Semi-Extended Tasks:
Efficient Stack Sharing Among Blocking Threads

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supported by DFG

Memory Consumption in Embedded Systems

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98% of sold processors

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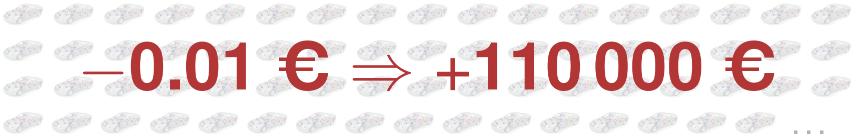

-0.01 € ⇒ $+110\,000$ €

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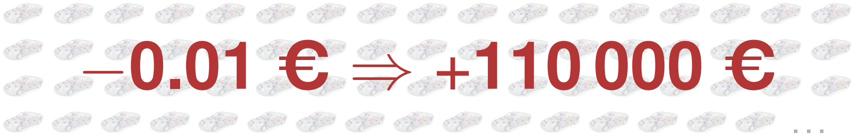

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. . .

Quantized RAM Purchase: Microchip ATXMega C3 Series:

Part	Flash	RAM	Price
ATXMEGA64C3	64 kB	4 kB	4.05 EUR
ATXMEGA128C3	128 kB	8 kB	4.11 EUR
ATXMEGA256C3	256 kB	16 kB	5.06 EUR
ATXMEGA384C3	384 kB	32 kB	6.12 EUR

Memory Consumption in Embedded Systems

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Quantized R C3 Series:

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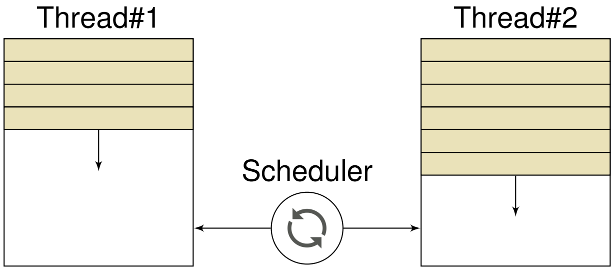
Living in Private: Normal Threads



- Normal threads live on their private stack
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  - Kernel switches arbitrarily between threads and stacks

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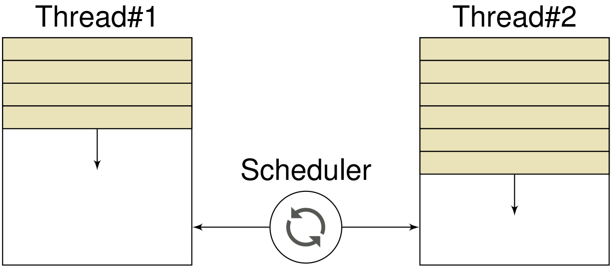
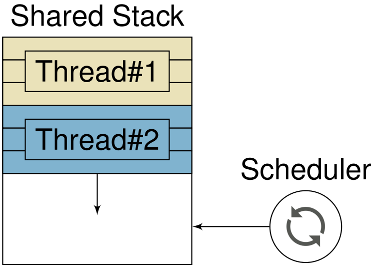


- Normal threads live on their private stack
  - Function calls push a new stack frame onto the private stack
  - Kernel switches arbitrarily between threads and stacks
- Real-time schedules are much more restricted
  - Not all preemptions/resumptions are possible at any point
  - Stack reusable if two threads are never simultaneously ready

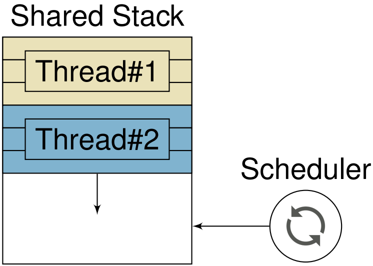
Living in a Commune: Basic Tasks



- OSEK/AUTOSAR has the concept of basic tasks
  - . . . live, tightly packed, on the same stack
  - . . . must have run-to-completion semantic and cannot wait

  ⇒ Only the top-most basic task can be running (by construction)

Living in a Commune: Basic Tasks



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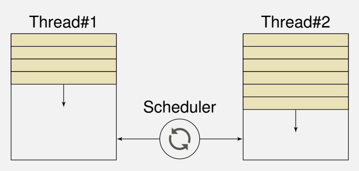
- Worst-case stack consumption depends on real-time parameters
  - Preemption thresholds, non-preemptability, priority-ceiling protocol

