Code Optimizations Using Formally Verified Properties

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October 2013

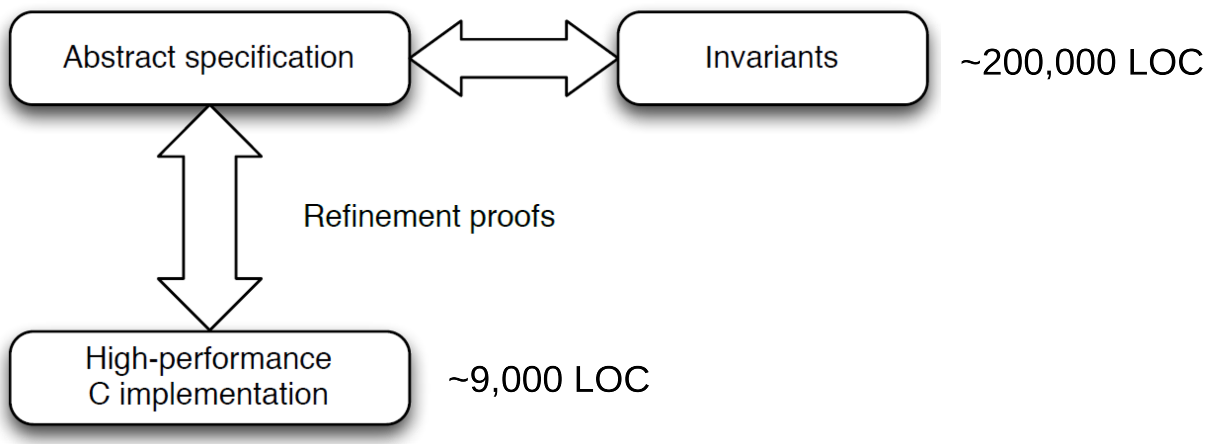
Australian Government
Department of Broadband, Communications and the Digital Economy
Australian Research Council

NICTA Funding and Supporting Members and Partners

Motivation

- seL4
  - Formally verified micro-kernel
    - Formal specification of functional behavior
  - Bug-free
  - Micro-kernel in C language ~9,000 LOC
  - Formal specification ~200,000 LOC

    [Klein et al, seL4: Formal verification of an OS kernel. SOSP'09]



Motivation

- Formal specification
  - Designed for proof
  - More human effort
  - More information
  - Code optimizations
  - …

Case Study I – Use of Invariants

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```
void deleteCallerCap (tcb_t *receiver) {
    callerSlot = TCB_PTR_CTE_PTR(receiver, 3);
    deleteCap(callerSlot);
}
```

```
void deleteCap(slot_t *slot) {
    …
    ret = finalizeCap(slot->cap);
    …
}
```

```
int finalizeCap (cap_t cap …) {
    switch (getCapType(cap)) {
        case cap_reply_cap:
        case cap_null_cap:
            fc_ret.remainder = cap_null_cap_new();
            fc_ret.irq = irqInvalid;
            return fc_ret;
        case cap_endpoint_cap:
            …
        case cap_async_endpoint_cap:
            …
    }
    …
}
```

tcb_cnode_index 3 ↦
(λ _ thread_state .
case thread_state of
BlockedOnReceive e d → (op ≡ **NullCap**)
| _ → (op ∈ {**ReplyCap**, **NullCap**}))

TCB_PTR_CTE_PTR(receiver,3)->cap
is cap_reply_cap (ReplyCap)
or cap_null_cap (NullCap)

