# Intrusion detection through monitoring of timing deviations

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# Motivation

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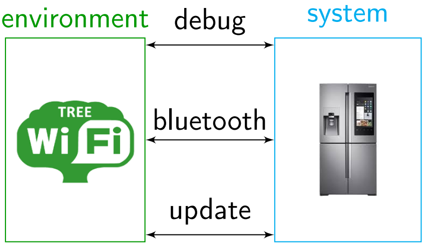
- Openness ...



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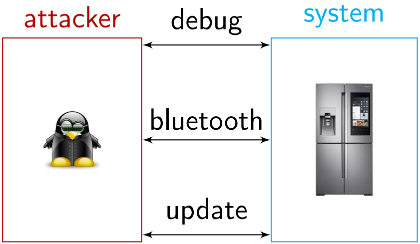
- Real-time embedded systems

- Openness … leads to more vulnerabilities



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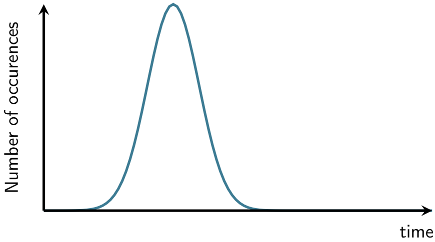


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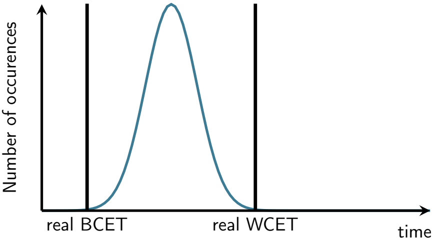


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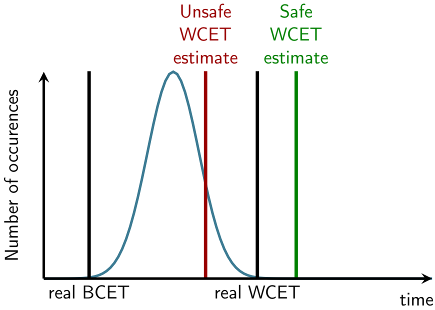


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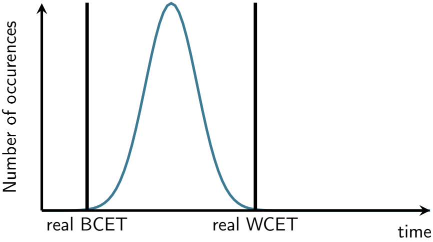


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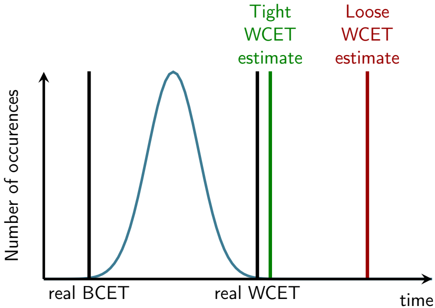


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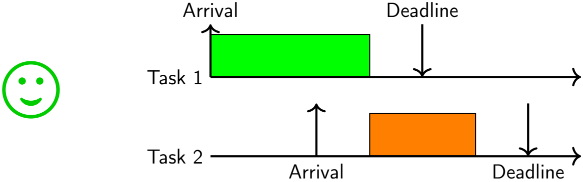
# Real-time - Schedule [2]

- Scheduling = Combine tasks WCETs and system requirements

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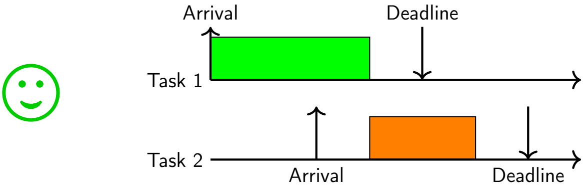


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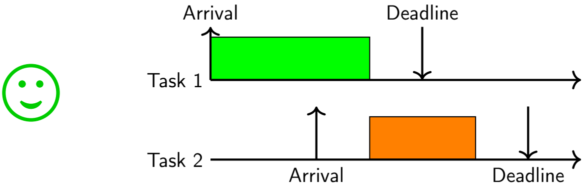


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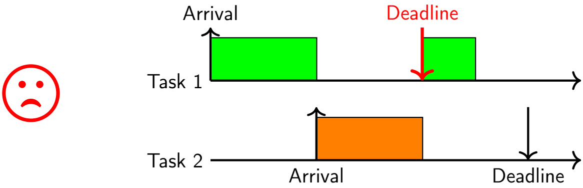