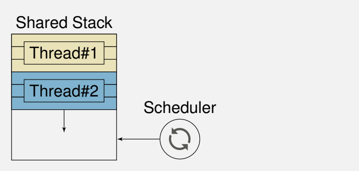
Problem Field

Extended Tasks



- + Fully flexible (can wait)
- – High static stack consumption

Basic Tasks



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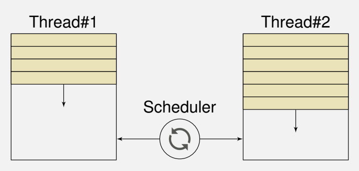

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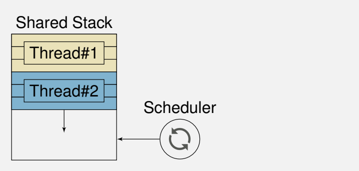

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Semi-Extended Tasks live on two stacks

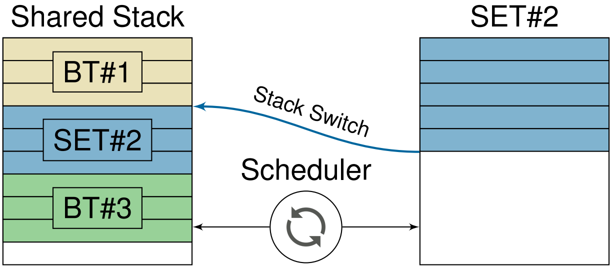
Approach

- Semi-Extended Task Mechanism
- Worst-Case Stack Consumption
- Optimize Stack Consumption with SETs

Approach

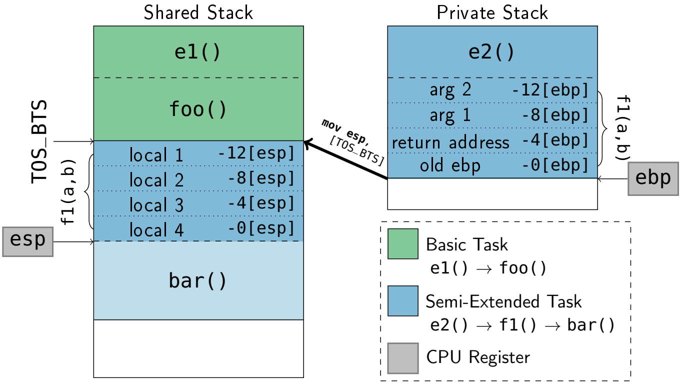
- **Semi-Extended Task Mechanism**
- Worst-Case Stack Consumption
- Optimize Stack Consumption with SETs

Semi-Extended Tasks (SET)



- SETs switch autonomously to the shared stack
  - Transition between stacks happens at stack-switch functions
  - SETs start as Extended Tasks and can become Basic Tasks
  - Special compiler-generated function prologue

Technical Detail: Function Prologue



```
<f1>:
    ;; Function — Prologue
    push   ebp              ; Save old framepointer
    mov    ebp, esp         ; Load new framepointer
    mov    esp, [TOS_BTS]   ; Switch to shared stack
    sub    esp, 16          ; Allocate local variables
```

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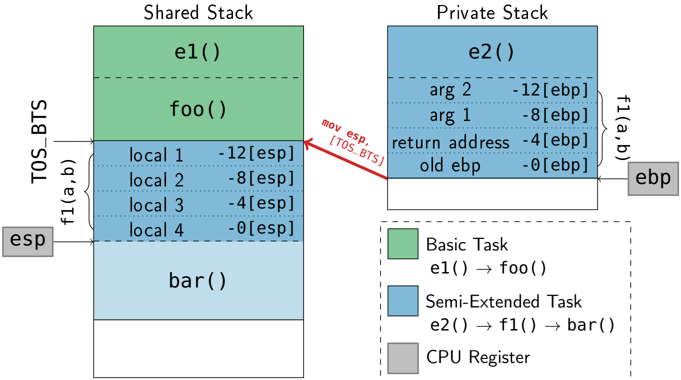

Shared Stack

e1()

foo()

local 1 -12[esp]

local 2 -8[esp]

local 3 -4[esp]

local 4 -0[esp]

bar()

