TUHH
Hamburg University of Technology

Compiler-based Extraction of Event Arrival Functions for Real-Time Systems Analysis

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Hamburg University of Technology

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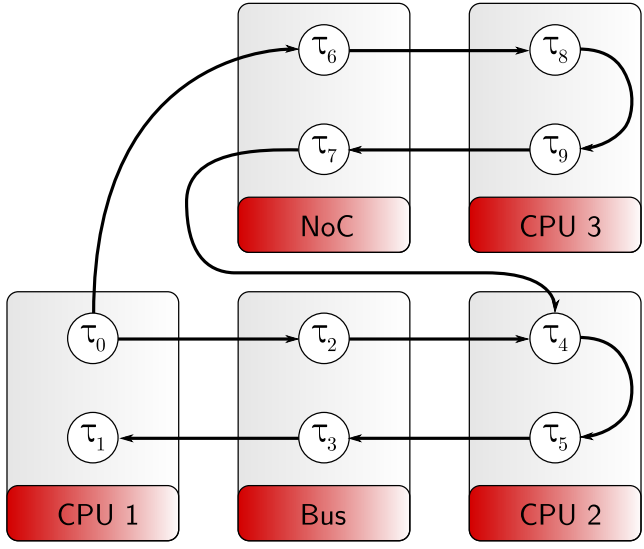
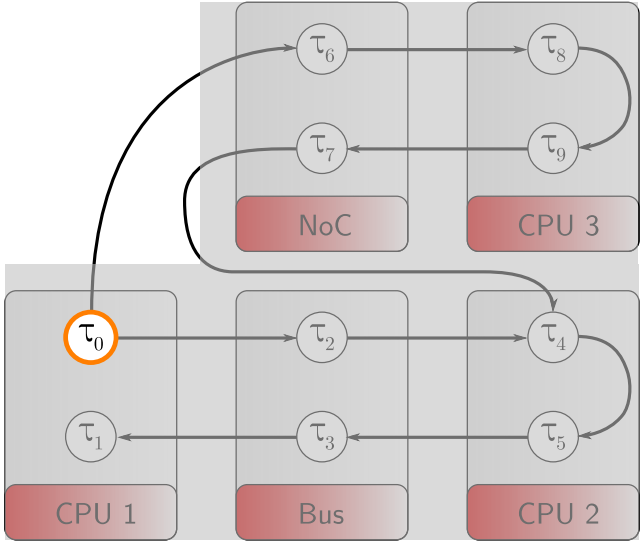

τ_6
τ_8
τ_7
τ_9
NoC
CPU 3
τ_0
τ_2
τ_4
τ_1
τ_3
τ_5
CPU 1
Bus
CPU 2


τ_6
τ_8
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NoC
CPU 3
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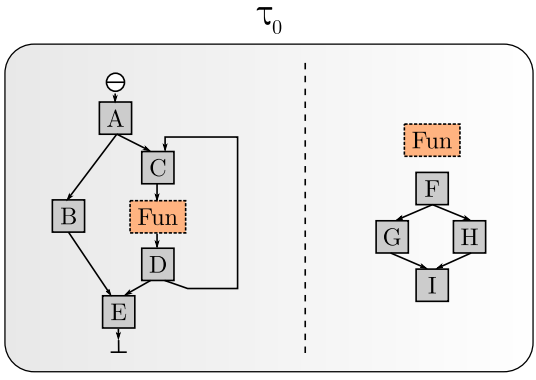
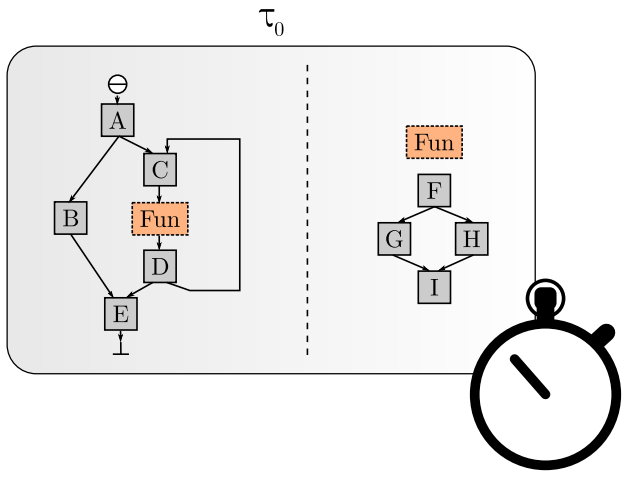

τ_0
A
C
B
Fun
D
E
Fun
F
G
H
I


τ_0
A
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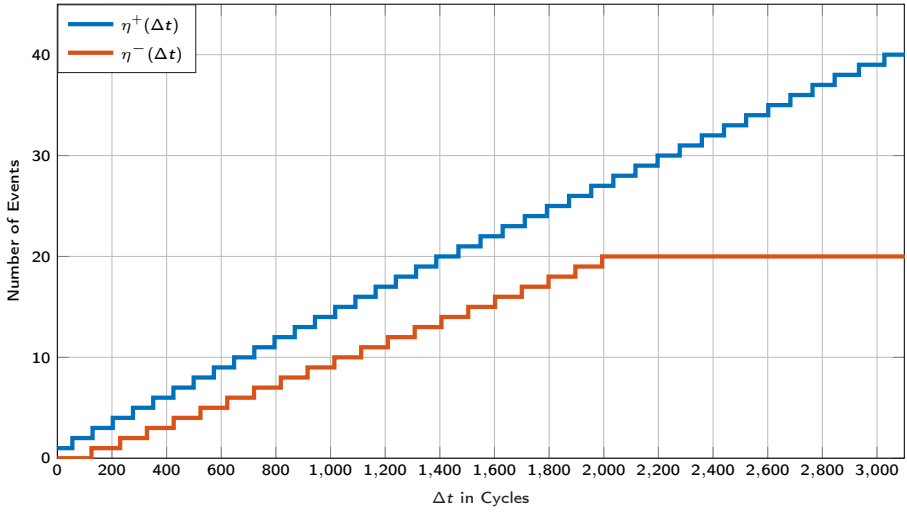
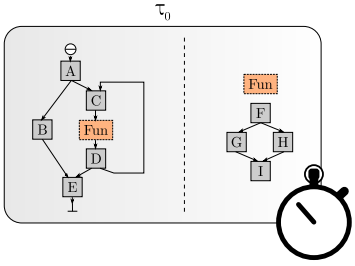

