T-Tex: Timed Threaded Execution for Real-time Security and Safety (OpenMP)

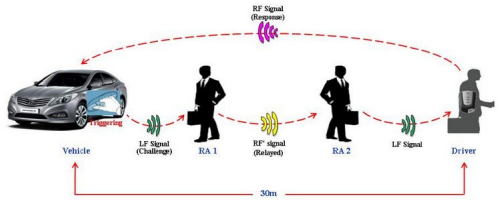
Swastik Mittal, Frank Mueller

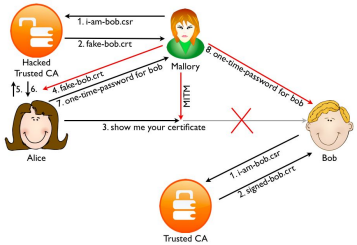
Contents

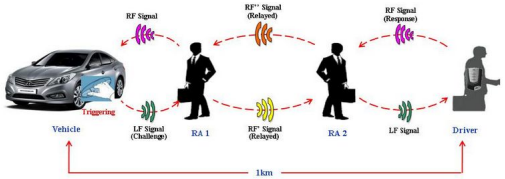
Real Time Systems & Security

- **Predictable systems**
  - **Predictability is key over performance**
  - **Event triggered real time systems**
    - **E.g.:** Braking system in autonomous vehicles
  - **Time triggered real time systems**
    - **E.g.:** Subsystem within drones
      - Drone: periodically communicate navigation and flight parameters.

- Process of detecting and preventing intrusion
- Two broad categories:
  - **System Security**
  - **Network Security**

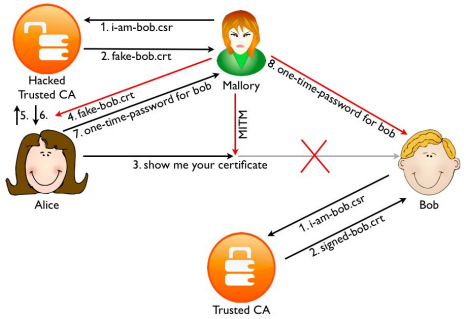


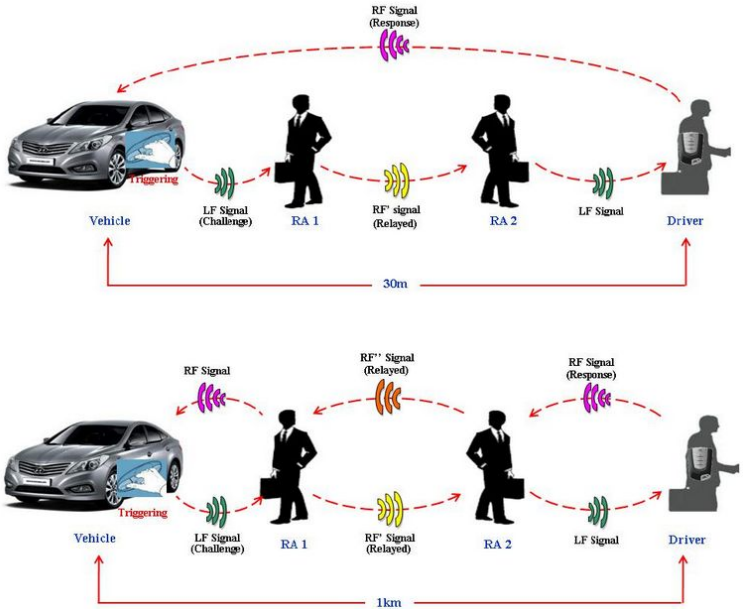




Computer Security

- Process of detecting and preventing intrusion
- Two broad categories:
  - **System Security**
  - **Network Security**



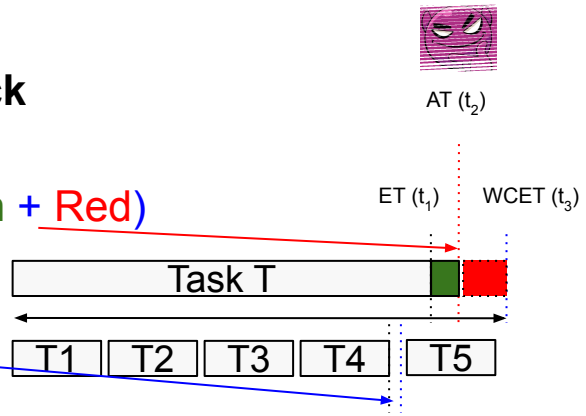


Attacks

- **System Attacks**
  - Buffer overflow
  - SQL Injection
  - Privilege escalation etc.
- Network Attacks
  - Man-In-the-Middle
    - E.g.: Relay and Replay attacks. (Common attacks in real time systems)
  - Denial of service
    - E.g.: ping-of-death, syn-flooding etc.
- **Delay Attacks**
  - Delay in intended execution time of the task/process
  - Fatal in a real-time system
    - Car crashing because of break delay

Takeaway

- Attacker may not take over system
  - But can **easily** cause delays (deadline miss)
  - **Need to detect such delays as early as we can**
- Predictable nature of real-time systems enable execution-time analysis
  - **Worst case execution time of a task (WCET)**
  - **For an attacker to execute an undetected delay attack**
    - mask delay using slack time
    - security vulnerability threshold (WCET - ET : Green + Red)
  - **Finer division of such tasks → lower WCET**
    - lower vulnerability (Eg. T4)
    - Early detection before significant impact
  - **Higher observed execution time compared to expected time (WCET) → signalled as delay attack.**



