Auto-Active Verification of Software with Timers and Clocks (STAC)

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Motivation

STAC = software that accesses the system clock, exchanges clock values, and uses these values to set timers and perform computation

- Key to real-time and cyber-physical systems
- Essential to keep software in sync with the physical world
- Examples = thread schedulers and time budget enforcers, distributed protocols (e.g., plug-and-play medical devices)

Goal : Formally verify STACs at the source code level using deductive (aka auto-active) verification

- Target: ZSRM mixed-criticality scheduler
  - Performs thread CPU allocation and time budget enforcement
  - Available as Linux kernel module implemented in C
  - Currently we focus on ZSRM budget enforcement only

To our knowledge, the first formally verified and performant timing enforcer

Why Verify Source Code?

Push assurance closer to executable level

- Use verified compilers (e.g., CompCERT) to close the final gap

Don't need to sacrifice performance

- Performance is a problem when we verify models
- And is a no-go for low-level system software

Easier to integrate with existing systems

- Linux kernel module means anyone using Linux can use it
- Can be modified to work with other OSs (ZSRM in VxWorks), such as SEL4
- What You Verify Is What You Execute!

Why Use Auto-Active Verification?

Soundness

Language expressivity

- Pointers, recursion, loops

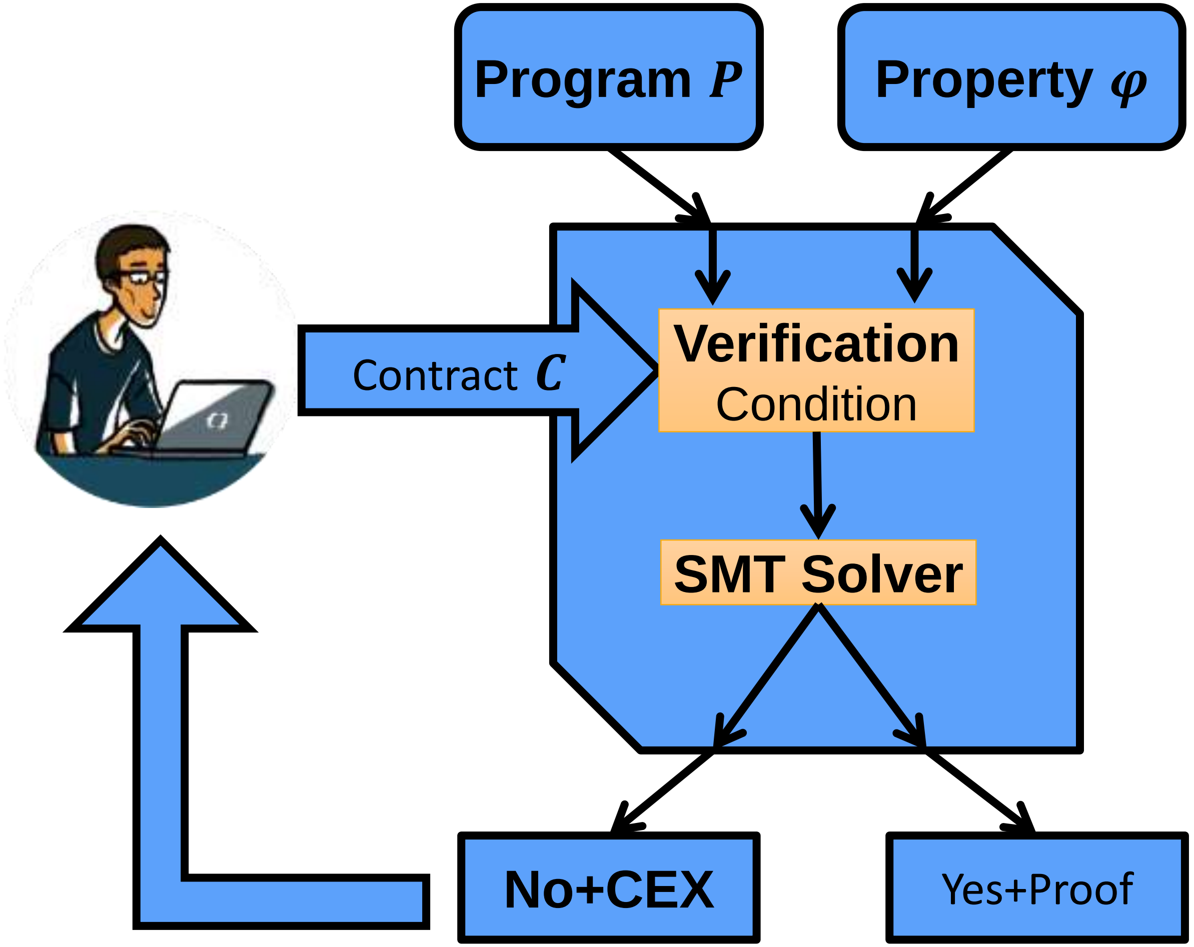
Rich specification

- Quantifiers
- Predicates
- Separation

Tool maturity

- Frama-C
  - https://frama-c.com/
  - Contracts expressed in ACSL

Good Balance between human intuition and brute force search



Auto-Active Verification

Terminology

Threads/tasks

- $T = \{\tau_1, \tau_2, \ldots\}$
- Executes with preemption (i.e., broken up into chunks)
  - Chunks not known at design time
- Initially each task is one continuous computation (e.g., a function)
  - later we will add periods