$\eta^+(\Delta t)$
$\eta^-(\Delta t)$
Number of Events
0
10
20
30
40
0
200
400
600
800
1,000
1,200
1,400
1,600
1,800
2,000
2,200
2,400
2,600
2,800
3,000
Δt in Cycles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A
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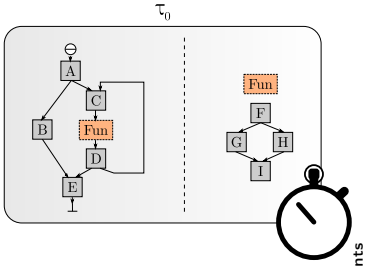
τ_0
A
C
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D
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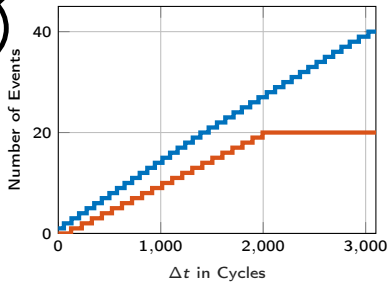
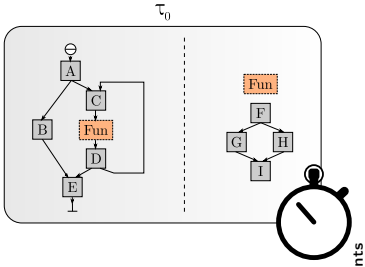

Number of Events
40
20
0
0
1,000
2,000
3,000
Δt in Cycles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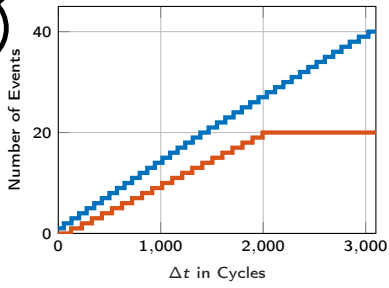
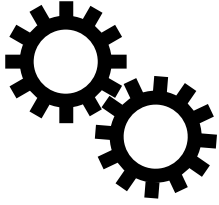
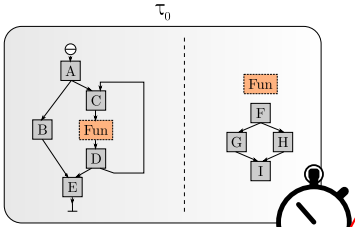

Number of Events
0
20
40
0
1,000
2,000
3,000
Δt in Cycles

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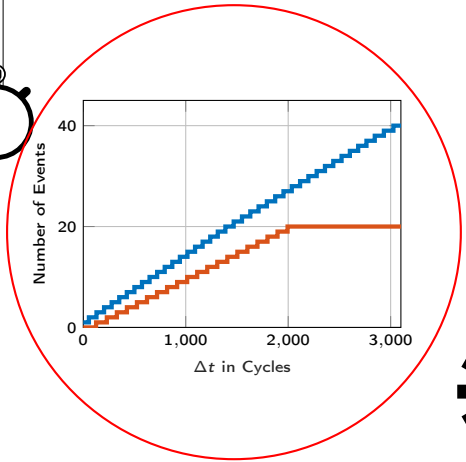
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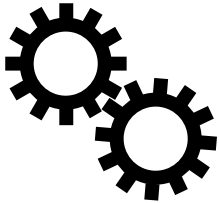
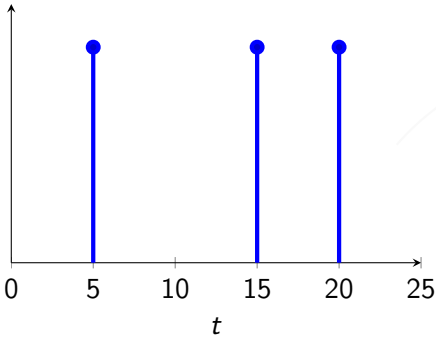
Δt in Cycles




0
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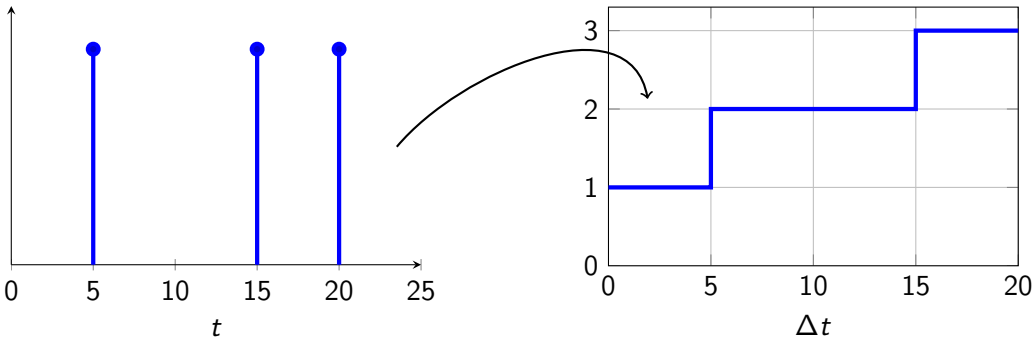
25
t