OpenMP

- **Multiprocessing framework**
  - widely used paradigm in parallel programming
- **Task scheduling** in OpenMP
  - **Implicit**: fine-grained data/loop parallelism (E.g., #pragma omp for)
  - **Explicit**: fine-grained parallelism originally for recursion (E.g., #pragma omp task)
    - Used by real-time community as coarse-grained tasks
      → abstraction inversion, mismatch (see results in papers)
- **OpenMP lacks real-time capabilities**
- **OpenMP-RT [LCTES'24]** fills this gap: introduces real-time capabilities to OpenMP
  - Priority based thread pools
    - Schedule OpenMP threads utilizing linux real-time priority band
  - Supporting access to shared resources
    - in a lock free and wait free manner
- **Execution time analysis of such real-time systems is critical**
  - **Early intrusion detection → our T-Tex work (coming next!)**

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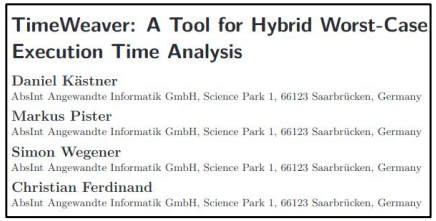
Contents

- Introduction
  - Real-Time Systems
  - Computer Security
  - OpenMP
- T-Tex
  - Related Work (WCET Analysis, Delay Detection)
  - Assumptions & Attack Model
  - Idea & Design
  - Implementation
  - Experimental Framework & Evaluation
  - Conclusion

T-Tex Novelty

- Code execution time analysis is not new
- T-SYS [ICCPS'22]
  - First to do complete kernel code protection via execution time analysis
    - but is **single threaded**

- **T-Tex contributions & novelty:**
  - **kernel timer crediting (never done before)**
    - Accurate execution time analysis
      - Eliminate blocking time by other task
  - **finer code region than basic block**
    - Instruction level
  - **Protecting all forms of loops**
    - statically or dynamically bounded


TimeWeaver: A Tool for Hybrid Worst-Case Execution Time Analysis

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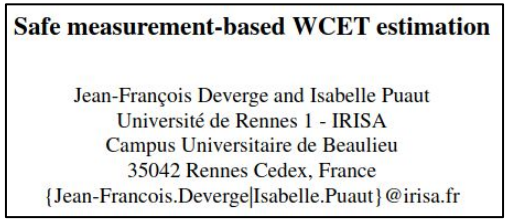
Safe measurement-based WCET estimation

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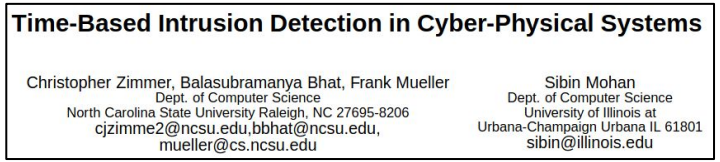
Time-Based Intrusion Detection in Cyber-Physical Systems

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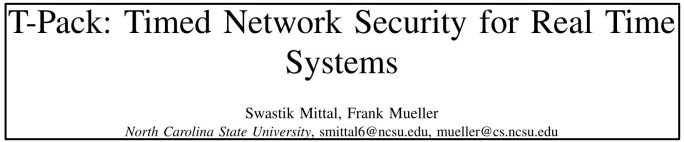
T-Pack: Timed Network Security for Real Time Systems

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Motivation & Hypothesis

- Motivation
  - **Early detection** of delay
    - **no cost**
    - minor performance overhead for multithreaded RTS
      - uses simple monitoring techniques
- Hypothesis
  - Finer code division of OpenMP application
    - WCET analysis
  - Accurate execution time by considering overheads
    - Context switching
    - Resource contention

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Assumption & Attack Model

- **Oversubscription of threads on cores:** Reap parallel programming performance benefits
- **Core pinning:** Unbounded delays because of thread migration
- **Maximum number of parallel executing tasks known a priori**
  - Critical for static WCET analysis
- **Attack Scenarios**
  - **Kernel protected from any attack** (task priority & timer modification is not possible)
  - **Number of threads executing code region cannot be modified during execution**
    - Workload distribution already done by OpenMP
  - Possible attacks
    - **Buffer overflow attacks**
    - **Scheduling additional tasks** (not affecting the number of context switches)
      - Shared resources delay (memory delays)

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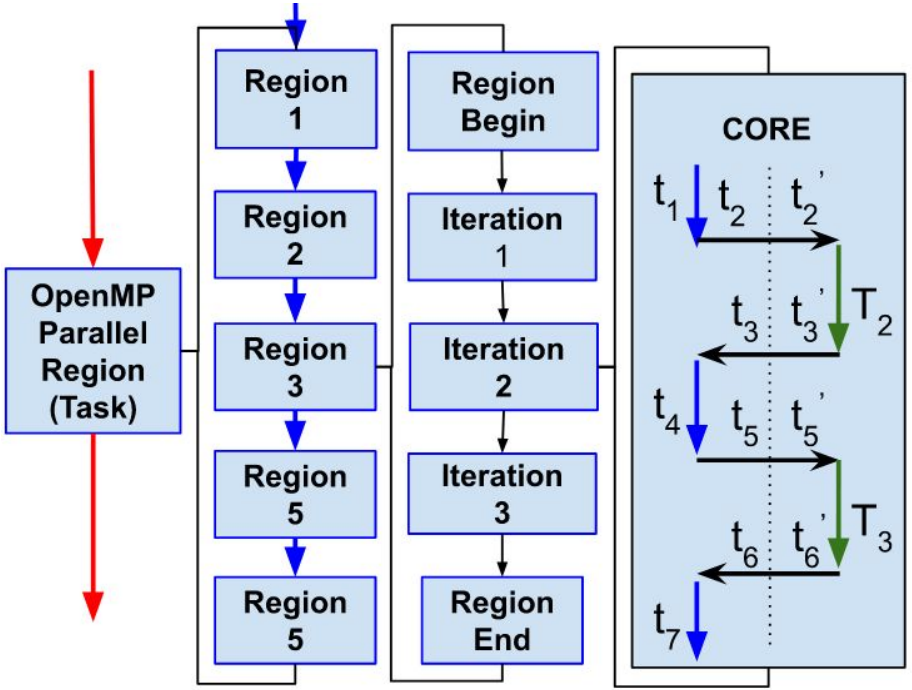
Idea