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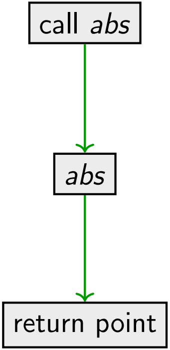

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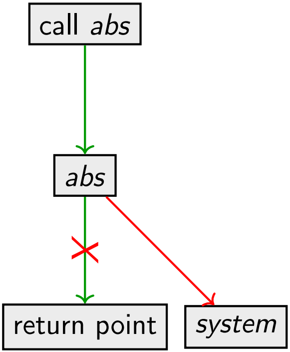

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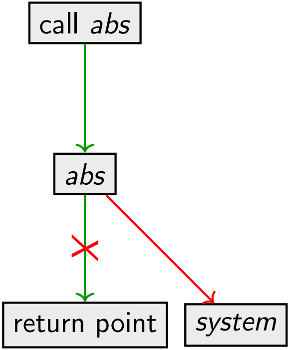


- Example

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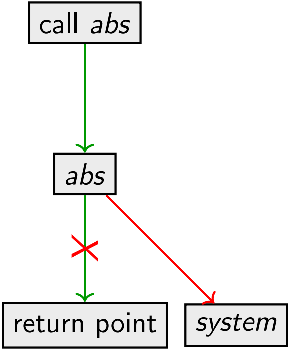


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| buffer | i | retval |
|---|---|---|

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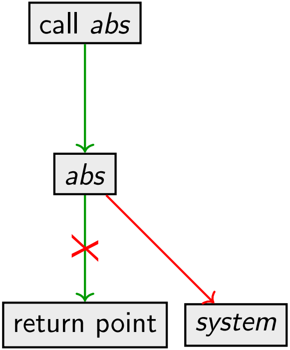


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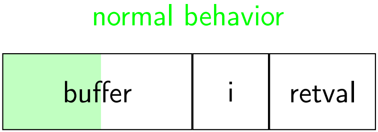

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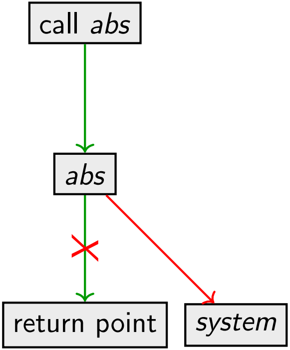


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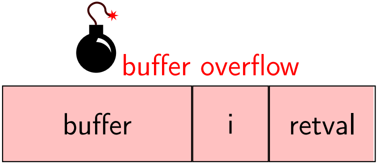

# State of the art

- Diversity techniques
  - Schedule level diversity [3]
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| Name | Domain | Information | Overhead / Intrusiveness |
|---|---|---|---|
| T-Rex[5] | RT | Checkpoint / WCET | High |
| T-ProT[5] | RT | Checkpoint / WCET | High |
| T-AxT[5] | RT | Time/Space correlation | High |
| Yoon et al.[6] | RT | Syscall learning | Small |
| Chevalier et al.[7] | G | Control-Flow | Small |

# Contribution

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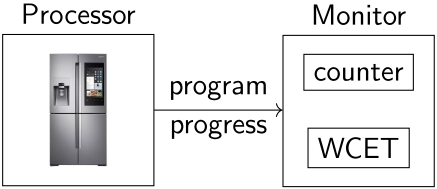
- Hardware monitor (0 overhead)



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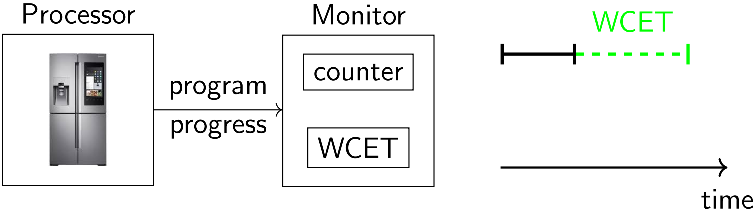