TOS_BTS

f1(a,b)

esp

mov esp, [TOS_BTS]

Private Stack

e2()

arg 2 -12[ebp]

arg 1 -8[ebp]

return address -4[ebp]

old ebp -0[ebp]

f1(a,b)

ebp

🟩 Basic Task e1() → foo()

🟦 Semi-Extended Task e2() → f1() → bar()

⬜ CPU Register

```
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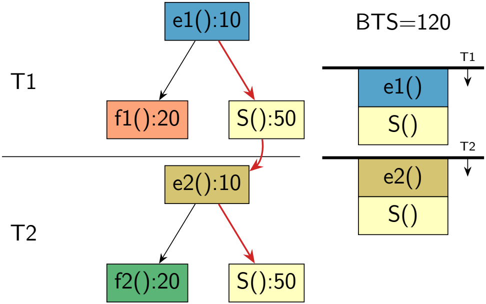
Approach

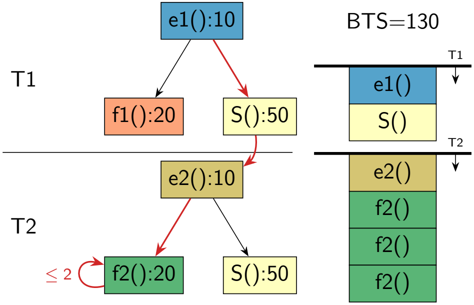
- Semi-Extended Task Mechanism
- **Worst-Case Stack Consumption**
- Optimize Stack Consumption with SETs

Worst-Case Stack Consumption (WCSC)



- WCSC analysis must consider different constraints
  - Intra-Thread Callgraphs

Worst-Case Stack Consumption (WCSC)



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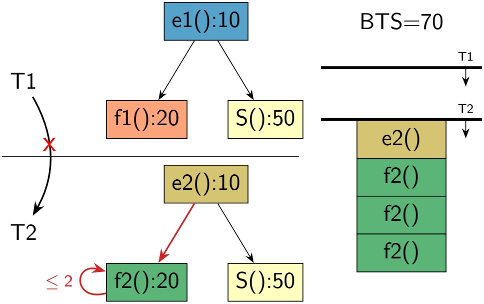

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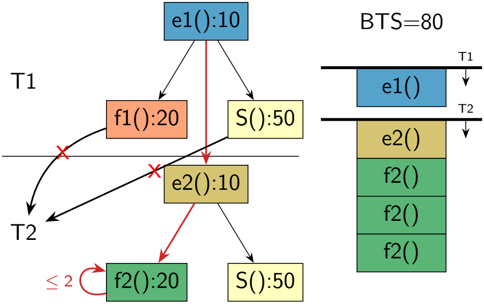

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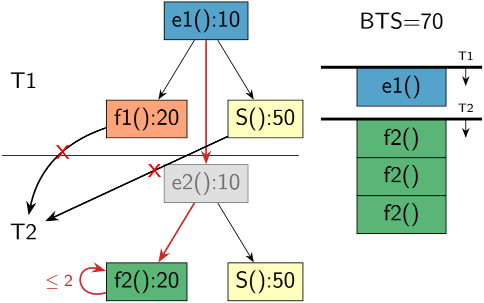

- WCSC analysis must consider different constraints
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  - Preemption Constraints
  - Global Control Flow
  - SET Stack Switches

Worst-Case Stack Consumption (WCSC)

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  - Model WCSC analysis as a maximum-flow problem
  - Search for costliest {preemption chain, function stacking}
  - Allows for fine-grained preemption constraints:

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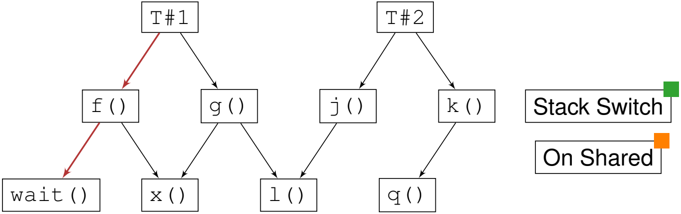
- Fine-Grained Preemption Constraints
  - Extract constraints from global control-flow graph
  - Flow-sensitive static analysis of application and RTOS
  - Presented in previous work: LCTES'15, TECS'17

Approach