3
2
1
0
0
5
10
15
20
Δt


0
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15
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25
t
3
2
1
0
0
5
10
15
20
Δt

```
int globalData[ 2 ] = -1, 1;
volatile int comm;

int main() {

  for ( int i = 0; i < 20; ++i ) {

    if ( comm == 0 ) {
      globalData[ i % 2 ] = -1;
    }

  }

  return 0;
}
```

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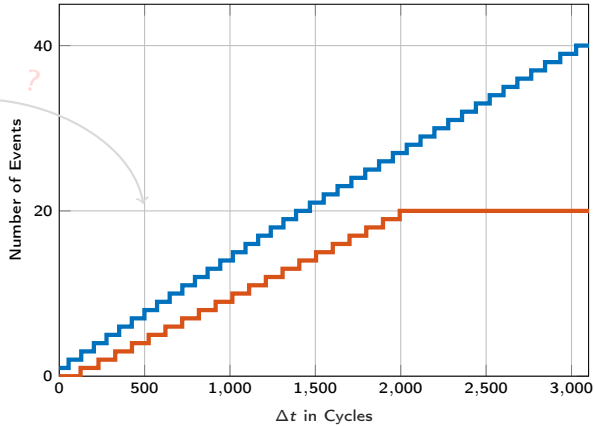

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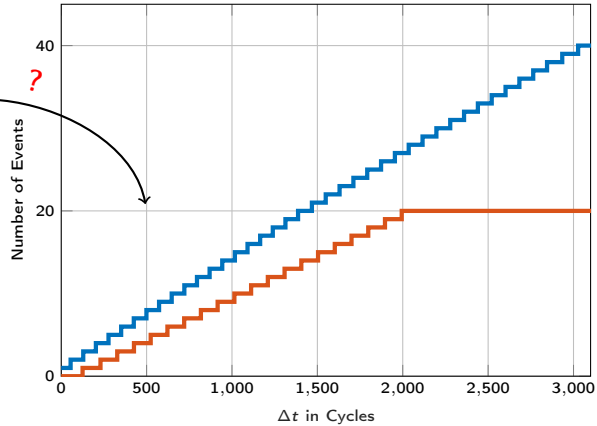

Extracting Curves?

- Capture traces
  - ⇒ Potentially unsafe
- Rely on specifications
  - ⇒ Potentially overly pessimistic
- Extraction based on the low-level representation

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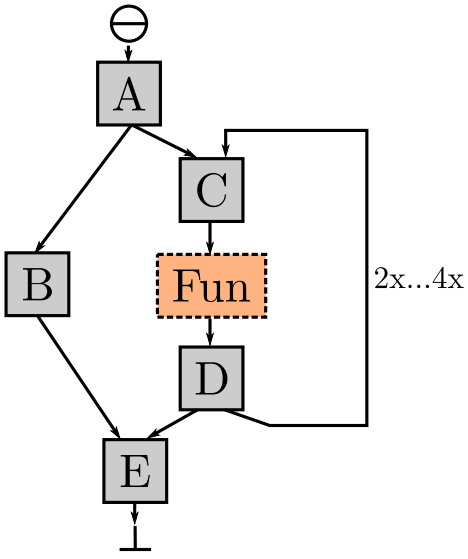
  - $\Rightarrow$ Potentially unsafe
- Rely on specifications
  - $\Rightarrow$ Potentially overly pessimistic
- **Extraction based on the low-level representation**


A
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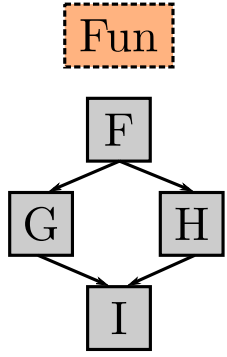
2x...4x