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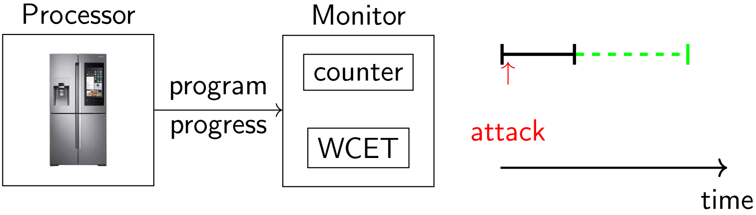
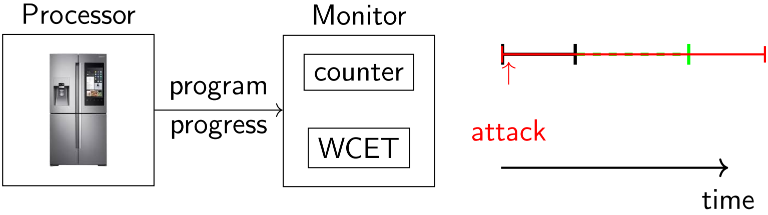


- Hardware monitor (0 overhead)
- Detecting attacks that exceed the WCET (limited threshold)



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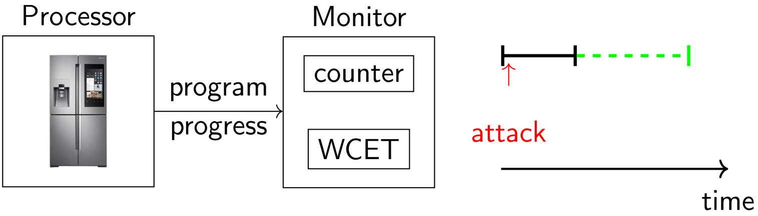

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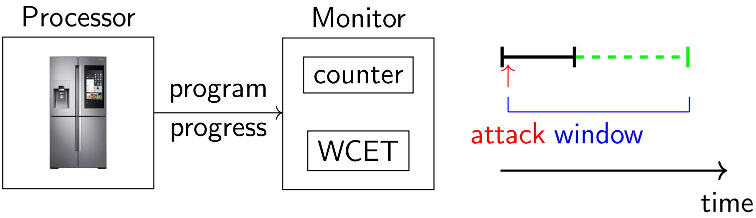

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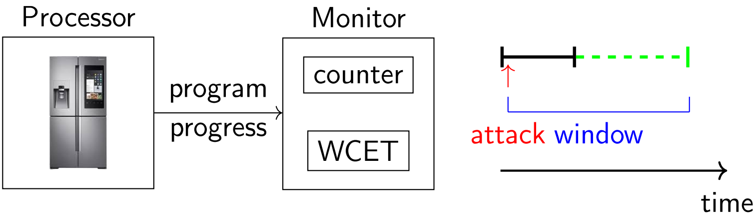


- Attack scenario : Control-Flow Hijacking

# Outline

- Region definition
- Automatic region selection
- Monitoring example
- Experiments
- Future Work

# Regions of interest

- *Single Entry Single Exit* (SESE) regions [3]

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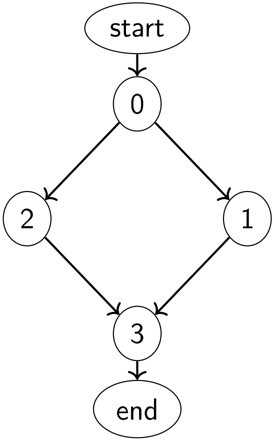


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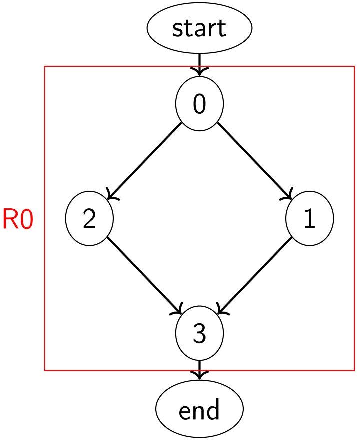


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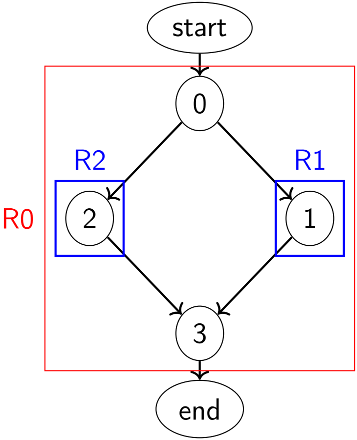


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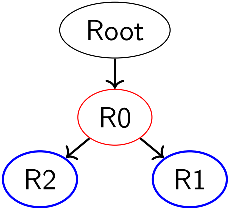
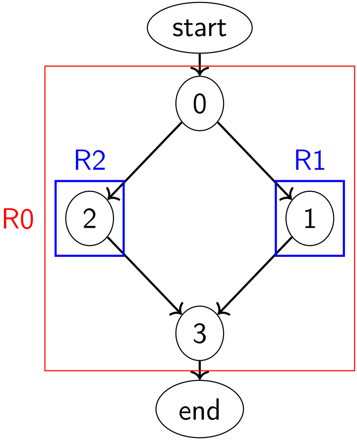
  - Simple nesting

