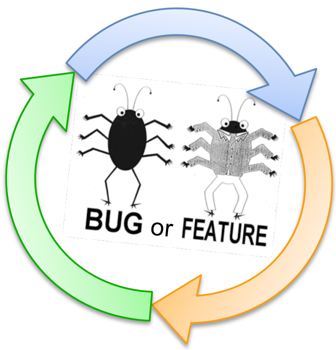
Symbolic Analysis of Protocol Loops



http://comsys.rwth-aachen.de

Liveness of a Protocol – Infinite Loop Detection

- **Why are infinite loops an issue with protocols?**
  - The outmost (protocol) loop should run infinitely (intended loop)
  - The input handler should always finalize (non-intended loop)
  - Infinite inner loop is a bug
- **When is a loop infinite?**
  - If it comes to the same state, again and again!
    - maybe with (different) intermediate steps
- **When is a loop erroneous**
  - If it does not consume any input any more?
- **How can we detect re-occurring same states?**

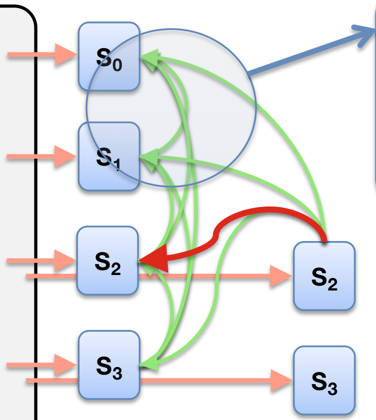


Source: baynote.com

Efficient Implementation of Same State Detection

- **Two states are the same if all their memory is the same**
  - Including call stack and instruction pointer
- **Compare each new state S_X to all its predecessor states**
  - How can this be achieved **efficiently**?

```
bool x = false;
x = true;
while (x) {
    x = true;
}
```



`memcmp(NULL1, NULL2, 0xFF…FF);`

- For every predecessor state
- Naïve implementation is prohibitively expensive!

Efficient Implementation of Same State Detection

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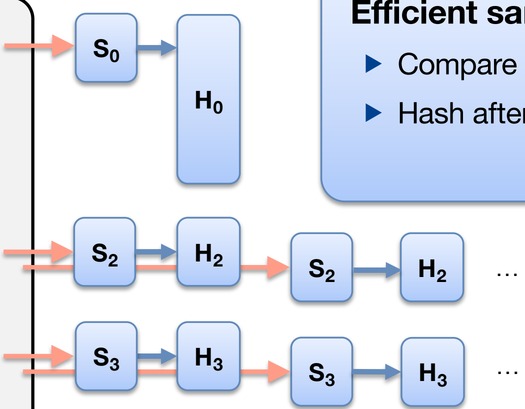

Efficient same state detection?

- Compare hashes instead of states
- Hash after blocks, not instructions

Efficient Implementation of Same State Detection

- **Two states are the same if all their memory is the same**
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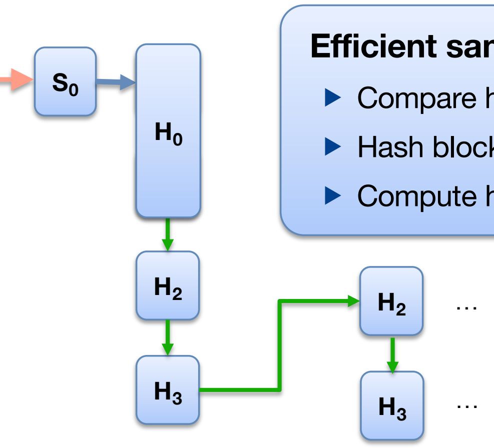
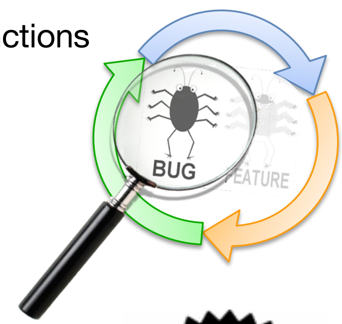
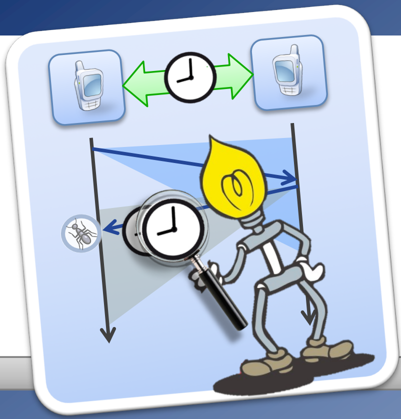


Efficient same state detection?
- Compare hashes instead of states
- Hash blocks, not instructions
- Compute hashes iteratively