Fun
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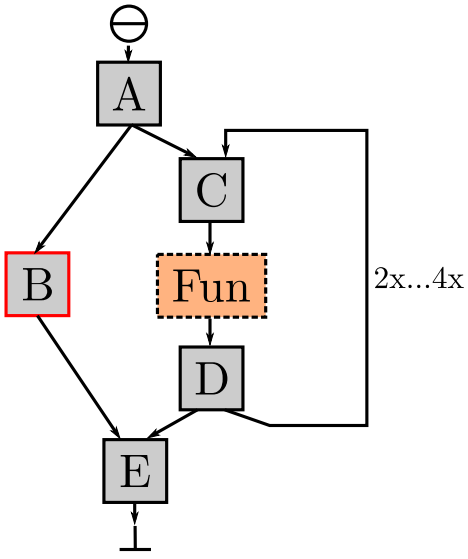
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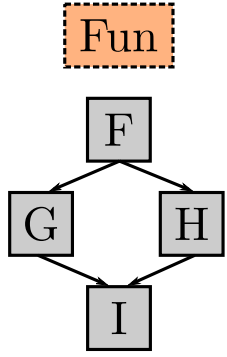
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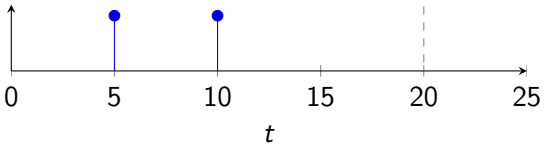
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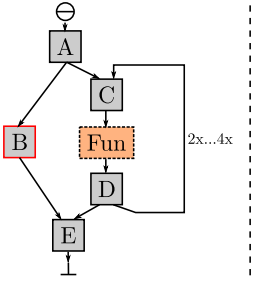
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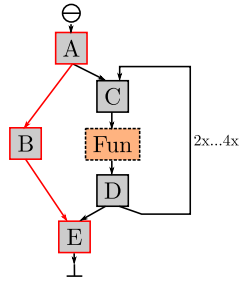
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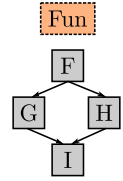
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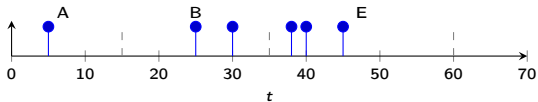
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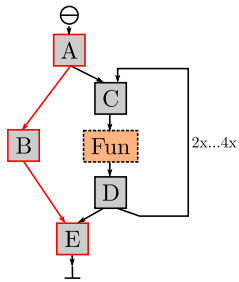
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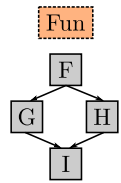
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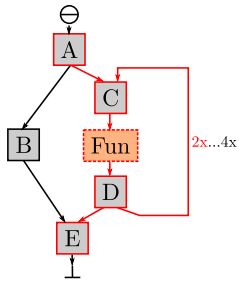
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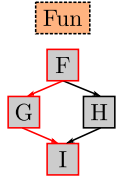
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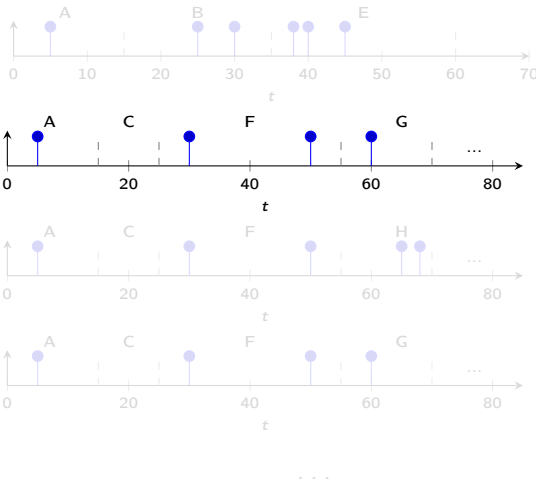
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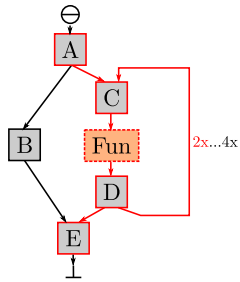
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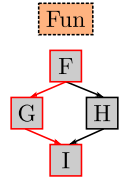
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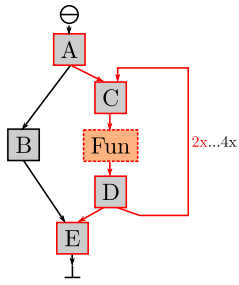
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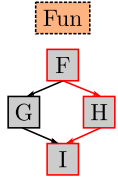
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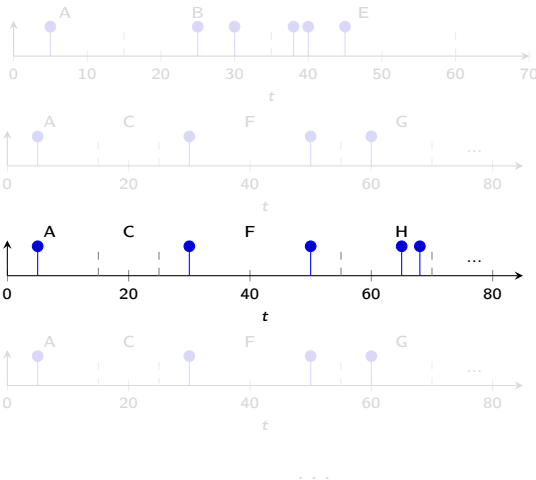
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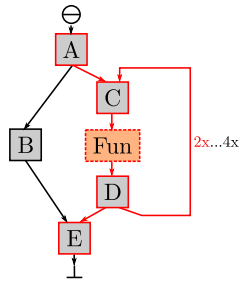
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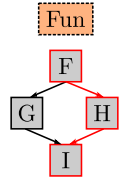
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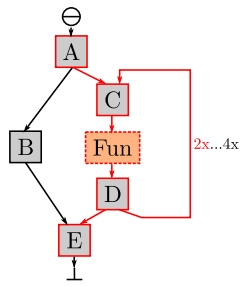
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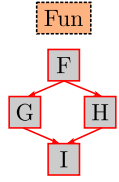
2x...4x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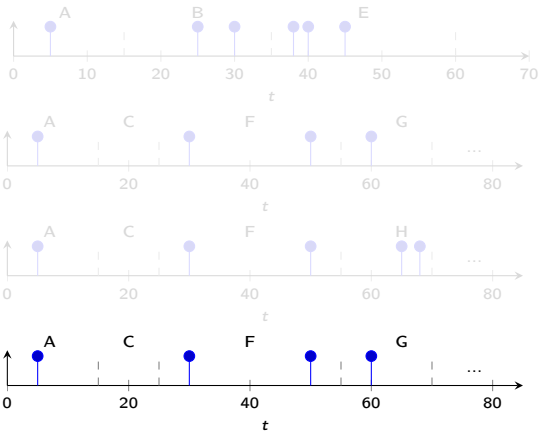
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70
t
A
C
F
G
...
0
20
40
60
80
t
A
C
F
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A
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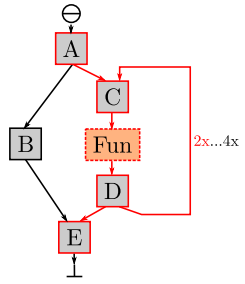
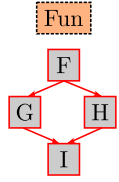
80
t


A
C
Fun
D
B
E
2x...4x


Fun
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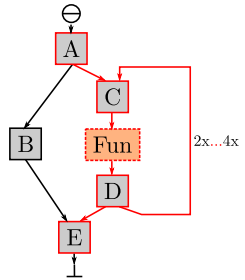
t

...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C
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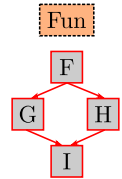
Fun
F
G
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I

Path Analysis for Arrival Functions

- Explicit path analysis quickly becomes practically infeasible
  - ⇒ Sliding window for all traces

⇒ Adapt path analysis techniques

⇒ Introduce granularity
  - Trade-off between precision and runtime

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Overview

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Event Arrival Functions

- Abstract notion of interfering events (e.g., task activations, shared memory accesses, ...)