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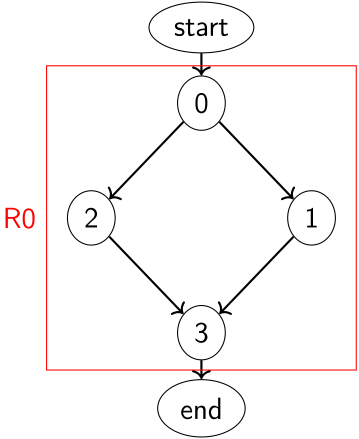


MIT R0 =
WCET R0

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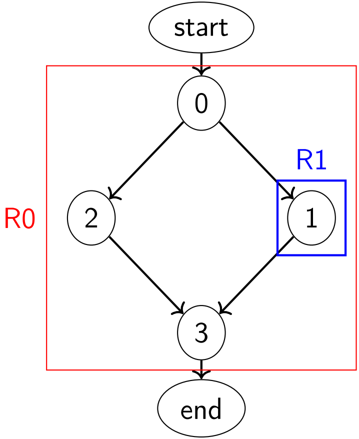


MIT R0 =
WCET ( R0 \ R1 )

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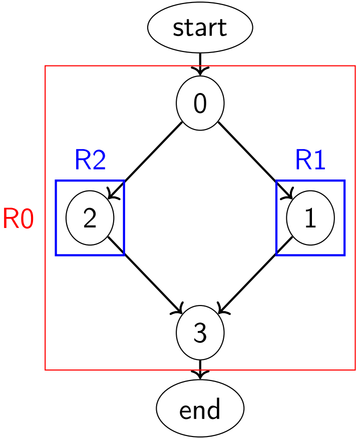


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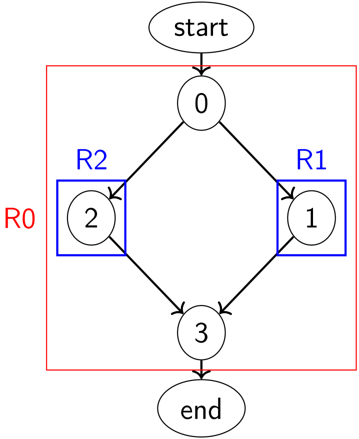


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MIT = monitor threshold

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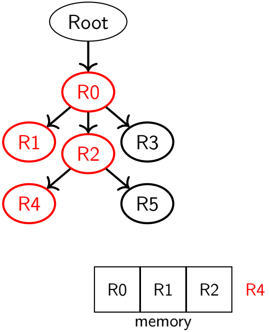

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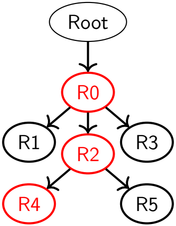


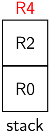

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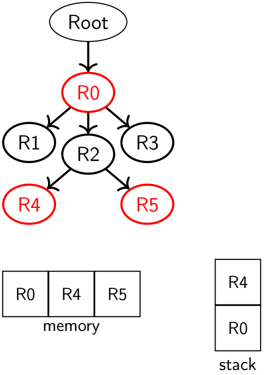

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  - Cover the whole program
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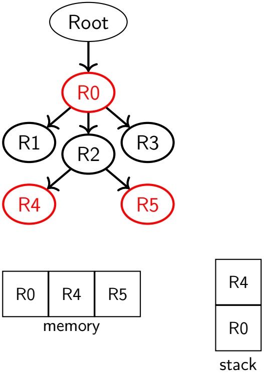
  - Reduce maximal threshold



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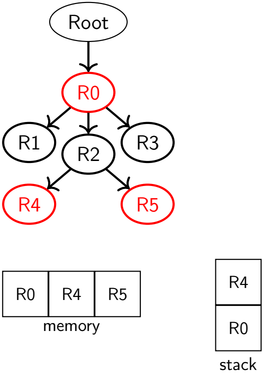


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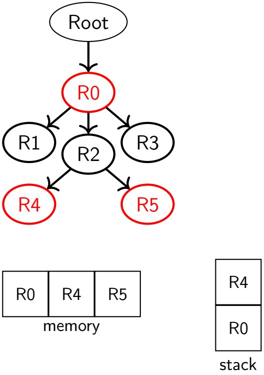