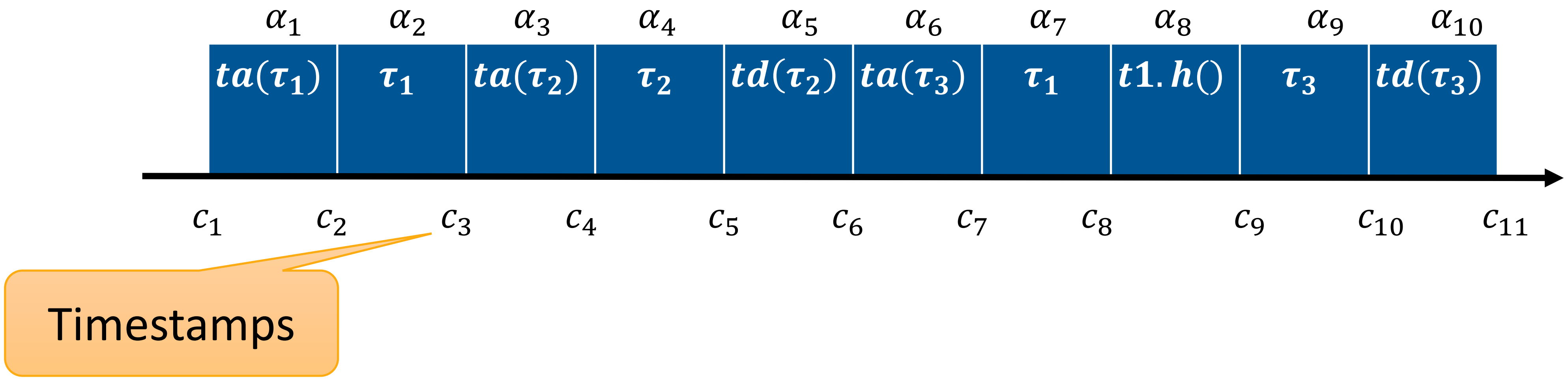
Enforcer Functions EF = System calls ∪ Timer handlers

- Execute atomically (i.e., without preemption)
- System calls
  - Task arrives : $ta(\tau)$
  - Task departs : $td(\tau)$

Execution/Timeline

Time = Global "Newtonian" clock

- Flows monotonically, dense real-time



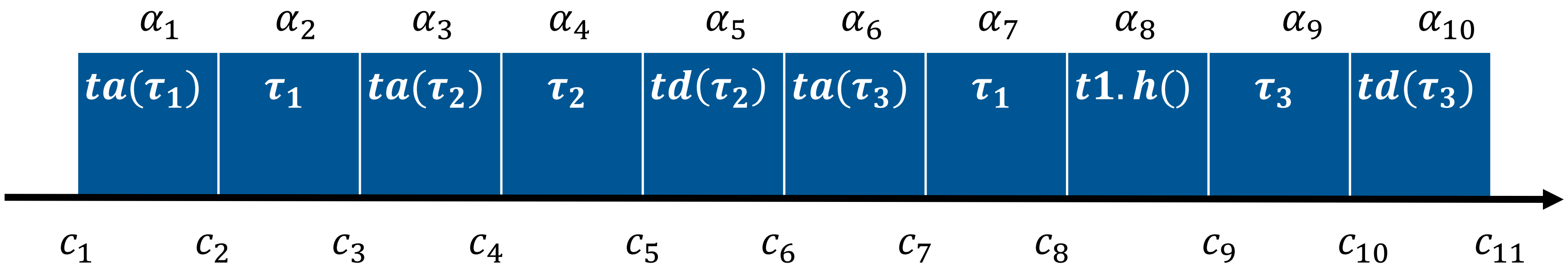
$$\text{Execution } \pi = s_1 \xrightarrow{\alpha_1} s_2 \xrightarrow{\alpha_2} s_3 \ldots s_{n-1} \xrightarrow{\alpha_{n-1}} s_n$$