Results

- **So far, a total of seven previously undetected bugs were detected**
  - **Five bugs** in the GNU Coreutils
    - e.g. in "`tail`": 130 line `while(1)` loop calling 2 functions
  - **Two bugs** in `busybox`
    - e.g. In a 490 line `while(1)` loop calling 2 functions
  - All bugs have been reported, confirmed and fixed
  - **The coreutils bugs have existed for over 12 years!**





The Next Challenge

Symbolic Analysis of Temporal Uncertainty

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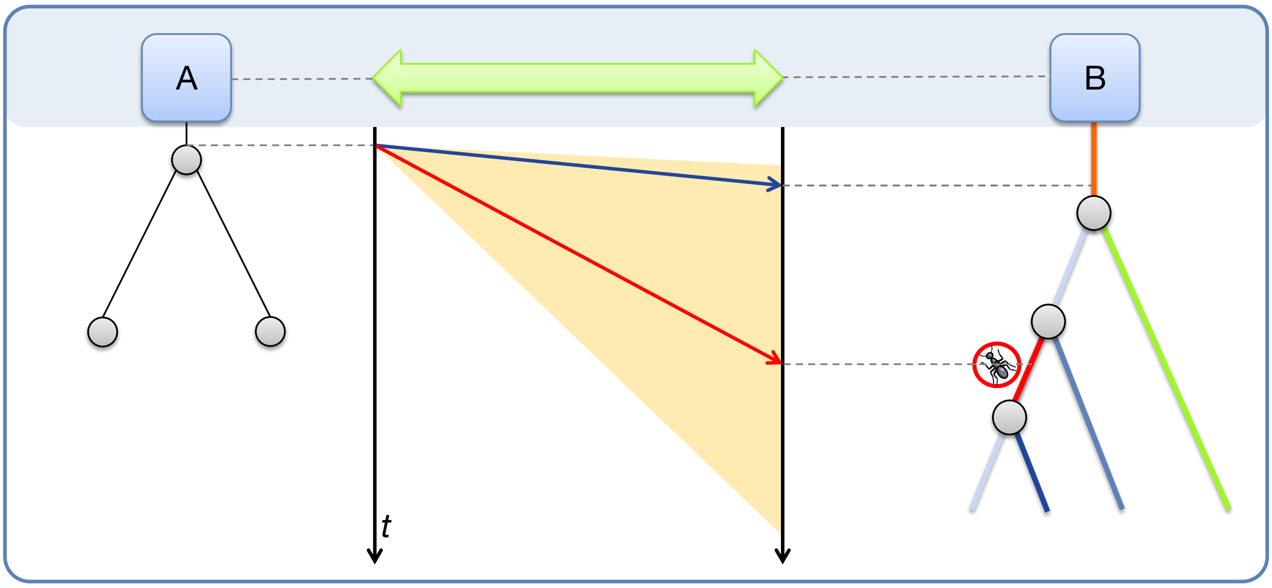
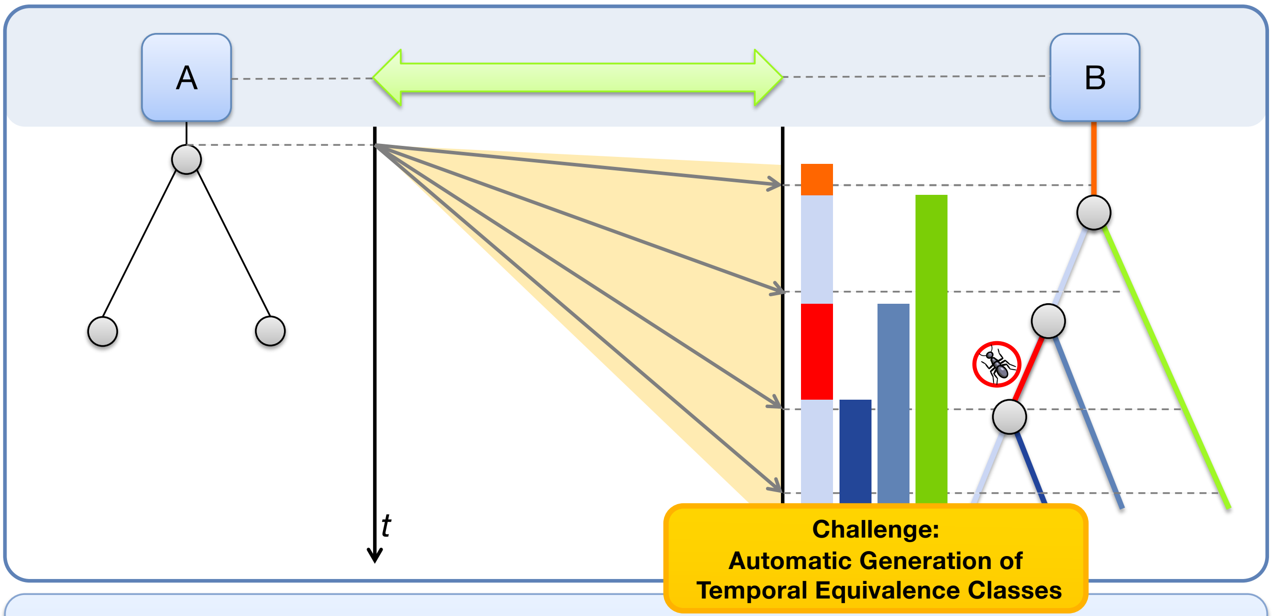