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Find best *selected* set

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Greedy algorithm : At each iteration, reduce the region with maximum threshold (= MIT)

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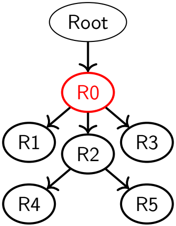


| region | step 0 | step 1 | step 2 |
|---|---|---|---|
| R0 | 2000 | | |
| | | | |
| | | | |

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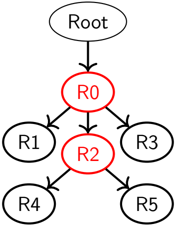


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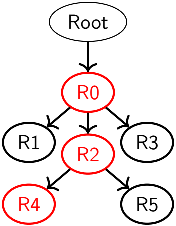


| region | step 0 | step 1 | step 2 |
|---|---|---|---|
| R0 | 2000 | 200 | 200 |
| R2 | | 800 | 100 |
| R4 | | | 400 |

# SESE Selection algorithm properties

- Polynomial complexity

| | |
|---|---|
| MIT Estimation | $O(n^2)$ |
| Operation (without estimations) | $O(n^3)$ |

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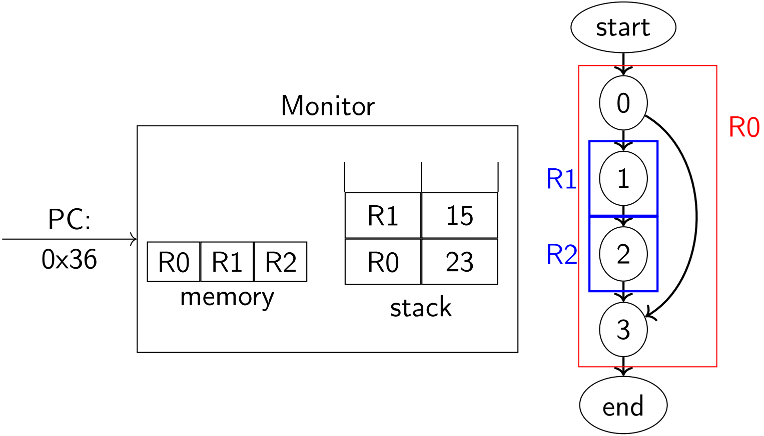
- Minimal threshold with infinite constraints

# Monitoring example

| region | entry | exit | MIT | sub-region |
|---|---|---|---|---|
| R0 | 0x0 | 0x80 | 100 | **R1, R2** |
| R1 | 0x20 | **0x36** | **25** | ∅ |
| R2 | **0x36** | 0x60 | 40 | ∅ |



# Monitoring example

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|---|---|---|---|---|
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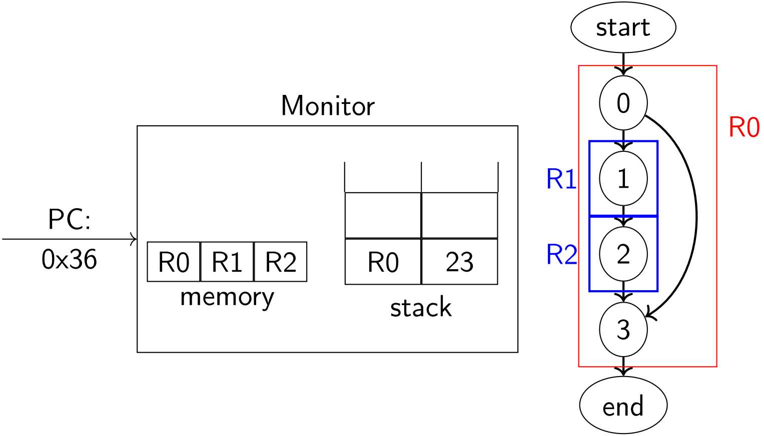
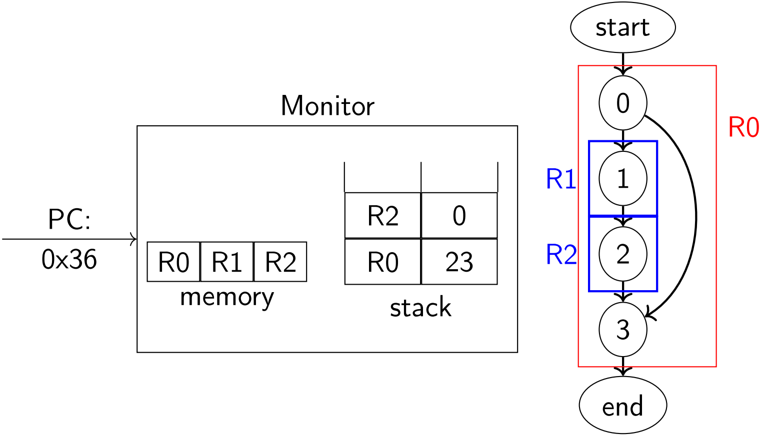
| R1 | 0x20 | **0x36** | **25** | ∅ |
| R2 | 0x36 | 0x60 | 40 | ∅ |