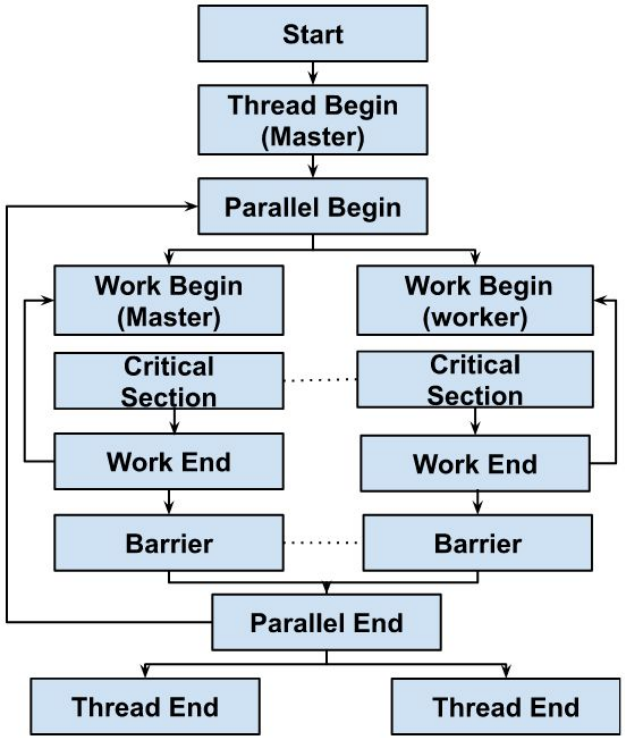
- **T-Tex: Threaded Time Execution tracking**
  - per-thread time varies depending on core contention
- **Identifying OpenMP regions**
  - Each region can be executed by different # threads
    - #pragma omp for vs #pragma omp sections
    - Affecting execution time of the region
- **Loop Identification**
    - Execution time of loops: depends on # threads
    - Timing loops is critical
      → need to identify static and dynamically bounded loops
- **Kernel timer crediting (Novel execution time analysis)**

Design: Protected Region



- Code division
  - Parallel region → multiple regions 1-5
- Region division
  - Each region further divided
    - Eg: Loop (3 code regions)
    - Loop of 30: (0-10,10-20,20-30)
- Thread suspension accounting
  - Eliminate T_2 & T_3 for accurate execution time
  - Blocks timed task

Identify OpenMP Regions (OMPT)



OpenMP Control Flow Graph

- Parallel Region (parallel Begin)
  - **implicit task**
  - **executing at different thread priority**
    - See OpenMP-RT
- **OMPT (OpenMP Tracer interface)**
  - Enables run-time profiling
  - **Identifies OpenMP regions using callbacks** at run-time
    - Sub regions using work begin
    - How to identify specific regions?
      - Callbacks **modified to pass id values**
  - **Maintains unique thread specific data → as a void pointer**
    - Store per thread timer information

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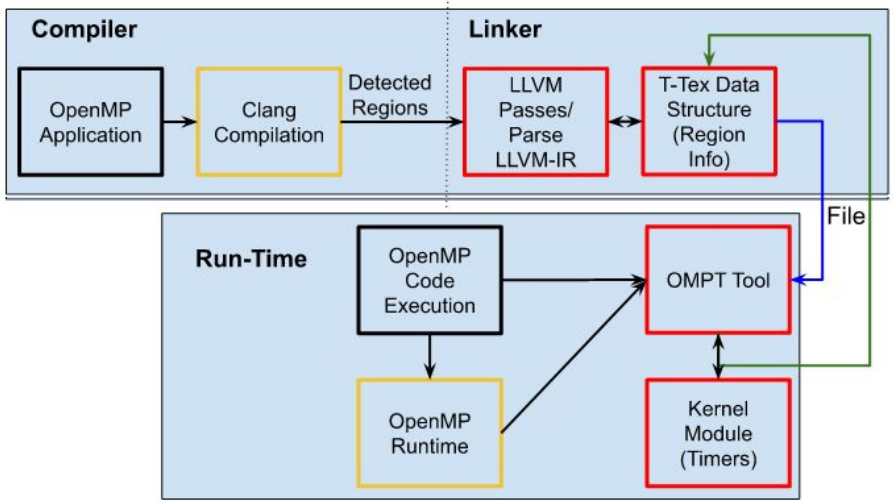
Implementation: LLVM+Clang