```
int finalizeCap_clone (cap_t cap …) {
    fc_ret.remainder = cap_null_cap_new();
    fc_ret.irq = irqInvalid;
    return fc_ret;
}
```

Case Study II – Use of Program Safety

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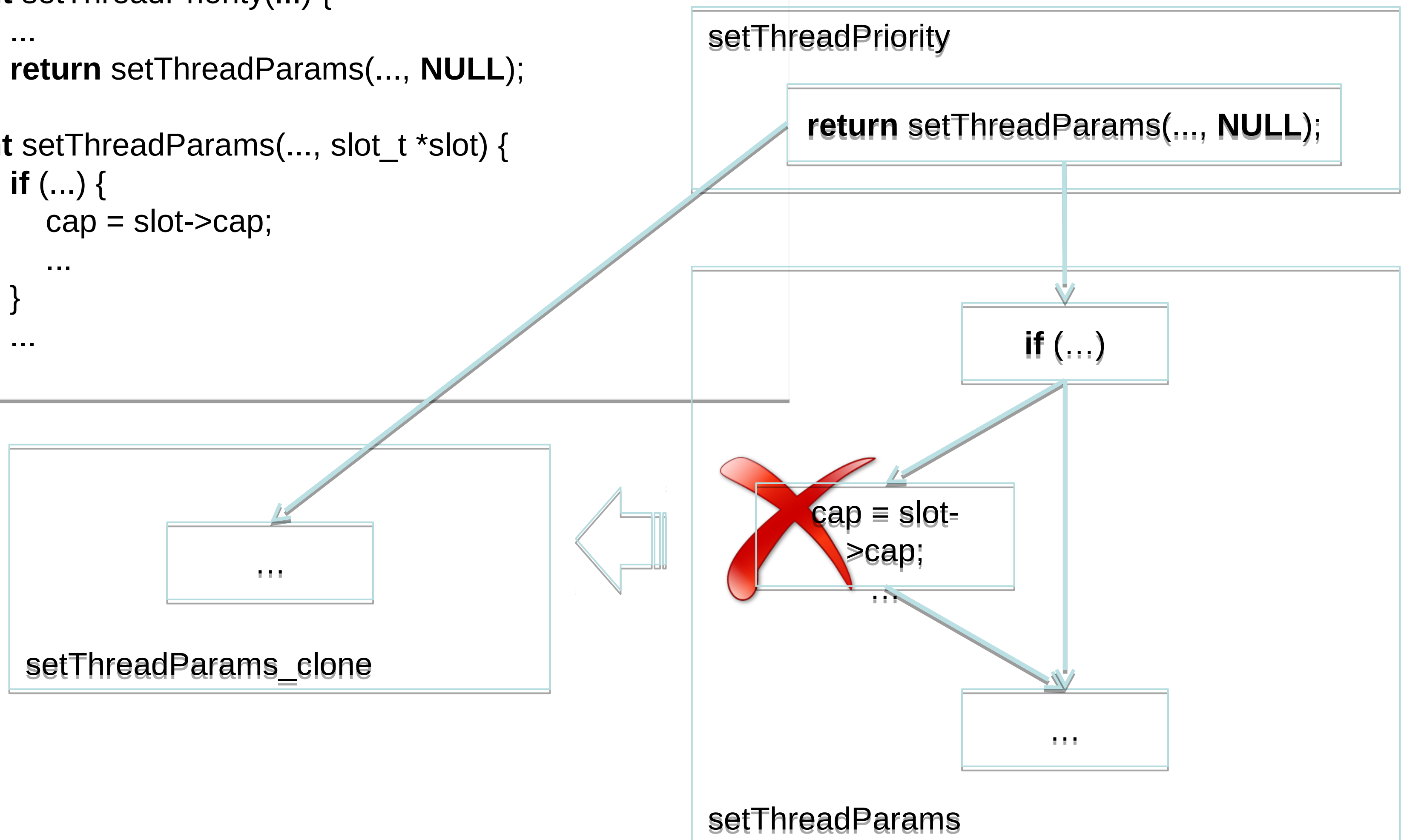
```
int setThreadPriority(...) {
    ...
    return setThreadParams(..., NULL);
}
int setThreadParams(..., slot_t *slot) {
    if (...) {
        cap = slot->cap;
        ...
    }
    ...
}
```



Overview