# Monitoring example

| region | entry | exit | MIT | sub-region |
|---|---|---|---|---|
| R0 | 0x0 | 0x80 | 100 | **R1, R2** |
| R1 | 0x20 | **0x36** | **25** | ∅ |
| R2 | **0x36** | 0x60 | 40 | ∅ |



# Monitoring example

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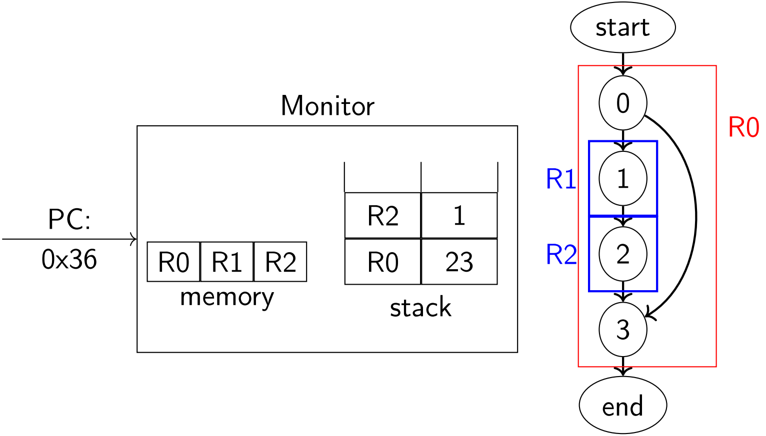


# Realisation

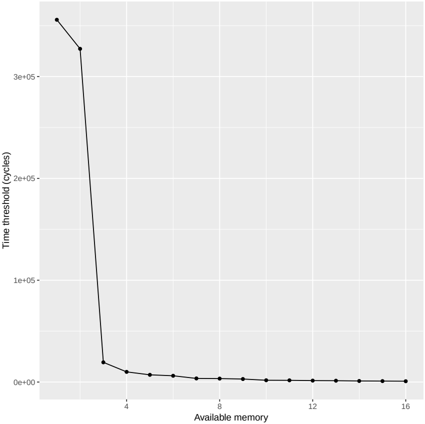
- Implemented a CFG + SESE extraction + selection algorithm for Leon3 architecture
- Implemented and tested the monitor in HLS using Catapult
- Not yet integrated on a CPU

# Experimental setup

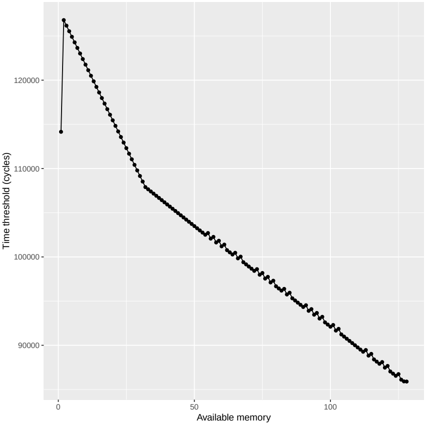
- Leon3 architecture
- Mälardalen benchmarks
- *aiT* for MIT estimation (with annotations)
- Goal : Measure the performance of the algorithm