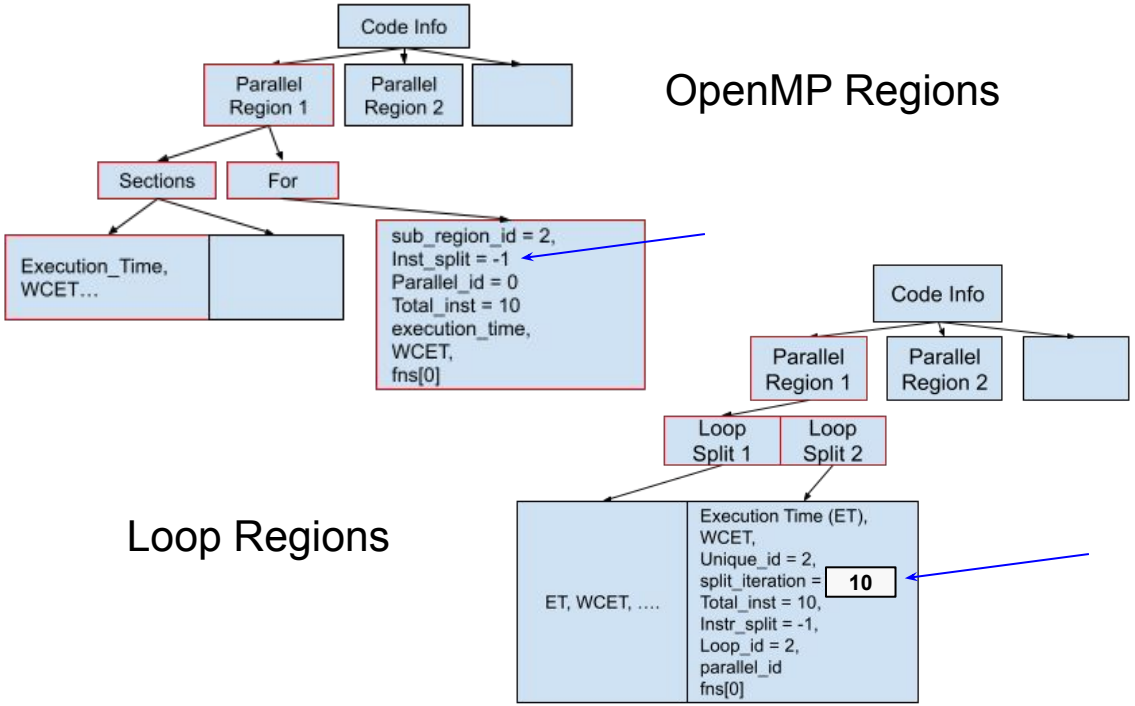


T-Tex Execution Pipeline: LLVM Compiler tool chain used for code instrumentation

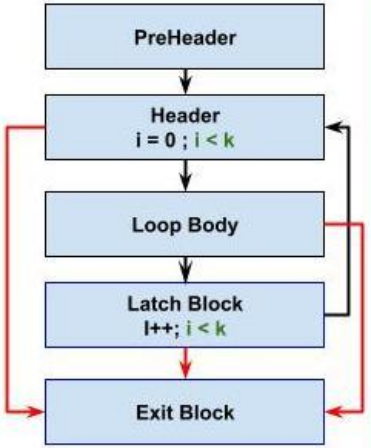
- **Clang parser**: Regions detected via AST
- **LLVM Pass in Linker**: Supports multiple files
- **Phase 0**: Pessimistic approach, identifies all regions
- **Region Handling**:
  - OMPT pre-identifies regions
  - Runtime calls modified to pass IDs
- **Loop Tracking**: Detects first loop iteration, stores ID-related info
  - **Attaches custom added callback (in OMPT)**
- Save region information within T-Tex Data Structure
  - Store details in a file

T-Tex Data Structure

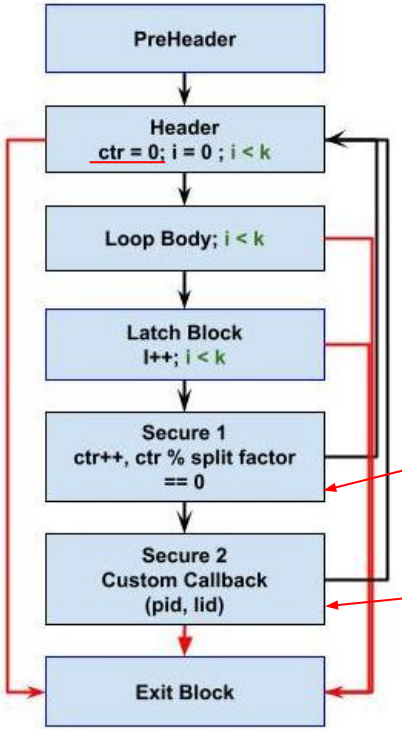
```
#include <bits/stdc++.h>

Tabnine | Edit | Test | Explain | Document | Ask
void func(){
}

Tabnine | Edit | Test | Explain | Document | Ask
int main(){
    #pragma omp parallel
    {
        #pragma omp sections
        {
            #pragma omp section
            {
                func();
            }

            #pragma omp section
            {
                printf("test");
            }
        }

        #pragma omp for
        {
            for(int i = 0 ; i < 30 ; i++) {
                for(int j = 0 ; j < 100 ; j++) {
                    func();
                }
            }
        }
    }
}
```