- Use of invariants
  - Hard to implement invariants at C level
  - Demand-driven approach
- Use of program safety
  - Some compilers have implemented the similar function but cause more serious bugs or security vulnerabilities
    - [Wang et al. Undefined behavior: what happened to my code? Apsys'12]
- Optimizations
  - Context separation
  - Code transformation according to the results of use of invariants and use of program safety

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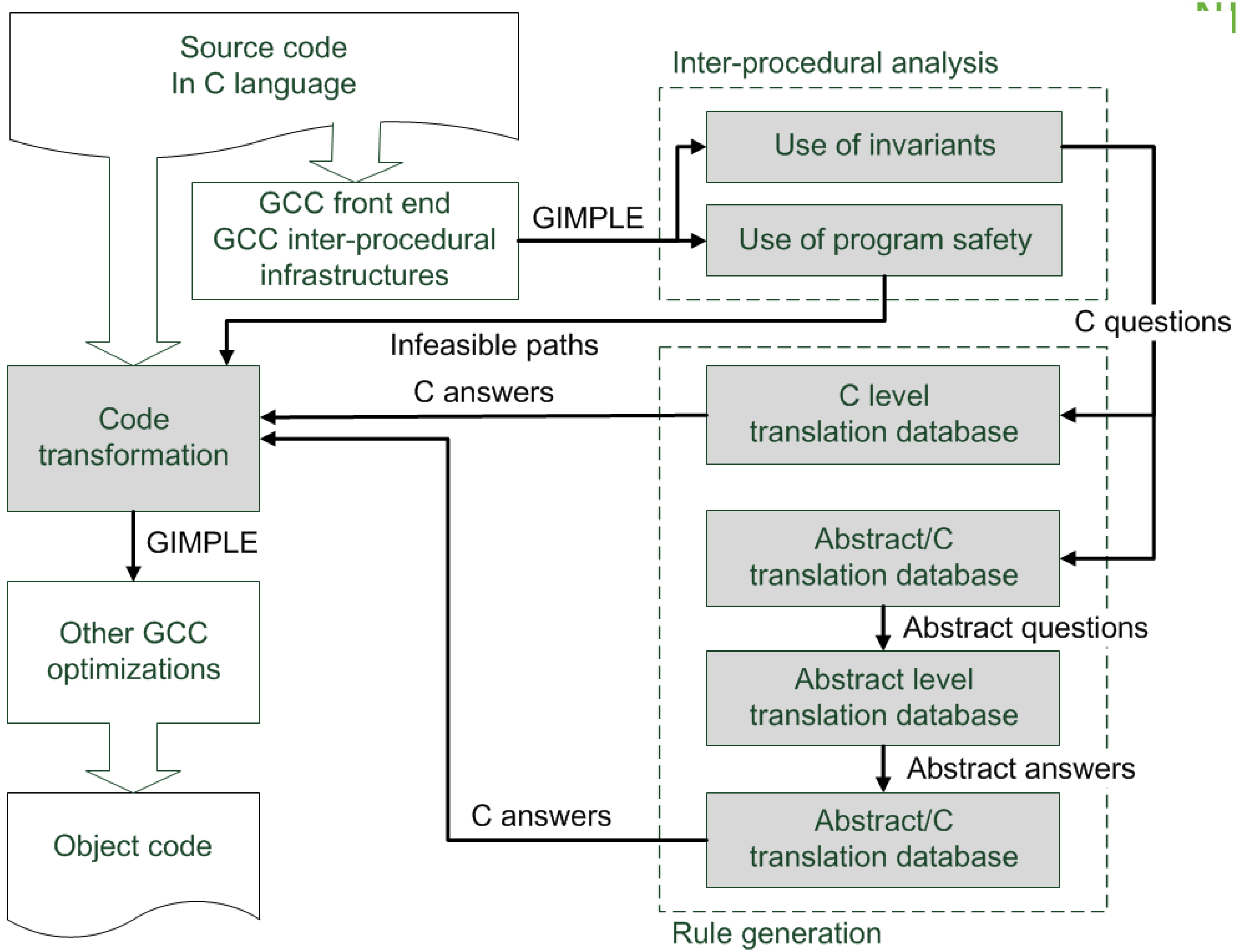