# SESE Selection - Maximal threshold evolution

- Normal behavior

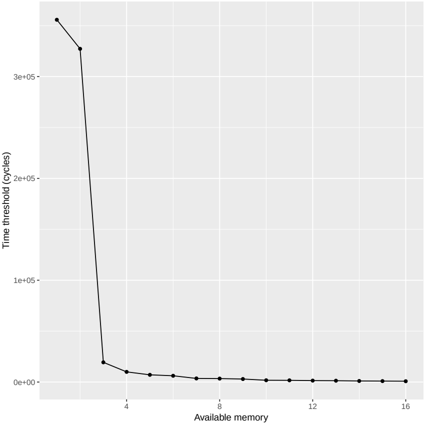



- Specific benchmark

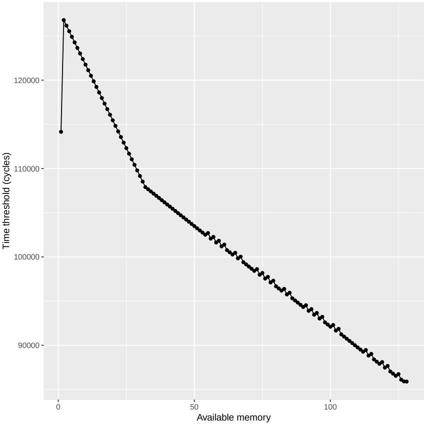


# SESE Selection - Maximal threshold evolution

- Normal behavior

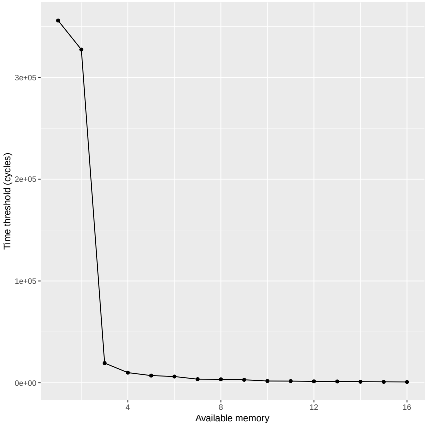



- Specific benchmark

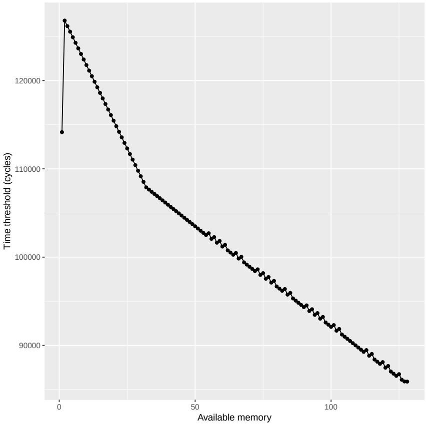


# SESE Selection - Maximal threshold evolution

- Normal behavior

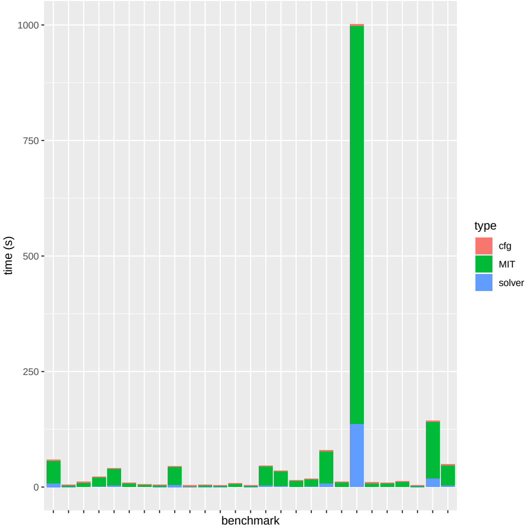



- Specific benchmark

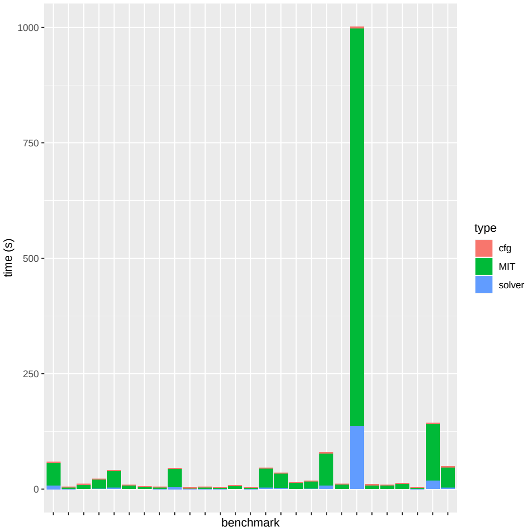



Major improvement first, small optimizations later

# SESE Selection - Runtime

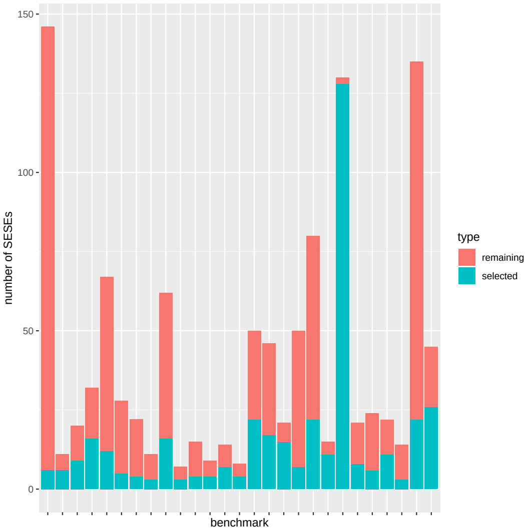


# SESE Selection - Runtime

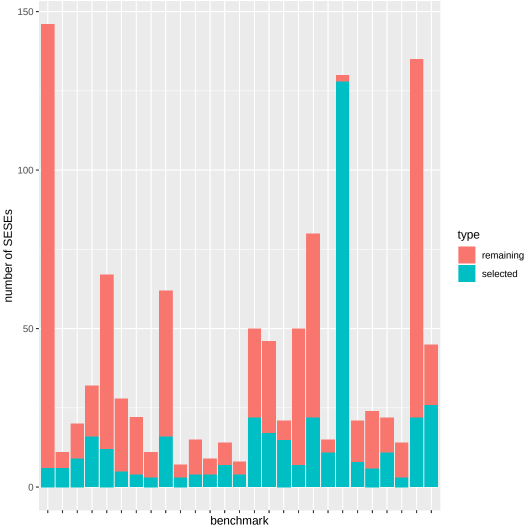



Most of the running time spent in MIT estimations

# SESE Selection - Maximal memory usage



# SESE Selection - Maximal memory usage




Minimal threshold without a time-consuming exploration

# Bibliography

[1] Reinhard Wilhelm et al. "The worst-case execution-time problem - overview of methods and survey of tools".In: ACM Trans. Embedded Comput. Syst. 2008

[2] Buttazzo, G. "Hard Real-Time Computing Systems: Predictable Scheduling Algorithms and Applications"

[3] Kristin Krüger et al. "Vulnerability Analysis and Mitigation of Directed Timing Inference Based Attacks on Time-Triggered Systems". In: ECRTS 2018