- Semi-Extended Task Mechanism
- Worst-Case Stack Consumption
- **Optimize Stack Consumption with SETs**

Where to Switch Stacks?

- Select stack-switch function to minimize the WCSC.
  - Parents of blocking system calls are forbidden
  - Children of stack-switch functions are forbidden



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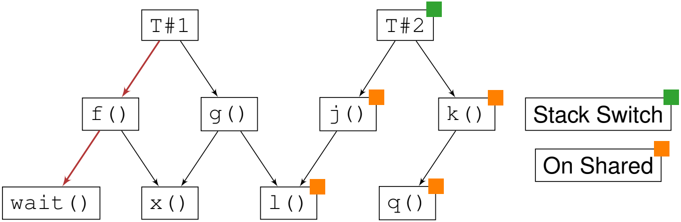

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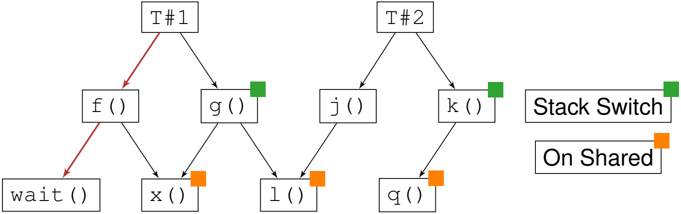

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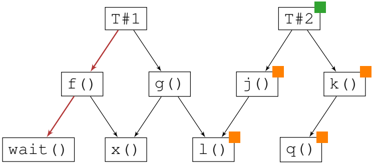

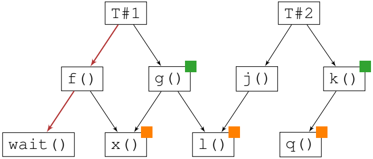

Minimizing the WCSC: Two-level Optimization

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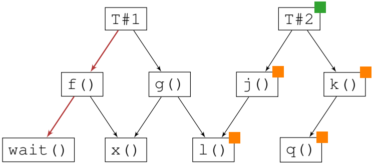
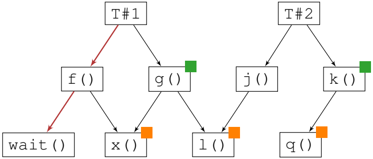




Minimizing the WCSC: Two-level Optimization

⇒ Genetic Algorithm with WCSC as Fitness Function

Results

- Generated Benchmark Scenarios
- Stack-space Savings

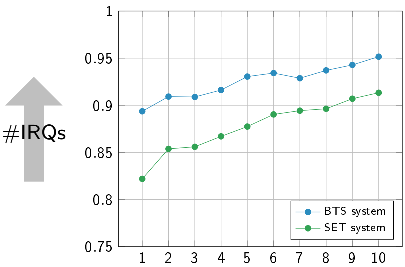
Generated Benchmark Scenarios

- Evaluation with $\geq$ 14000 generated systems
  - Based on a base configuration, scale in 5 dimensions
  - Compare ET-only, BT-only, and BT+SET systems

Dimension	Base	Range
#Threads	20	20 – 50
#blocking Threads	1	0 – 15
#IRQs	1	1 – 20
#Functionen	200	100 – 1000
#Critical Regions	1	1 – 10

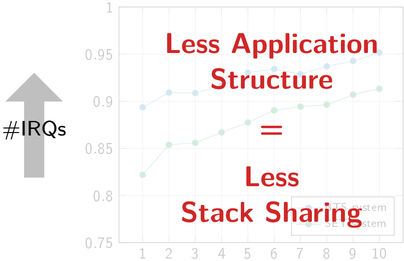
- Integration into Whole-System Generator
  - dOSEK: Python framework for system analysis and kernel generation
  - LLVM: Extract sizes of stack frames and stack-switch prologue
  - Gurobi: state-of-the-art ILP solver

Stack-Consumption Factors



Only Private Stacks

Stack-Consumption Factors



Less Application Structure