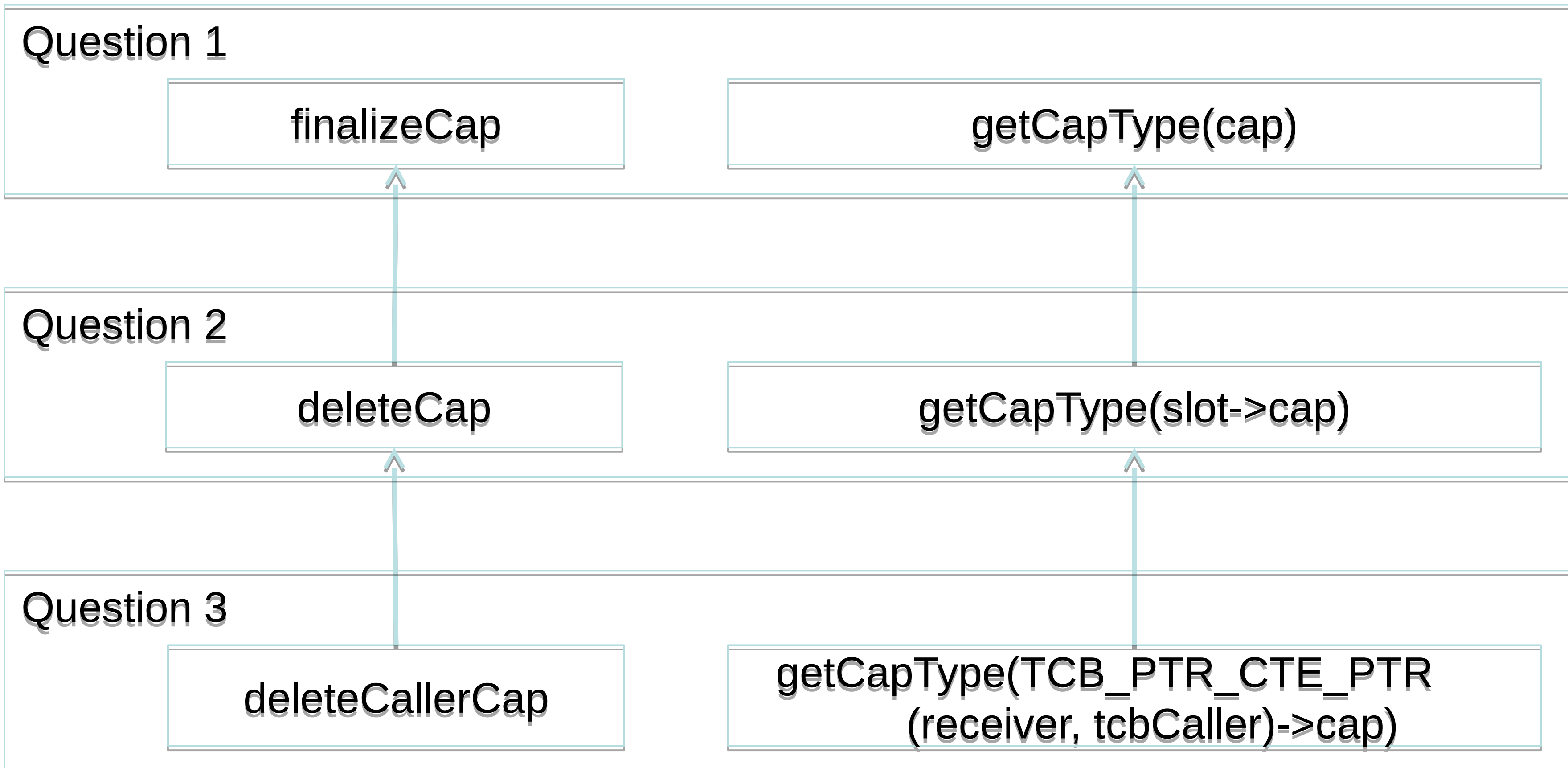
Overview



NICTA Copyright 2012 From imagination to impact

Approach I: Use of Invariants



Approach I: Use of Invariants

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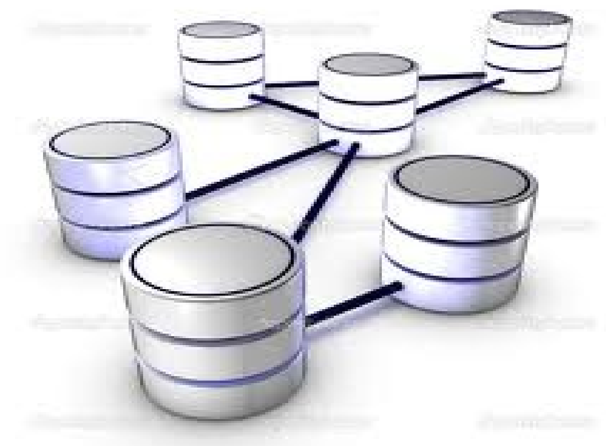
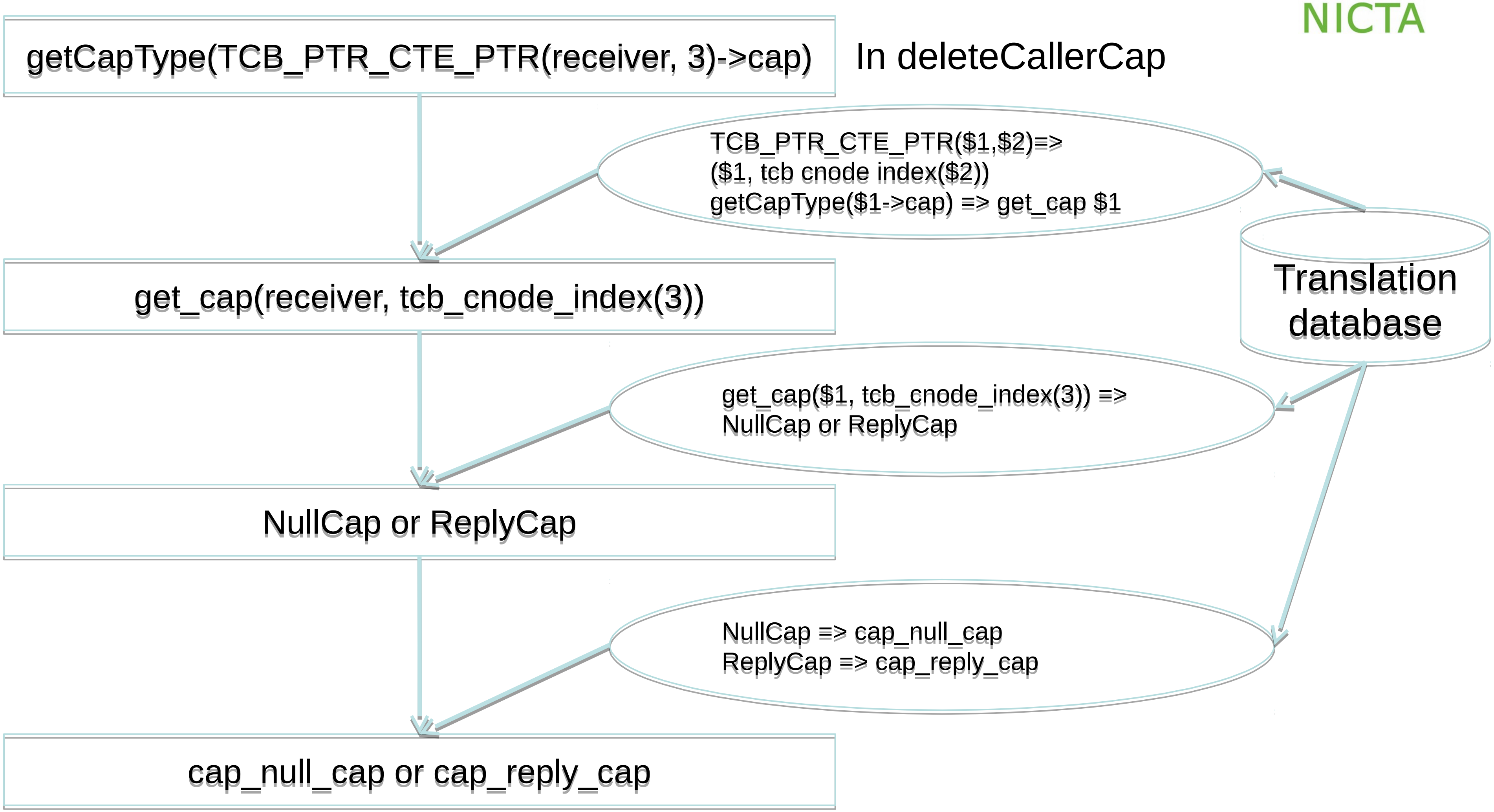
- Accumulated translation database
  - C=>C
  - C=>abstract, abstract=>abstract, abstract=>C
- Input by manual
  - 125 rules / 1540 answers