Definition

Let $\eta_i^+(\Delta t)$ and $\eta_i^-(\Delta t)$ denote for each task i the maximum and minimum number of events issued within a time window of size Δt.
Their pseudo-inverse counterparts $\delta^+(n)$ and $\delta^-(n)$, return the maximum/minimum time interval between the first and the last event in any sequence of n event arrivals.

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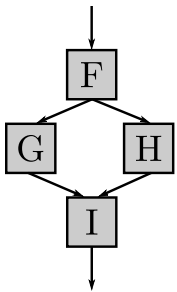
Implicit Path Enumeration Technique

- Describe all feasible paths by formulating an Integer Linear Program (ILP) [DAC95]
- Enforcing complete path through a program using junction rules



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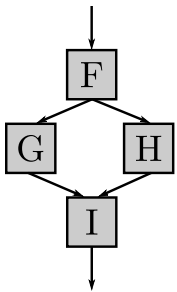

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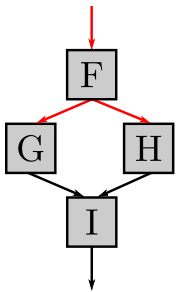

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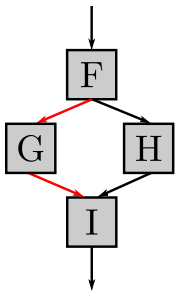

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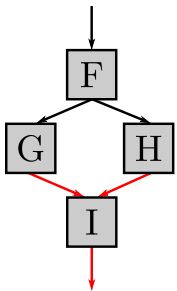

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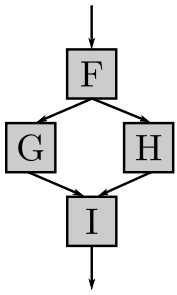
- First introduced by Jacobs et al. [RTNS15]
- Introduce "movable" sources and sinks
- Determine max. (resp. min.) number of events per basic block
- Maximize (resp. minimize) accumulated number of events over sub-path
  - $\Rightarrow$ While accumulated time $w \leq \Delta t$ (resp. $w \geq \Delta t$)



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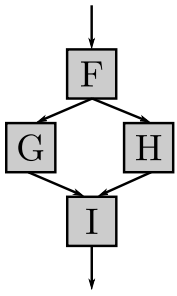

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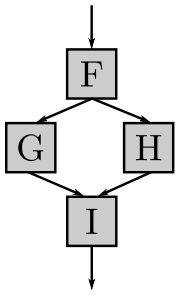

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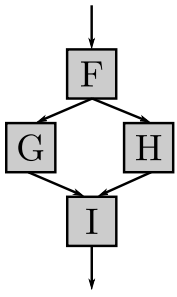

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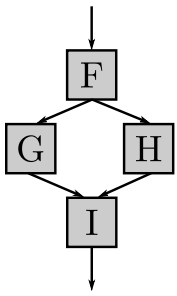

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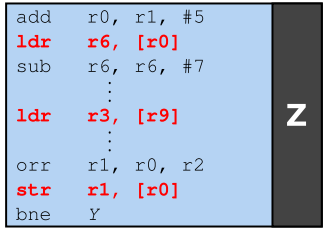

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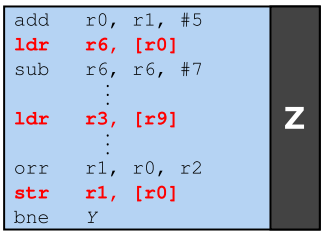

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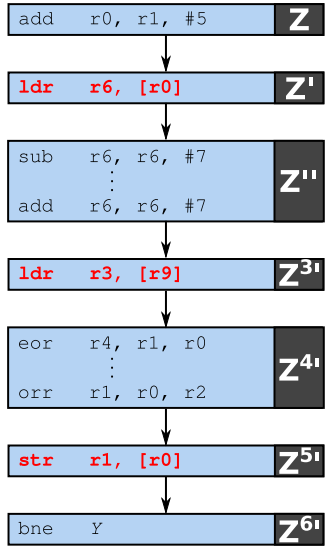

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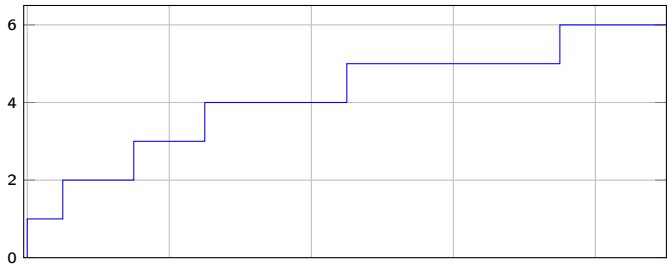

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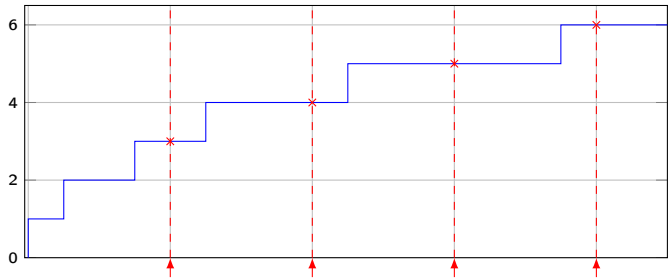