How T-Tex Splits Loops



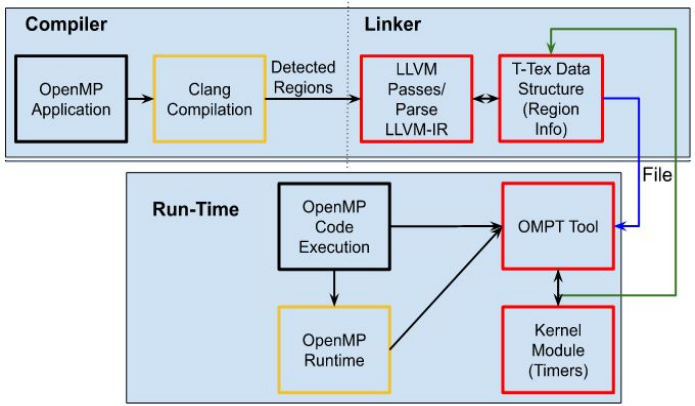
a)
Loop CFG without T-Tex



b)
Loop CFG with T-Tex

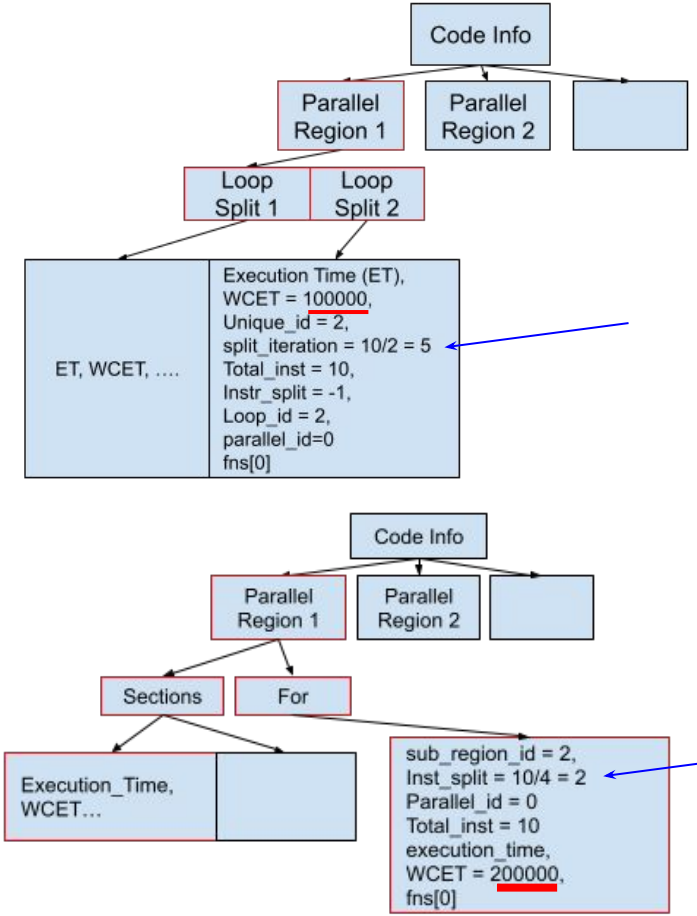
- **Identify statically & dynamically bounded loops**
  - difficult to track induction variable; instead:
  - **Add additional induction variable (ctr)**
    - LLVM phi-node
      - ctr value in header depends on calling block
      - 0 for preheader
- Add additional basic blocks
- Secure1
  - Checks & increments
  - Call header or Secure2
- Handles multiple scenarios
  - LatchBlock != Header
  - LatchBlock == Header
  - Multiple LatchBlocks

At Runtime



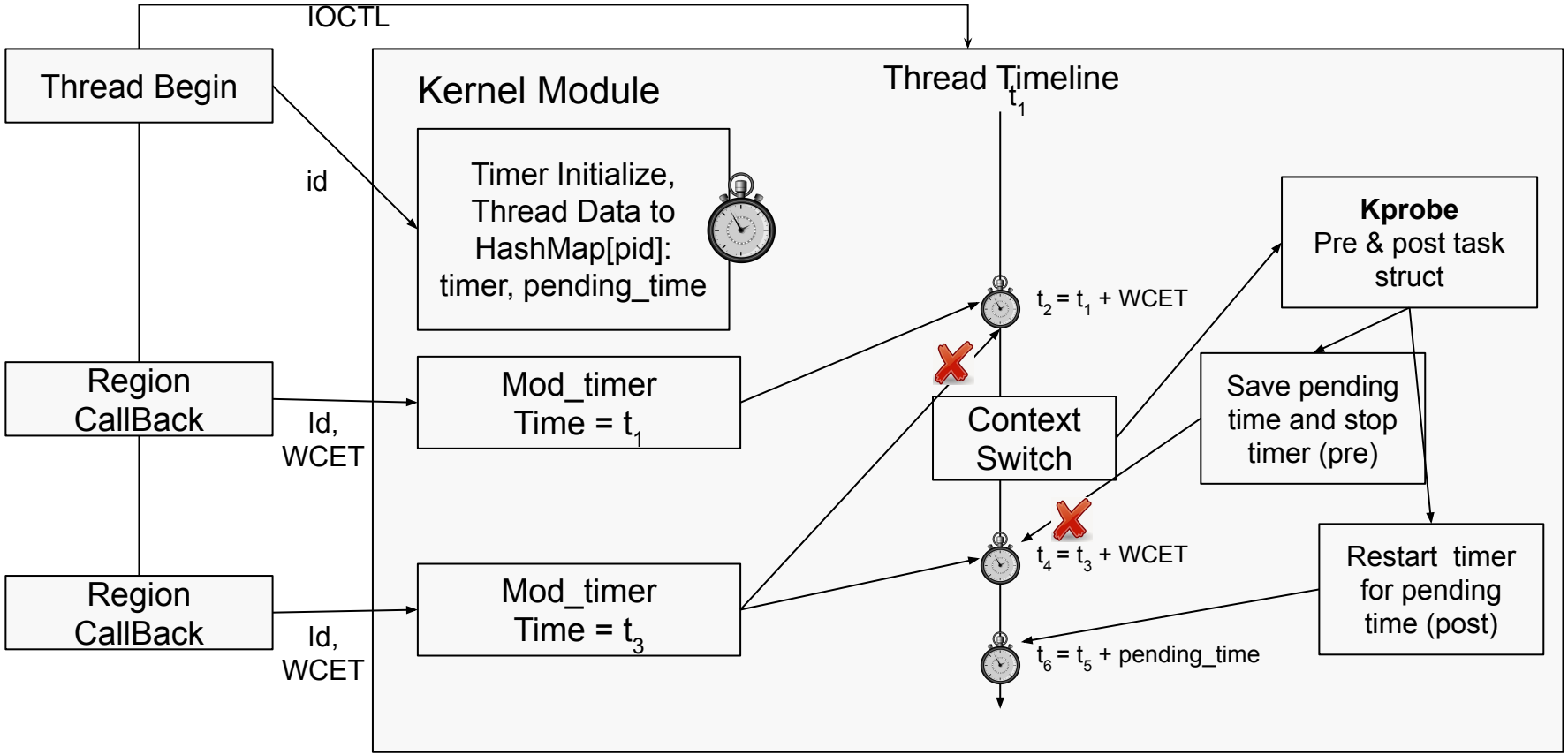
T-Tex Execution Pipeline

- Modified callbacks
- **Data structure information read from file**
- Executing timers at region callback
  - **Record execution time for previous region**
    - Eliminate the timer
    - Start timer for new region
      - **How do we get the timer value?**
  - Callbacks provide region IDs
  - Retrieve time values of region
    → from **data structure (using the ID's)**
- **Executed region information appended**
  - Thread specific data of OMPT
  - Critical for update WCET analysis
  - **How to use this information?**