  - Many questions are similar with different contexts



Approach I: Use of Invariants

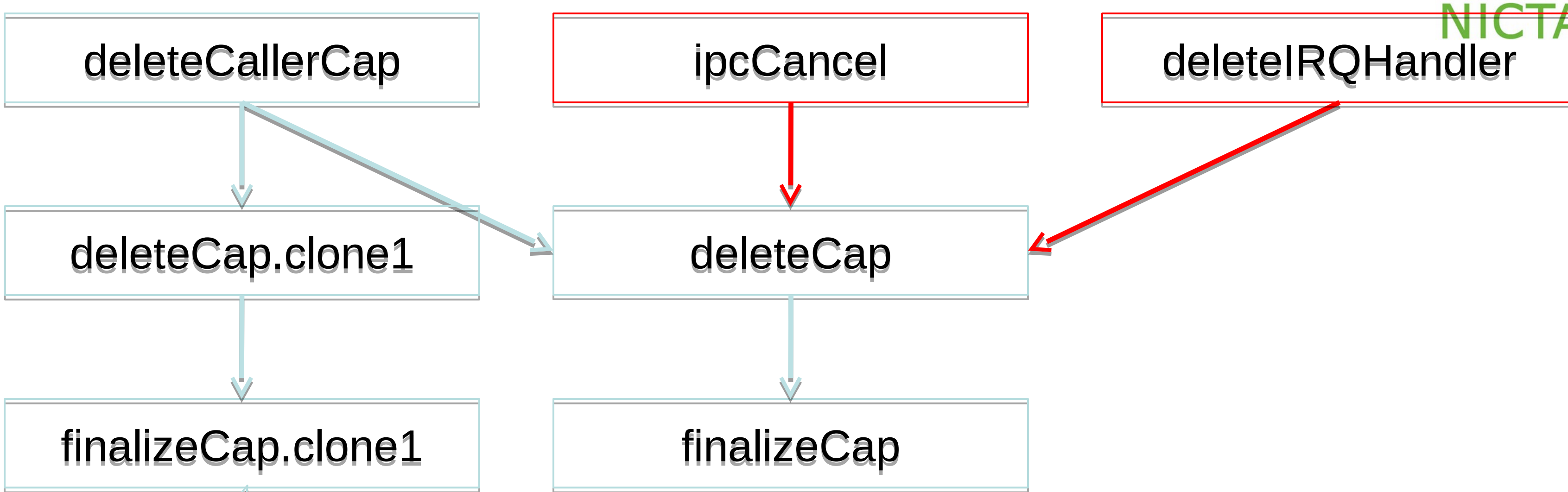


getCapType(cap) in finalizeCap is indirectly answered!

Approach II: Use of Program Safety

- Find a static “buggy” path
- This “buggy” path must be infeasible due to the bug-free program
- Pass the the infeasible path to the next stage for further optimizations
- Null-pointer dereference, uninitialized memory read, memory leak…

Optimizations