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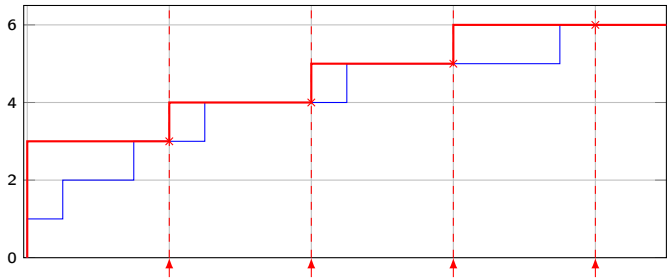

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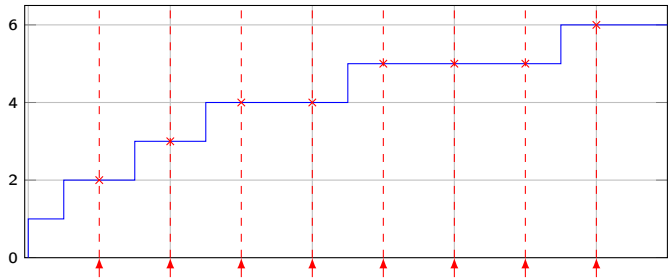

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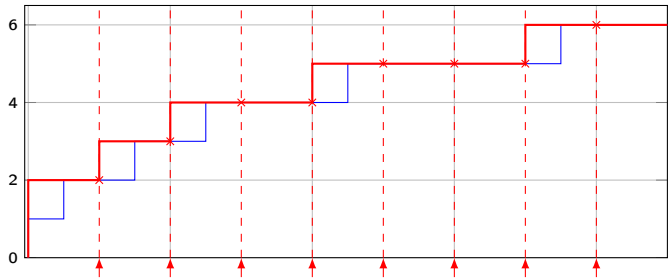

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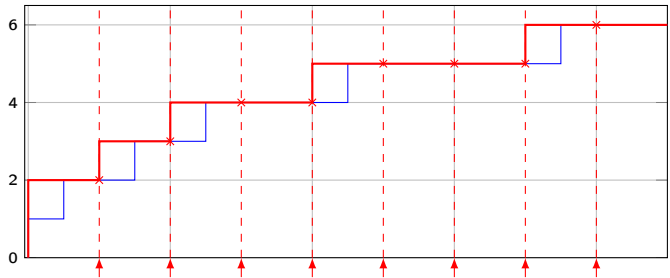

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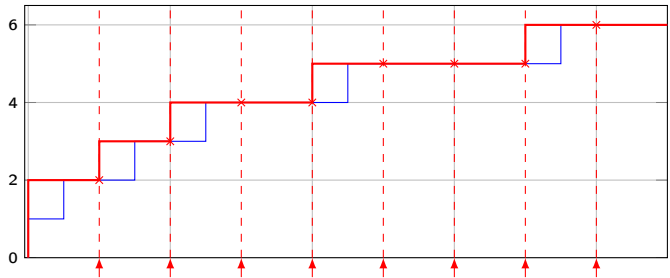
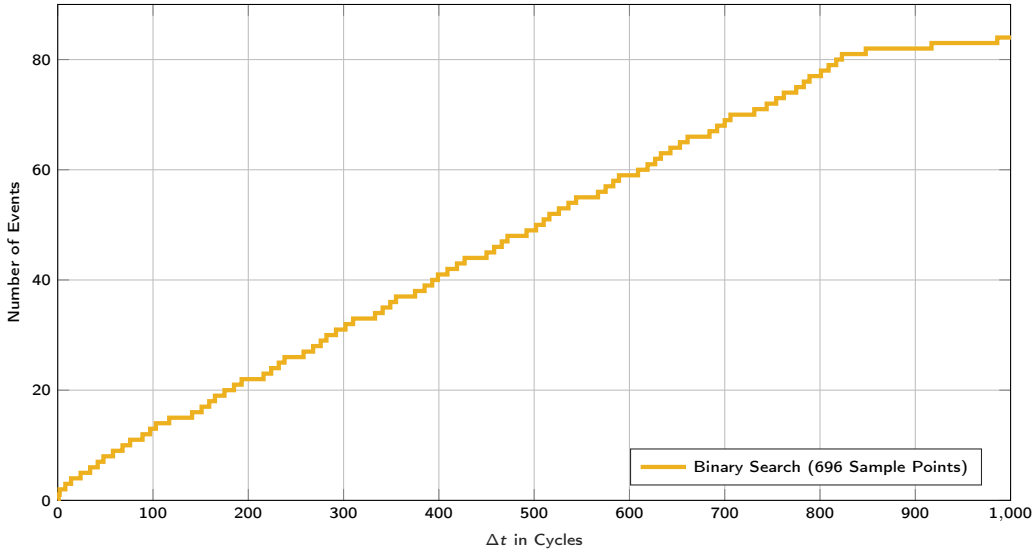
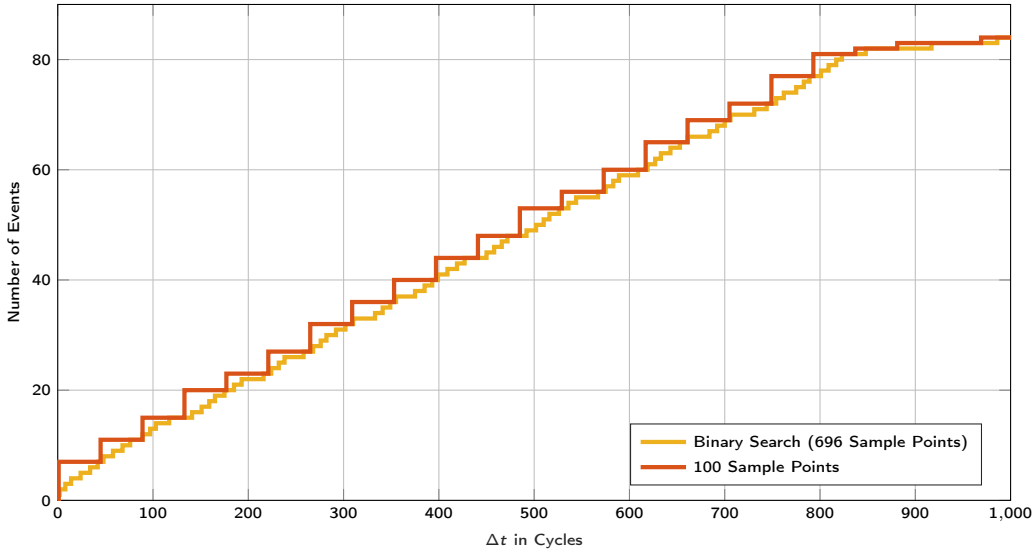