[4] Joachim Fellmuth et al. "Instruction Caches in Static WCET Analysis of Artificially Diversified Software". In: ECRTS 2018

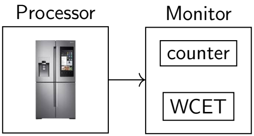
[5] Christopher Zimmer et al. "Time-based intrusion detection in cyber-physical systems". In: ICCPS 2010

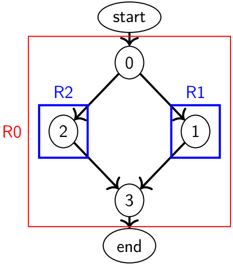
[6] Man-Ki Yoon et al. "Learning Execution Contexts from System Call Distribution for Anomaly Detection in Smart Embedded System". In: IoTDI 2017

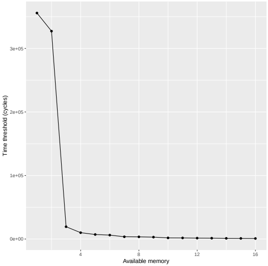
[7] Ronny Chevalier et al. "Co-processor-based Behavior Monitoring: Application to the Detection of Attacks Against the System Management Mode". In: Computer Security Applications Conference 2017

# Summary & Future Works

- Summary

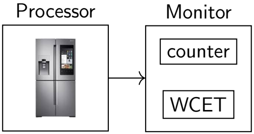


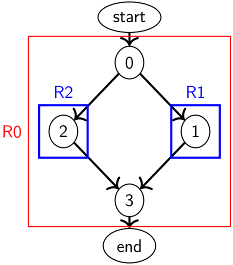



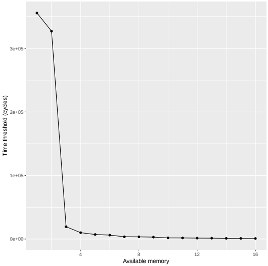




- Future Work

- Summary




- Future Work
  - Integrate the monitor on a CPU
  - Implement fault models
  - Further reduce the threshold with inner basic block SESEs

# Solving SSP - Issues

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- Use Integer Linear Programing ?

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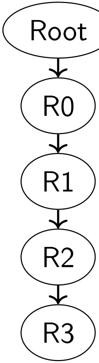
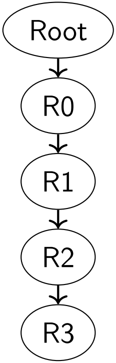



- Use Integer Linear Programing ?

# Solving SSP - Issues




- Use Integer Linear Programing ?

Worst case :
$O(2^n)$ MIT estimations