```
int finalizeCap_clone1 (cap_t cap …) {
    fc_ret.remainder = cap_null_cap_new();
    fc_ret.irq = irqInvalid;
    return fc_ret;
}
```

```
int finalizeCap (cap_t cap …) {
    switch (getCapType(cap)) {
        case cap_reply_cap:
        case cap_null_cap:
            fc_ret.remainder =
cap_null_cap_new();
            fc_ret.irq = irqInvalid;
            return fc_ret;
        case cap_endpoint_cap:
            …
        case cap_async_endpoint_cap:
            …
    }
    …
}
```

Evaluation

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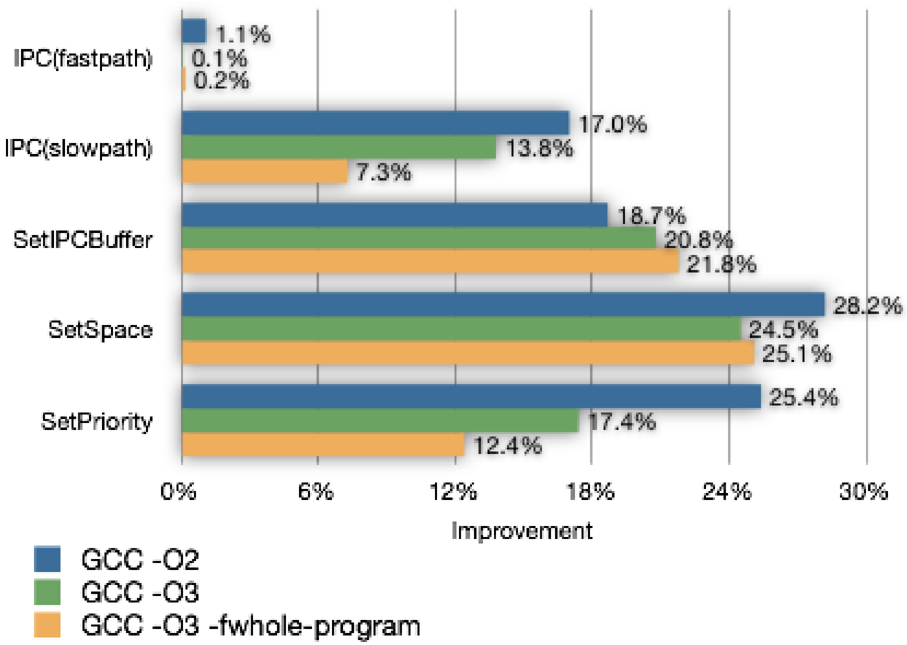
- GCC 4.5.2
  - Cross compiler for ARM on X86
- Target
  - BeagleBoard-xM with TI DM3730
  - 1GHz ARM Cortex-A8
  - 32KB 4-way set-assoc. L1 instruction cache
  - 32KB 4-way set-assoc. L1 data cache
  - 128KB unified L2 cache