Analyzing uncertain event times – Why is time so important?

- **State** of system at **arrival time** of input **determines the behavior**
- Rigorous analysis requires analysis of all points in time!
- Moreover, **time is continuous – not discrete!**



Symbolic Time: Symbolic analysis of uncertain event times

Problems	**Challenges**
▶ Time is continuous – not discrete	→ How to derive temporal equival. classes?
▶ Temporal dependencies in code	→ How to detect them?
▶ Deriving all combinations and dependencies	→ How to make sure to consider all cases?

Challenges in Softwarized Communication Systems

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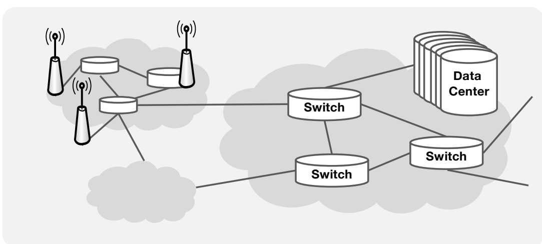
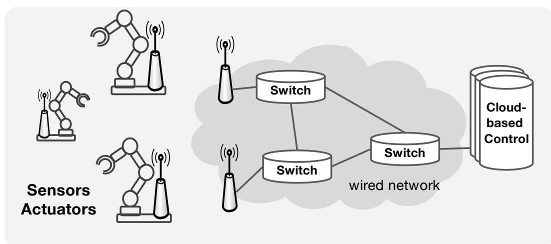
  - Protocols, billions of apps, etc.
  - Network elements become flexible (SDN, NFV, In-network processing)
- **Important: Analysis of real code – not models**



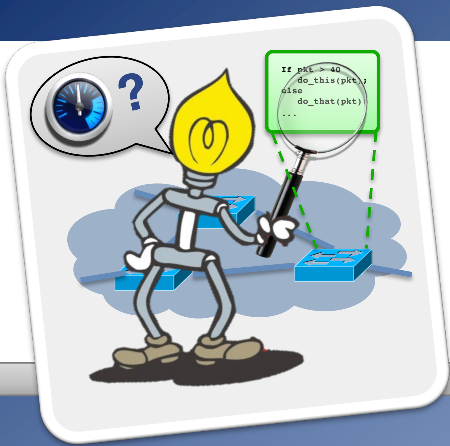
Networked Systems (protocols, apps)



Latency-critical networked control

Reliability!
(bugs, loops)

Predictable?
(performance, resources)



Symbolic Analysis of Protocol / NF Performance

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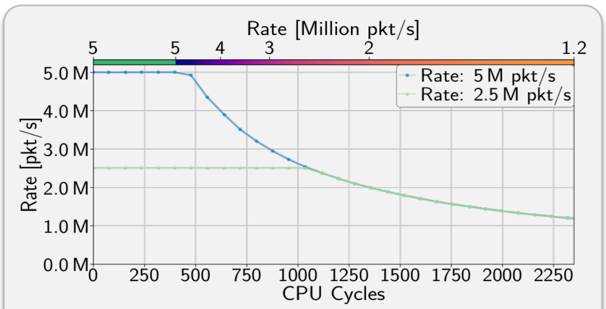
Performance Prediction of Softwarized Network Functions