- Analysis phase
  - WCET of each region calculated, saved in file
  - **Security vulnerability threshold (SVT)**
    → set by the user (E.g., 60us)
- Phase 1 (and then Phase 2,3,...)
  - Loops
    - split_iteration
      - 2 code regions needed to divided 100 us
        - Each code region < 60 us
    - Split instructions if split_iteration = 1
  - Regions
    - 4 code regions needed to split 200 us
    - Total instruction / 4
  - Handling common “func” call
    - **Assign function to region with highest WCET for code division**

Linux Kernel Timer Crediting



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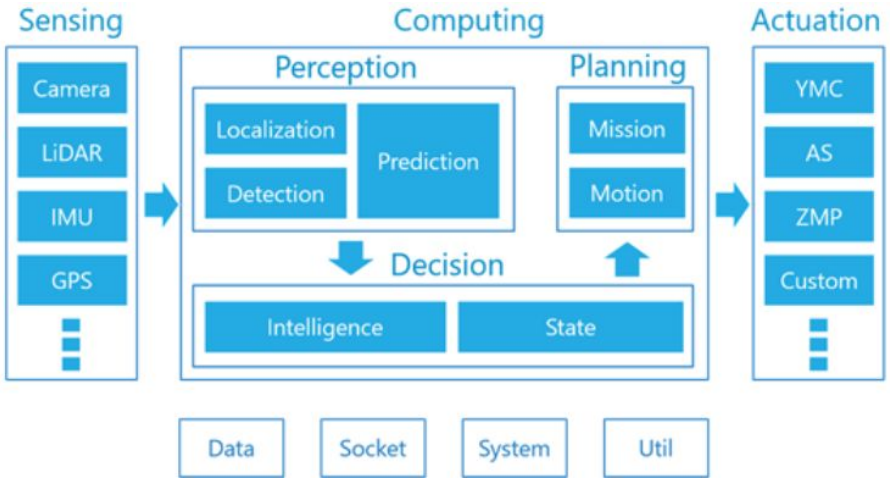
Evaluate

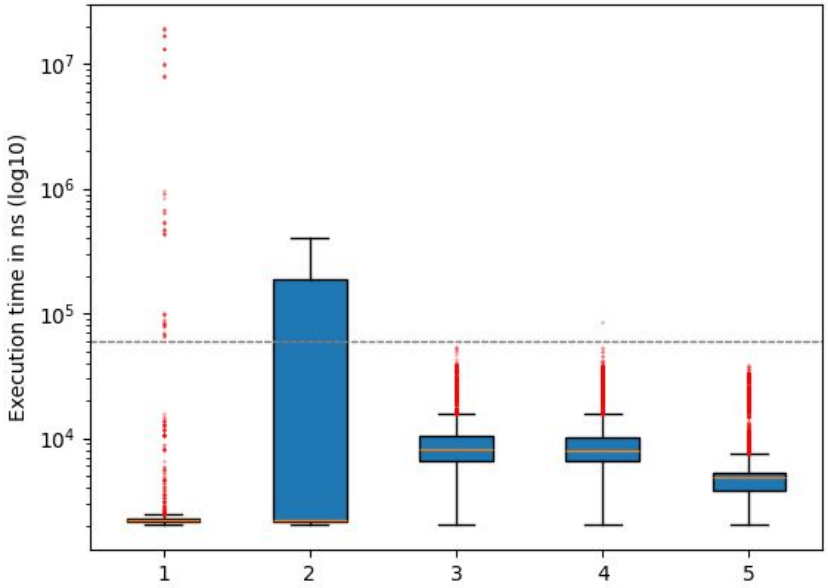
- **Multiphase code division using T-Tex**
  - Execution time below vulnerability threshold
- **Benefit of kernel timer crediting**
- **Accuracy under delay attacks**
  - Chain delay (executing delay in each code region)
- **T-Tex vs. Basic Block level security (~ T-SYS)**
- **Performance overhead**
- System:
  - x86_64 Intel i7-9750H processor at 2.60GHz
  - **OpenMP application executed via 4 threads on 2 cores (oversubscription)**
    - with real-time threading capabilities
      - linux real-time priority band replicating OpenMP-RT

Experiment 1: Daphne Benchmark



- Daphne benchmark
  - Benchmark to evaluate **autoware platform**
    - Autonomous driving framework
  - **Mirrors key modules of perception**
    - Points to Image
    - Euclidean Clustering (Object Detection)
  - **Object detection is a time critical task**
    - Demonstrates real-time task

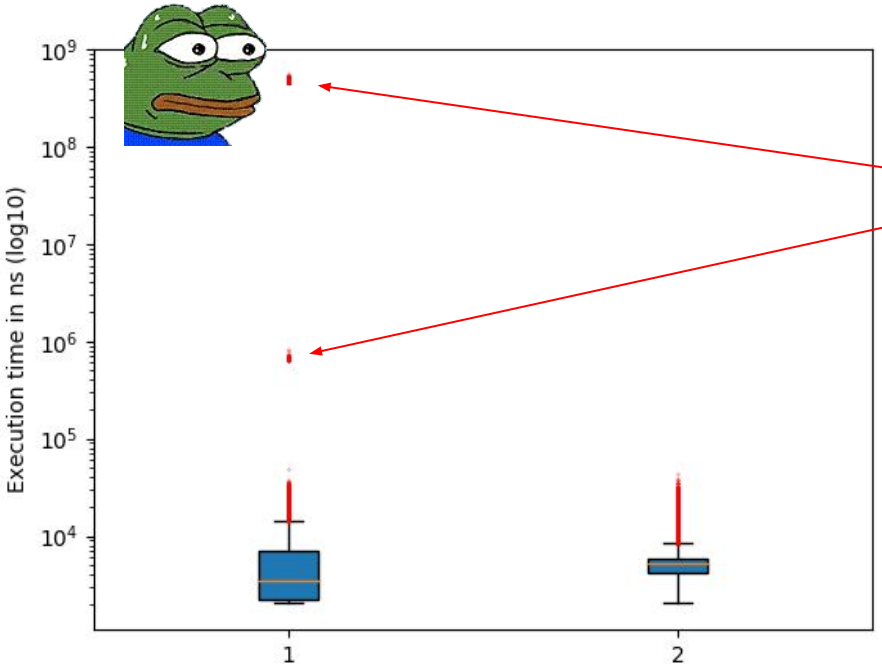
Multiple Phases of T-Tex



- Execution time values of code regions after T-Tex Phase **1. 2. 3. 4. & 5. (Box Plots)**
- Phase 5 achieves requested security threshold