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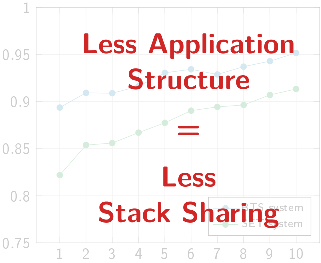
Less Stack Sharing

Stack-Consumption Factors

#IRQs



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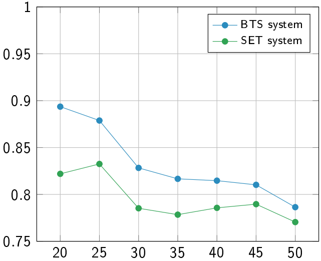

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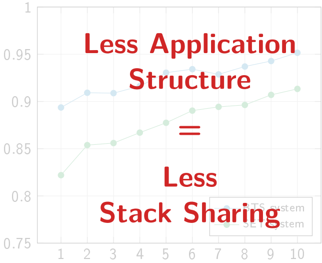

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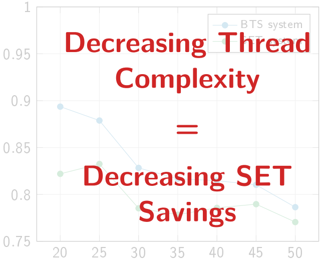

Decreasing Thread Complexity

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Decreasing SET Savings

#Threads

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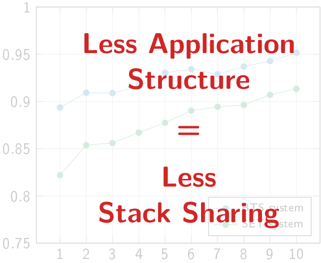

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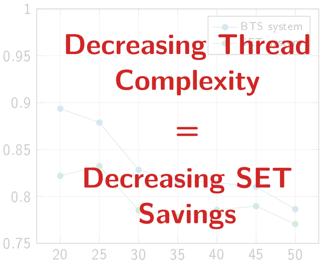

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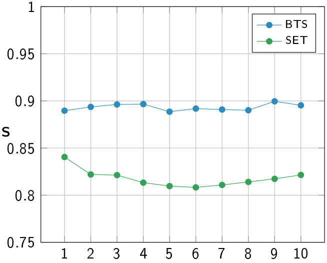

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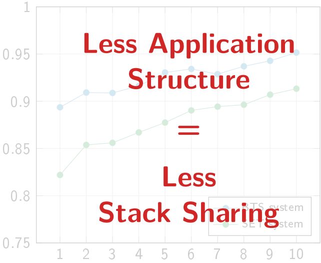

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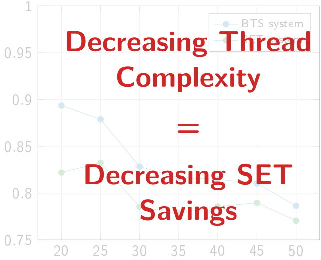

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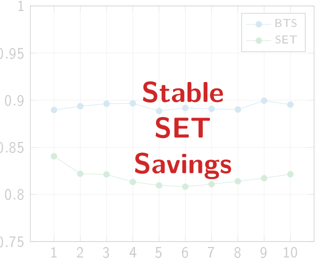

Stable SET Savings

Stack-Consumption Factors

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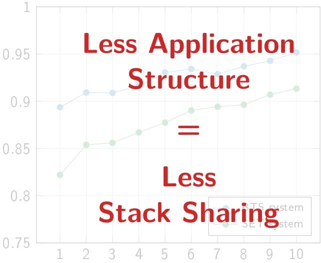

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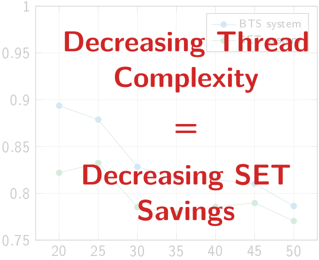

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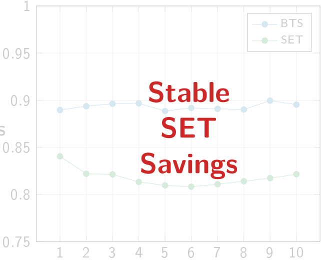
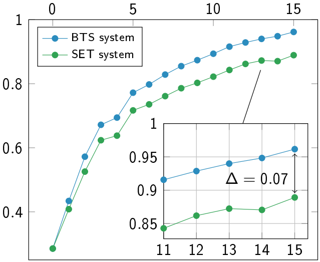


Stable SET Savings

#Waiting



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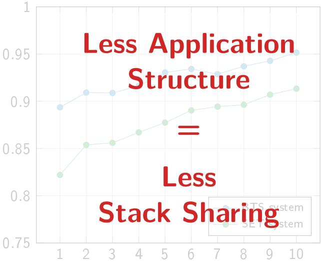

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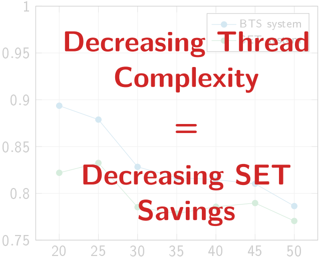