$$\text{State } s_i = (c_i, r_i, a_i)$$

Thread CPU Usage

$C(\pi, \tau)$ = total cpu usage by thread τ over execution π

- Add up durations of all the transitions labeled by τ



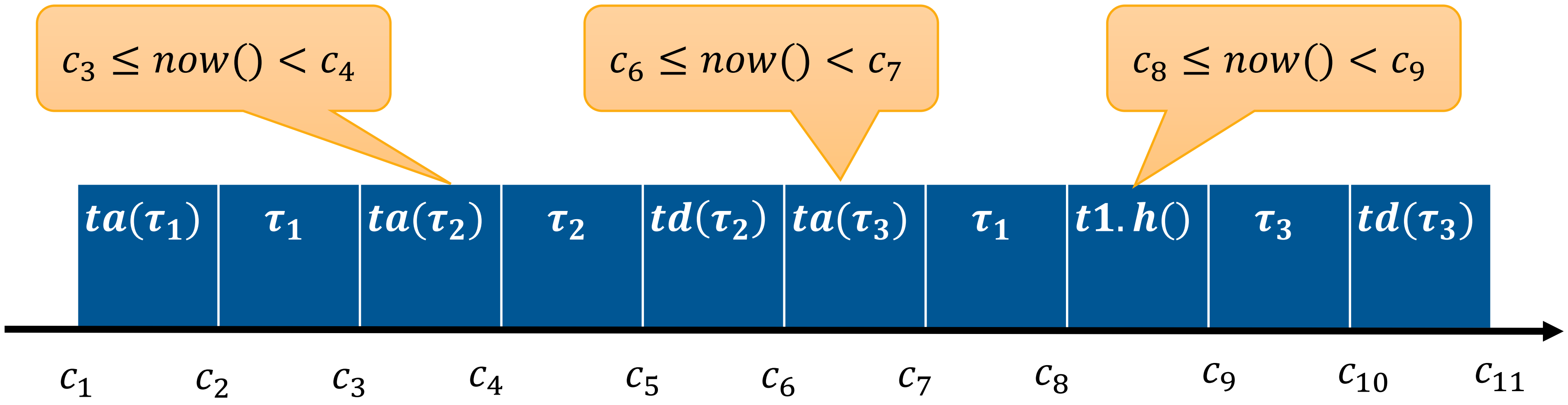
$$C(\pi, \tau_1) = (c_3 - c_2) + (c_8 - c_7)$$
$$C(\pi, \tau_2) = (c_5 - c_4)$$
$$C(\pi, \tau_3) = (c_{10} - c_9)$$

$C(\pi, \tau)$ can never be measured precisely
But can be over-approximated!

Measuring Current Time

System calls and timer handlers use a special function $now()$ to measure current time

We assume that $now()$ returns a value that is within the time boundary of the transition in which it is executed



We assume that multiple calls to $now()$ return strictly increasing values

- Implemented using hardware timestamp counter

Theorem: Over-Approximating CPU Usage

Theorem 1. *For any execution* $\pi = s_1 \xrightarrow{\alpha_1} s_2 \ldots s_{n-1} \xrightarrow{\alpha_{n-1}} s_n$ *and thread* τ, *the following four conditions hold:*

$$\begin{array}{ll} (\mathrm{C1}) & n > 1 \wedge \alpha_{n-1} = \tau \implies \tau.start(\pi) \leq c_{n-1} \\ (\mathrm{C2}) & n = 1 \vee \alpha_{n-1} \neq \tau \implies \tau.start(\pi) \leq c_n \\ (\mathrm{C3}) & n > 1 \wedge \alpha_{n-1} = \tau \implies C(\pi, \tau) \leq \tau.usage(\pi) + c_n - c_{n-1} \\ (\mathrm{C4}) & n = 1 \vee \alpha_{n-1} \neq \tau \implies C(\pi, \tau) \leq \tau.usage(\pi) \end{array}$$

Key Result

Using CPU Estimate to Enforce Budget

Each thread τ has a time budget $B(\tau)$

Definition 3 (Timer). *We say that a budget timer is always properly activated for a thread* τ, *denoted* $Timer(\tau)$, *if at the end of each execution* $\pi = s_1 \xrightarrow{\alpha_1} s_2 \ldots s_{n-1} \xrightarrow{\alpha_{n-1}} s_n$ *such that* $\alpha_{n-1} \in F \wedge sched(s_n, \tau)$ *there exists an active timer* $t \in a_n$ *such that* $t.c \leq c_n + B(\tau) - \tau.usage$.

Theorem 2. *For any thread* τ, *if* $Timer(\tau)$, *then* τ *never exceeds its budget, i.e., at the end of each execution* π, *we have* $C(\pi, \tau) \leq B(\tau)$.

Results extended to periodic threads as well

Verifying $Timer(\tau)$ on Source Code

Started with ZSRM implementation as Linux kernel module

Expressed $Timer(\tau)$ as ACSL annotations and verified with Frama-C

Complete source code with ACSL annotations publicly available

- http://www.andrew.cmu.edu/~schaki/misc/iccps17.tgz
- Compiles on recent Linux distributions
  - Tested to demonstrate good performance
- Verifies with Frama-C Aluminium
- Paper under submission

QUESTIONS?

Please attend the poster session