Number of Events
0
20
40
60
80
0
100
200
300
400
500
600
700
800
900
1,000
Δt in Cycles
Binary Search (696 Sample Points)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1,000
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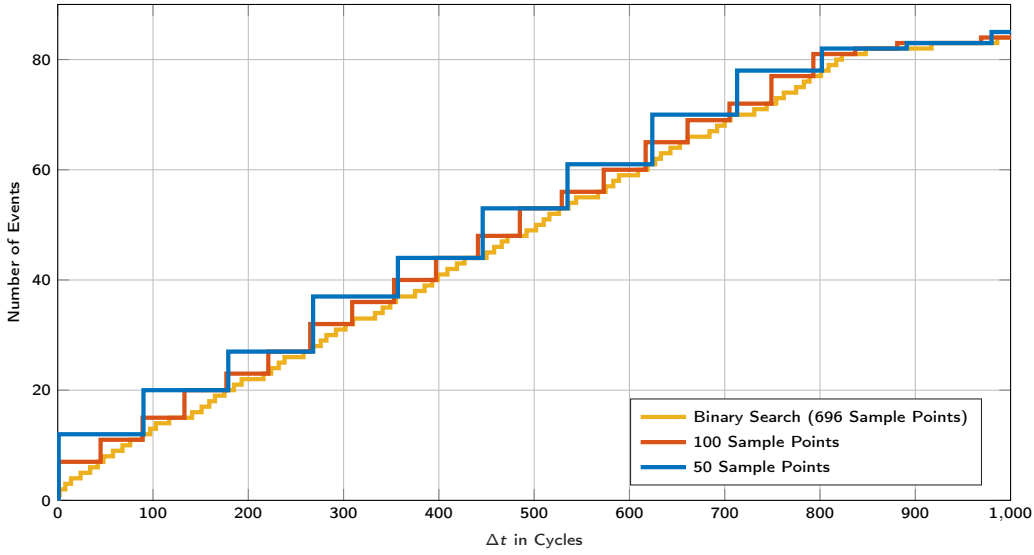
100 Sample Points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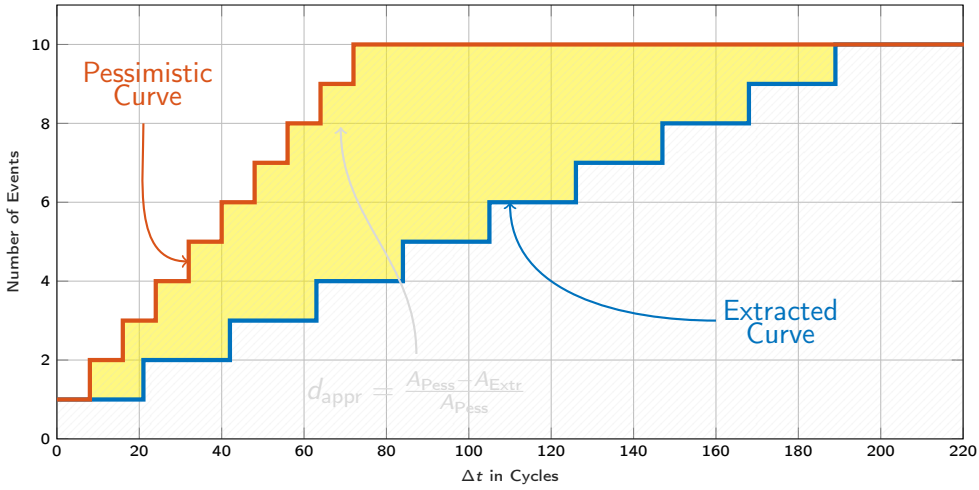
Binary Search (696 Sample Points)
100 Sample Points
50 Sample Points