- Compilation
  - 2.66GHz Intel Xeon with 10GB memory

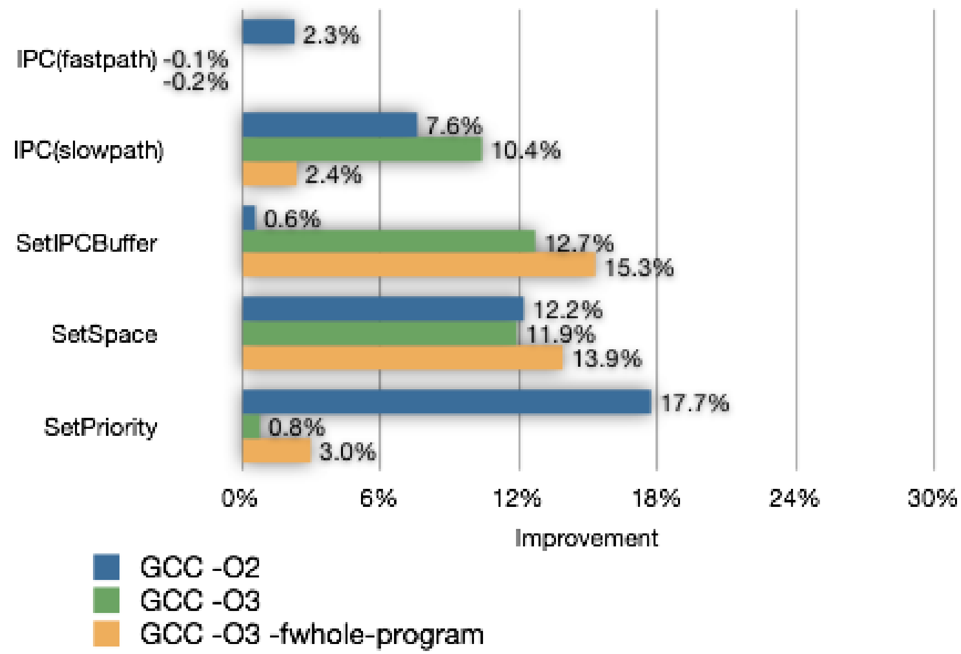
Evaluation

- Summary
  - Line of code: 9,525
  - Functions: 276
  - Total contexts: 217,439
  - C questions: 10,223
  - C answers: 1,540
  - Rules: 125
  - Separated contexts: 4,671

Evaluation



Relative performance of seL4 micro-benchmarks



Relative performance of seL4 micro-benchmarks without invariant-based optimizations

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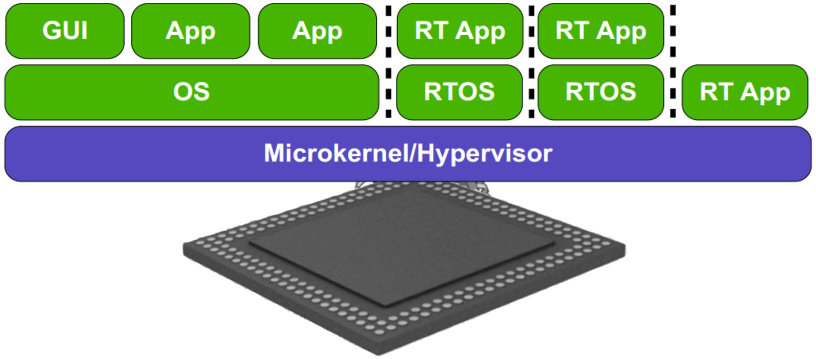
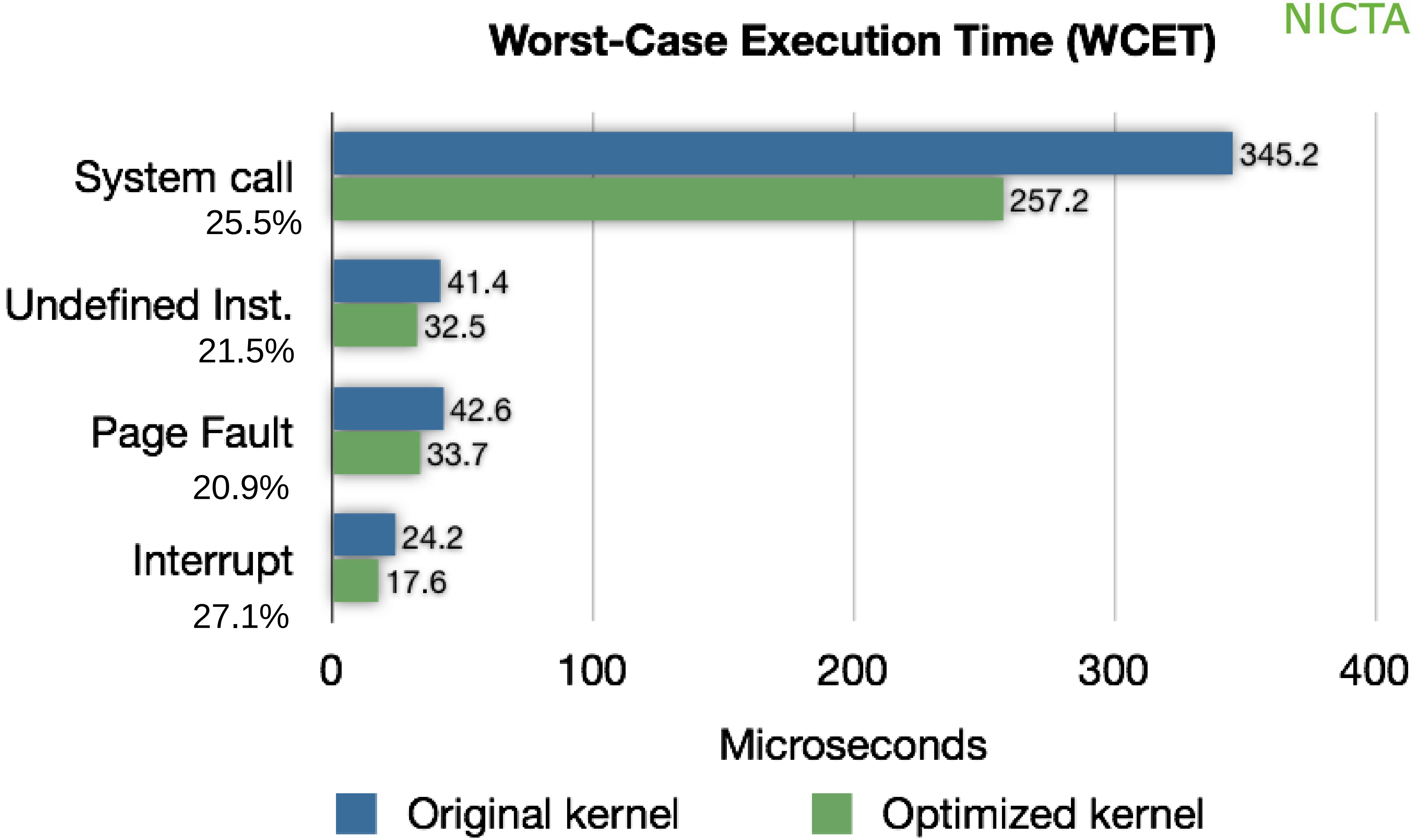
Evaluation

- Virtualized Linux based on seL4
- Performance improvement
  - LMBench 3.0
    - Linux operations: up to 20.8%
    - Context switch: up to 21.2%
    - Communication latency: up to 11.0%
    - Filesystem operations: up to 21.1%
    - Insignificant for bandwidth throughput items