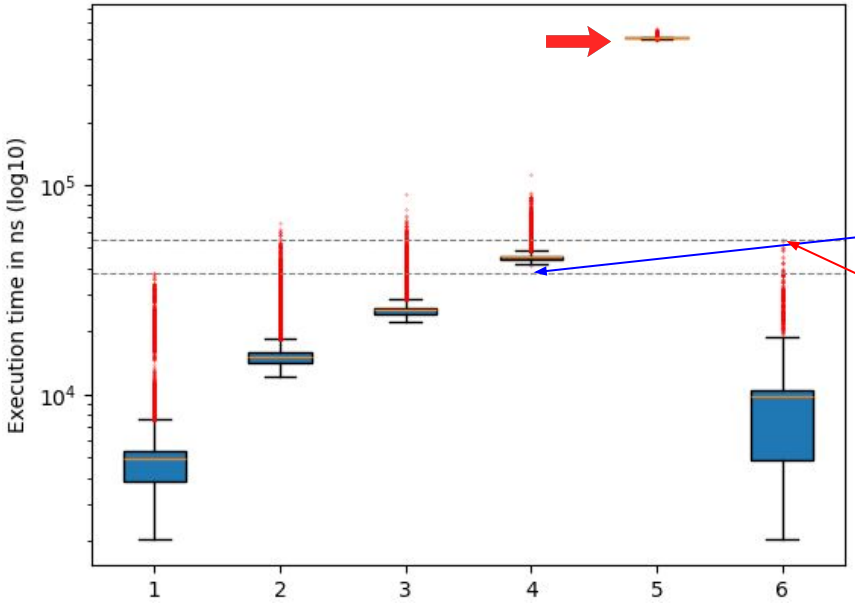
- T-Tex executes 5 phases
  → achieves 60us security threshold
  - 100K code regions
  - Execution of all regions < 60us

Need for Timer Crediting



- 1 - **WCET evaluate with no crediting**
  - T-Tex divides code based on WCET
  - **Impossible to break down regions**
    - **Finer division than instruction level needed**
- 2 - **WCET evaluated with crediting**
  → achieves 60us security threshold
- **Higher vulnerability for 1**
  - Higher WCET

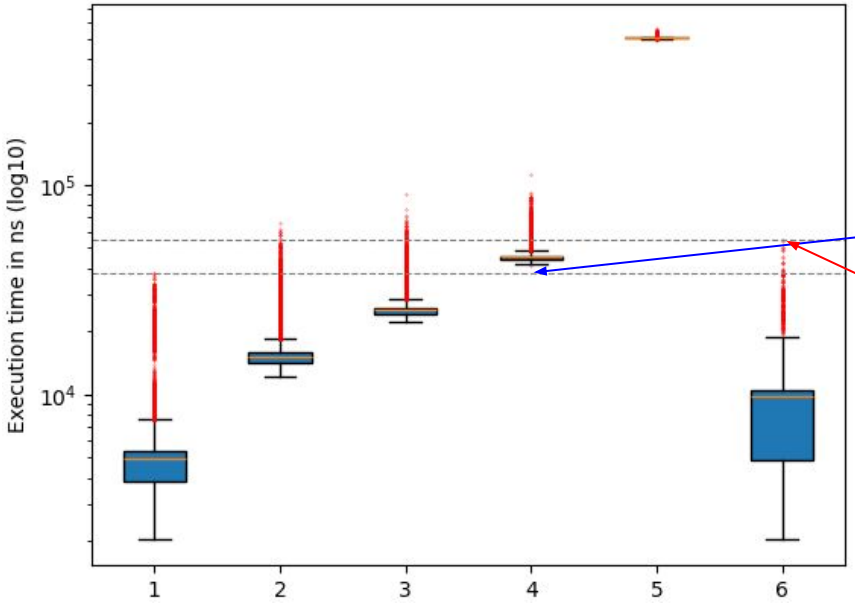
Attack Evaluation



- Execution time values of code regions under delay attack (T-Tex protection)
  - **1. No Delay 2. 10us 2. 20us 3. 40us 4. 500us & 6. ~ T-SYS (No Delay)**

- **Exec. time values under attack delays**
  - Delays in each code region
    - Replicates **chain of delay attacks**
  - **No overlap with 40us delay**
    - See 1st dotted line
- **Basic block level security**
  - **Replicates T-SYS**
    - **Overlaps with 40us delay**
      - See 2nd dotted line
- 100% attack detection for a 500us delay even with phase2 level of security