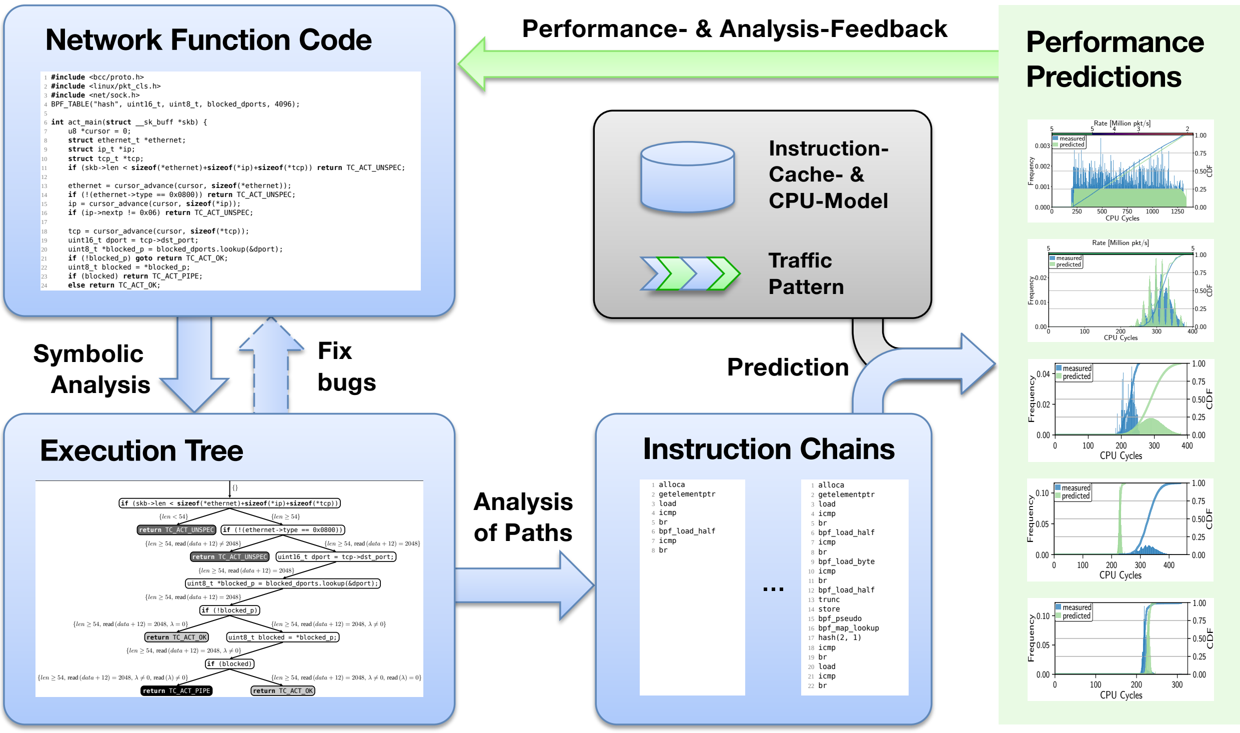
- **Challenge: Prediction of Processing Effort/Time of a NF**
  - Necessary processing resources?
  - Expected/worst latency?
  - Achievable data rate?
  - Influence among NFs?
  - Are we under attack?
  - …



Achieved throughput per processing effort of a NF

- **Influence Factors**
  - Code of the NF
  - Input Traffic (Pattern, Volume)
  - CPU Execution
    - Superscalar execution
    - Branch prediction
    - Caching

Pre-Deployment Performance Prediction of On-Path NFs



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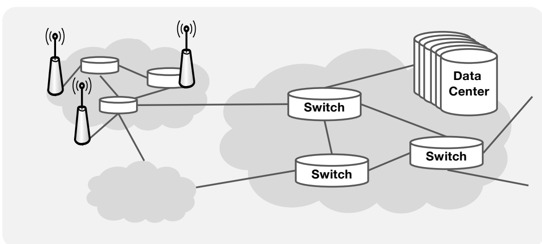
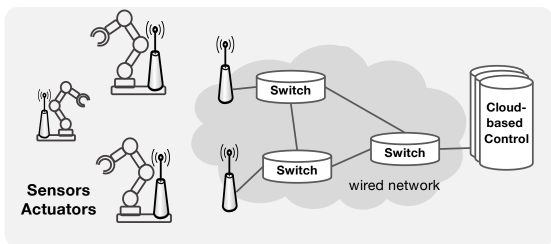


Networked Systems (protocols, apps)



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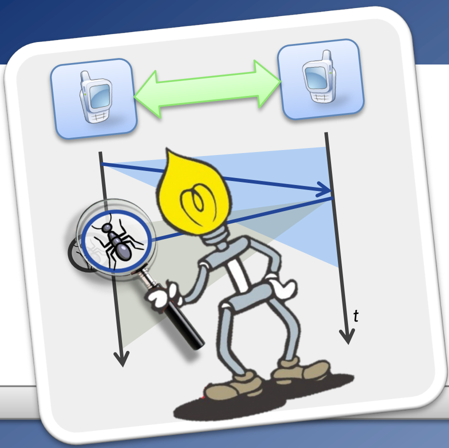

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SYMBIOSYS project homepage
→ https://comsys.rwth-aachen.de/research/projects/symbiosys/