Overview

Overapproximation Metric



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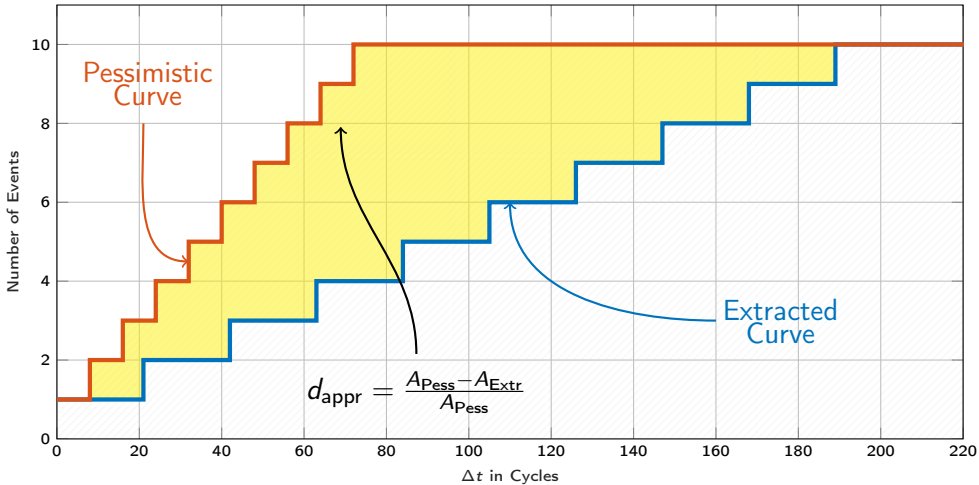
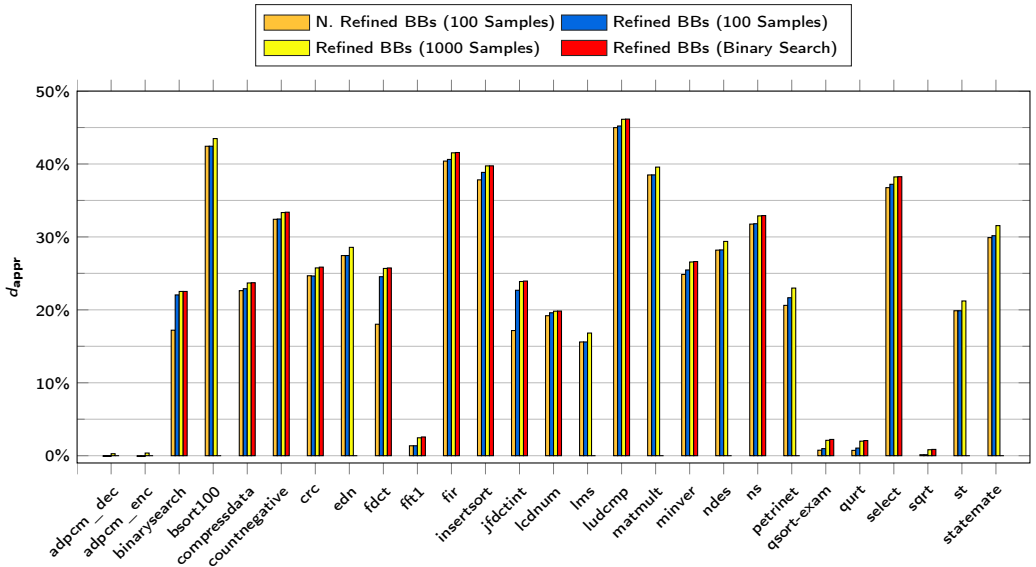
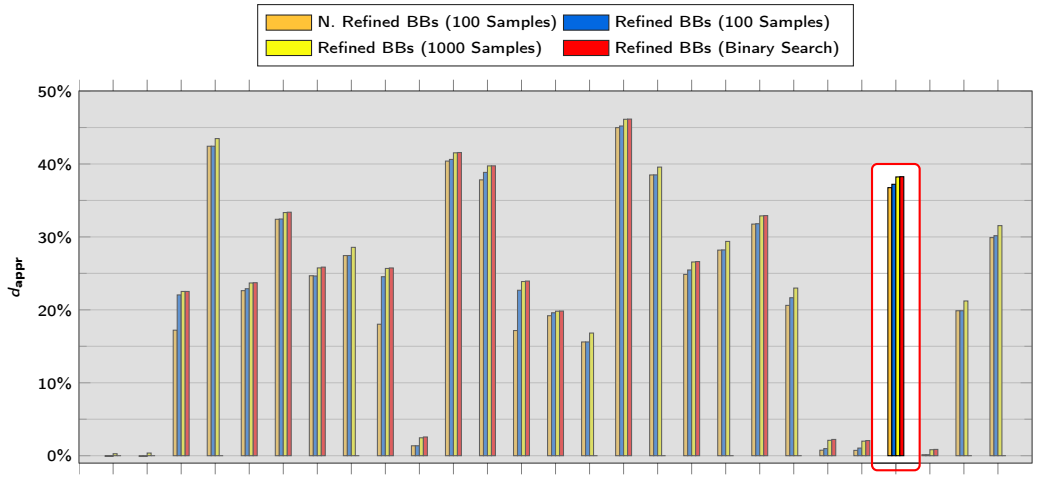


Evaluation Setup

- MRTC benchmark suite
  - `duff` benchmark excluded (due to timing analysis tool incompatibility)
- Evaluations performed on an Intel Xeon Server (20 cores at 2.3 GHz, 94 GB RAM)
- ILPs solved using Gurobi 7.5.0
- Compiled with the WCET-aware C compiler (WCC) using the `-O2` flag
- ARM7TDMI architecture (without caches)
- Data object access triggers an event


N. Refined BBs (100 Samples)
Refined BBs (100 Samples)
Refined BBs (1000 Samples)
Refined BBs (Binary Search)
50%
40%
30%
20%
10%
0%
d_{appr}
adpcm_dec
adpcm_enc
binarysearch
bsort100
compressdata
countnegative
crc
edn
fdct
fft1
fir
insertsort
jfdctint
lcdnum
lms
ludcmp
matmult
minver
ndes
ns
petrinet
qsort-exam
qurt
select
sqrt
st
statemate


N. Refined BBs (100 Samples)
Refined BBs (100 Samples)
Refined BBs (1000 Samples)
Refined BBs (Binary Search)
50%
40%
30%
20%
10%
0%
d_{appr}
adpcm_dec
adpcm_enc
binarysearch
bsort100
compressdata
countnegative
crc
edn
fdct
fft1
fir
insertsort
jfdctint
lcdnum
lms
ludcmp
matmult
minver
ndes
ns
petrinet
qsort-exam
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select
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Overview

Conclusion

- Automated upper and lower event arrival function extraction from code-level analysis
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Outlook

- Adding calling contexts
- Optimizations based on the extracted functions

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