Attack Evaluation



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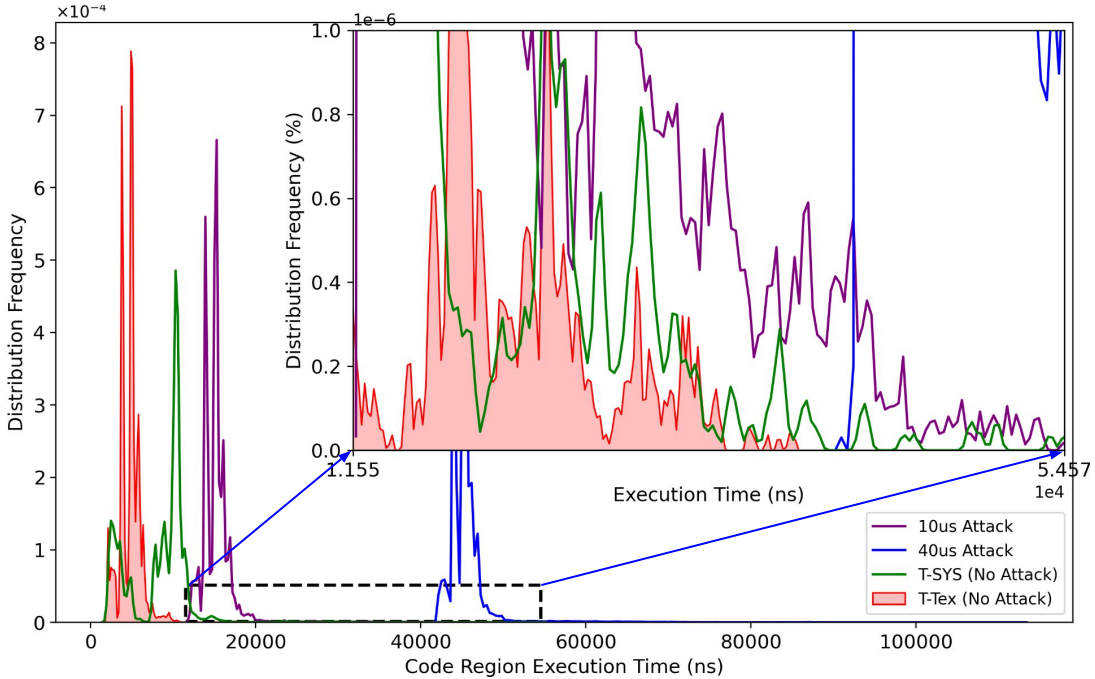
- **Basic block level security**
  - **Replicates T-SYS**
    - **Overlaps with 40us delay**
      - See 2nd dotted line
- How many code regions are affected?
  - A single value would result in higher WCET for multiple regions

Normal Distribution of Box Plots - Study Overlapping Regions



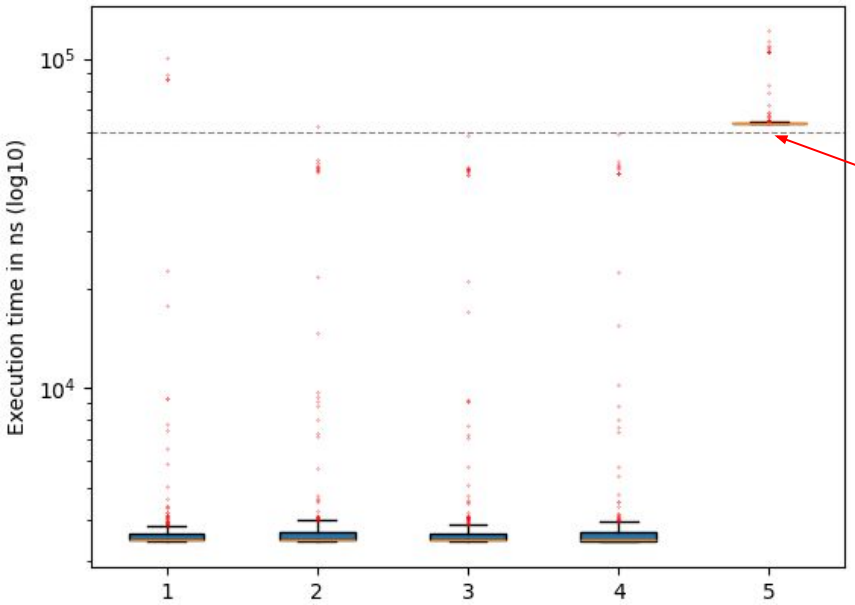
- **0.7% values in red overlap with purple**
  - **Effects 22K regions** (out of 100K regions)
  - **Less than 25% chance** for an attacker to mask a delay
- **0.05% of values in green overlap with blue**
  - No values in red overlap with blue
  - **800 regions**
    - **Higher vulnerability window**

Experiment 2: Parsec

Program	Application Domain	Parallelization		Working Set	Data Usage	
		Model	Granularity		Sharing	Exchange
blackscholes	Financial Analysis	data-parallel	coarse	small	low	low
bodytrack	Computer Vision	data-parallel	medium	medium	high	medium
canneal	Engineering	unstructured	fine	unbounded	high	high
dedup	Enterprise Storage	pipeline	medium	unbounded	high	high
facesim	Animation	data-parallel	coarse	large	low	medium
ferret	Similarity Search	pipeline	medium	unbounded	high	high
fluidanimate	Animation	data-parallel	fine	large	low	medium
freqmine	Data Mining	data-parallel	medium	unbounded	high	medium
raytrace	Rendering	data-parallel	medium	unbounded	high	low
streamcluster	Data Mining	data-parallel	medium	medium	low	medium
swaptions	Financial Analysis	data-parallel	coarse	medium	low	low
vips	Media Processing	data-parallel	coarse	medium	low	medium
x264	Media Processing	pipeline	coarse	medium	high	high

- OpenMP benchmark
  - Freqmine (FMI)
    - frequent itemset mining
  - **Less compute and loop intensive** application
- Evaluate compatibility and performance overhead

Results



- Execution time values of code regions after T-Tex Phase **1. 2. 3. & 4 (Box Plots)**
- **5. 60us delay attack**
- Phase 3 achieves requested security threshold
  - Phase 4 results in no updates

- **3 phases of T-Tex needed for 60us security threshold**
  - Less **code regions (220)**
- **100% detection for 60 us delay attack**
- **11% performance overhead** compared to no protection
  - **71% overhead in case of Daphne benchmarks**
  - **35% for phase 2 level of protection**
    - **100% detection for 500us** delay

Contents

Conclusion

- **Contributed → T-Tex: Timed analysis and attack detection technique**
  - For real-time multiprocessor applications **using OpenMP**
- Leverages the **LLVM compiler and OMPT profiler**
  - implements a multi-timer approach **supporting dynamic timed analysis**
- Successfully **detects 100% of attacks**: **40–60us delays**
- **11-72% overhead** depending on the OpenMP application
- **Novel kernel timer crediting** technique

Q/A?

Thank You!!