  - tar
    - Single file: 6.4%, batch of files and dirs: 16.0%
  - cp
    - Single file: 6.4%, batch of files and dirs: 12.9%

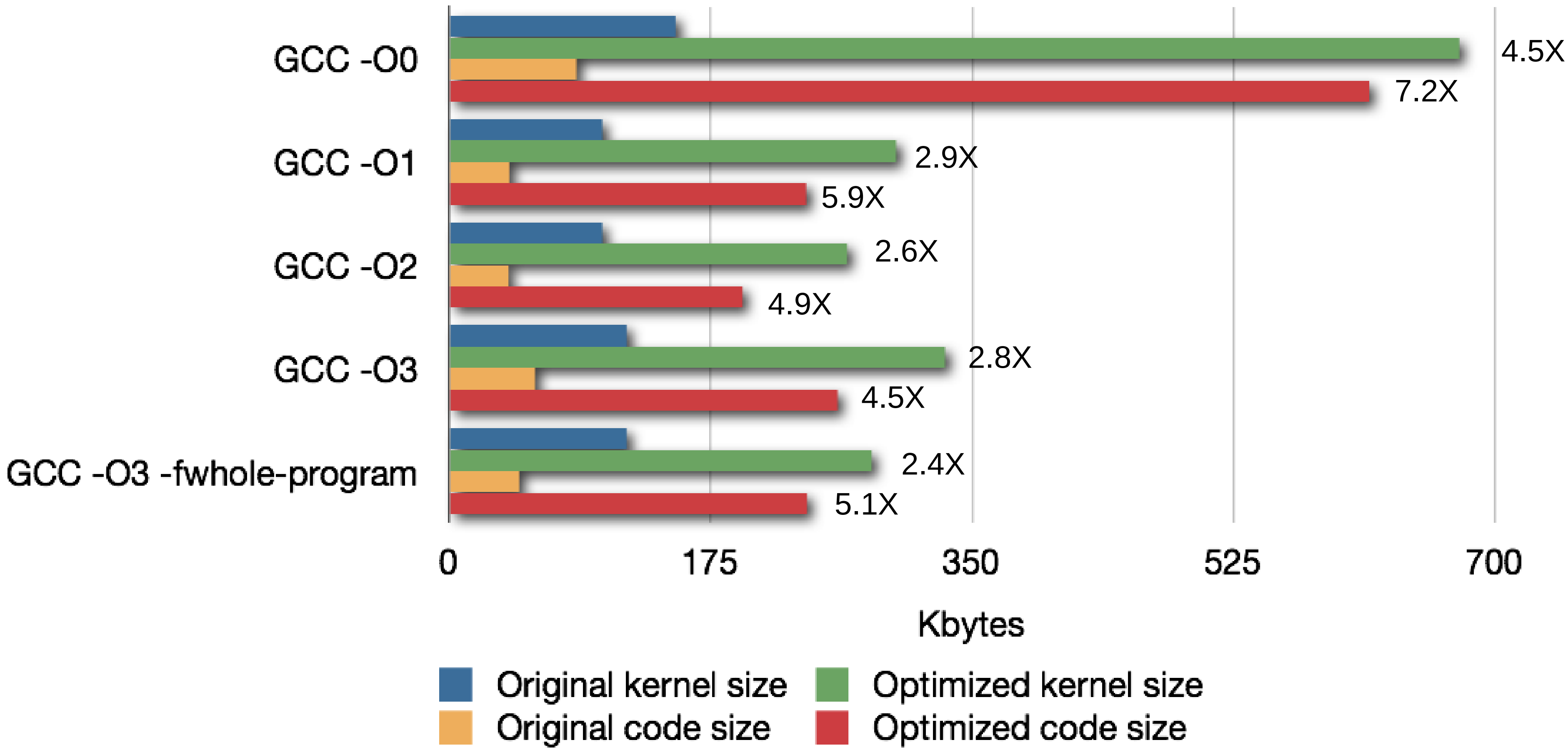


Evaluation



[Blackham et al. Timing analysis of a protected operating system kernel. RTSS'11]

Evaluation



GCC -O0
GCC -O1
GCC -O2
GCC -O3
GCC -O3 -fwhole-program
4.5X
7.2X
2.9X
5.9X
2.6X
4.9X
2.8X
4.5X
2.4X
5.1X
0
175
350
525
700
Kbytes
Original kernel size
Optimized kernel size
Original code size
Optimized code size

Conclusion/Contribution

- First implementation for code optimizations using formal verification
- Optimized a practical micro-kernel, seL4
  - Runtime performance improved by up to 28%
  - Real-world applications on virtualized Linux: 6-16%
  - Reduced worst-case execution time by 25% (IPC)

Thank You!

Q & A