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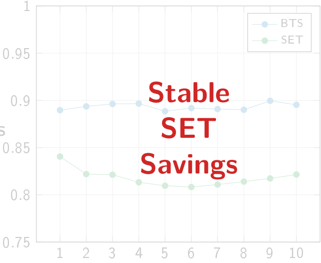

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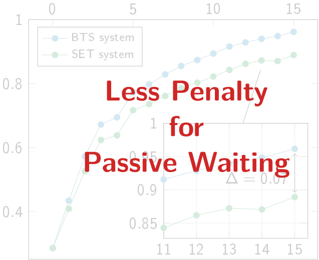


Less Penalty for Passive Waiting

Conclusion

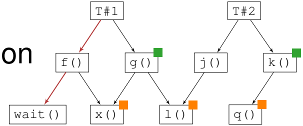
Conclusion

- Semi-Extended Tasks
  - SETs switch to shared stack if possible
  - Switching is efficient and does not involve the RTOS
  - Smaller penalty for passive waiting

- Fine-grained worst-case stack consumption analysis
  - Real-time properties (priorities, preemption thresholds)
  - Flow-sensitive preemption constraints
  - Supports semi-extended tasks

- Stack-space saving compared to pure BTS systems
  - 7 percent on average, up to 52 percent
  - 80 percent of all systems used less stack space

Genetic Algorithm as a Higher-Level Optimization

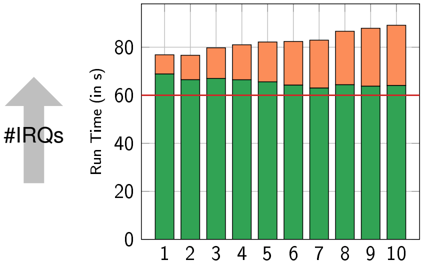


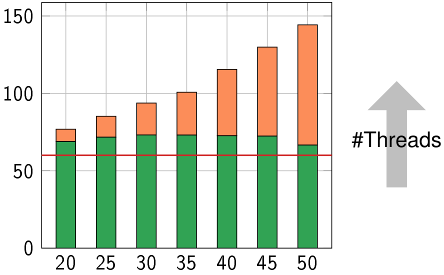
- Genetic algorithm to find a good configuration
  - Encode configuration as bit-vector
  - Bitmasks verify configuration
  - Configurations can be breed, mixed, and mutated

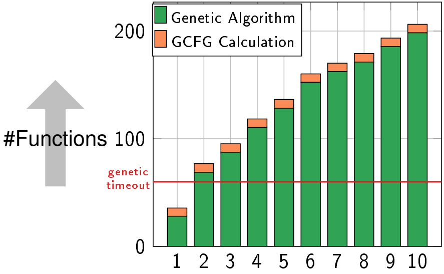
g()	x()	l()	T#2	j()	k()	q()
1	0	0	0	0	1	0

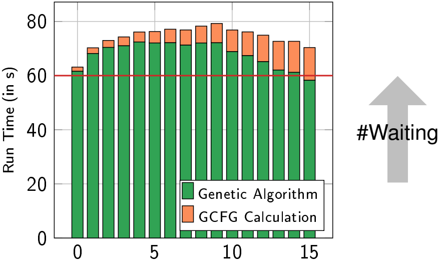
- Genetic Algorithm with Initial Population
  1. Generate new bit-vectors by mutation and cross-over
  2. Calculate fitness (WCSC) with IPET/ILP solver
  3. Select top 20 switch-configurations
  4. Goto 1, until satisfied (60 seconds of no progress)

Run-Time of Optimization


#IRQs
Run Time (in s)


#Threads


#Functions
genetic timeout
🟩 Genetic Algorithm
🟧 GCFG Calculation


#Waiting
Run Time (in s)
🟩 Genetic Algorithm
🟧 GCFG Calculation