ELISA
Enabling Linux in Safety Applications

WORKSHOP

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Towards Practical Program Verification for the Linux Kernel

Keisuke Nishimura, Jean-Pierre Lozi, Julia Lawall

Outline

- Overview: What is verification?
- Case Study: Applying verification to a small function, is_core_idle()
- Towards practical verification of the Linux kernel

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- Overview: What is verification?
- Case Study: Applying verification to a small function, is_core_idle()
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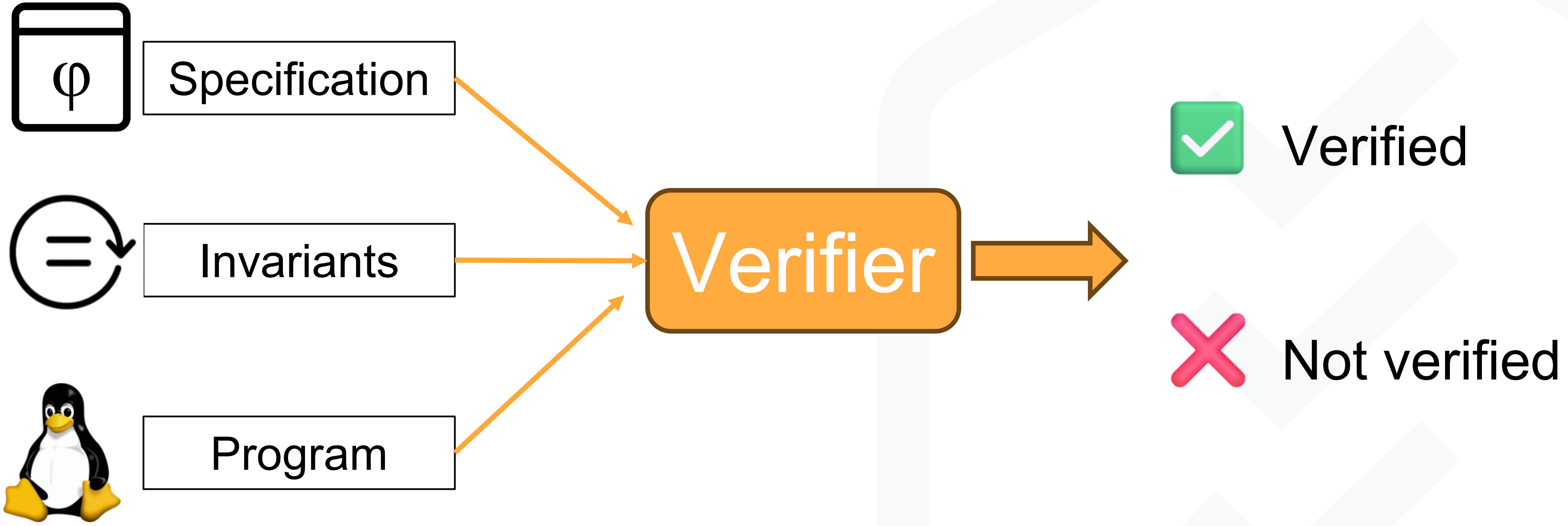
The Linux Kernel

- In theory, the operating system should always run properly.

- In reality, a lot of bugs:
  - Known bug patterns (e.g., NULL dereference)
    - There are many tools to detect them (but there are still many such bugs!)
  - Semantic bugs (e.g., missing privilege checks)
    - These are hard to detect systematically.

Deductive Program Verification: Overview



How Verifiers Work: Hoare Triple

- The verifier decides if a given program is correct.
- A correct program Prog is defined using the Hoare triple:

$$\{ \text{Pre-condition} \}\ \text{Prog}\ \{ \text{Post-condition} \}$$

How Verifiers Work: Hoare Triple

- The verifier decides if a given program is correct.

- A correct program Prog is defined using the Hoare triple:

{ Pre-condition } Prog { Post-condition }

If this pre-condition holds.

How Verifiers Work: Hoare Triple

- The verifier decides if a given program is correct.

- A correct program Prog is defined using the Hoare triple:

{ Pre-condition } Prog { Post-condition }

Then, after the execution of Prog

How Verifiers Work: Hoare Triple

- The verifier decides if a given program is correct.

- A correct program Prog is defined using the Hoare triple:

{ Pre-condition } Prog { Post-condition }

This post-condition holds

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How Verifiers Work: Hoare Triple

- Hoare triple: Example

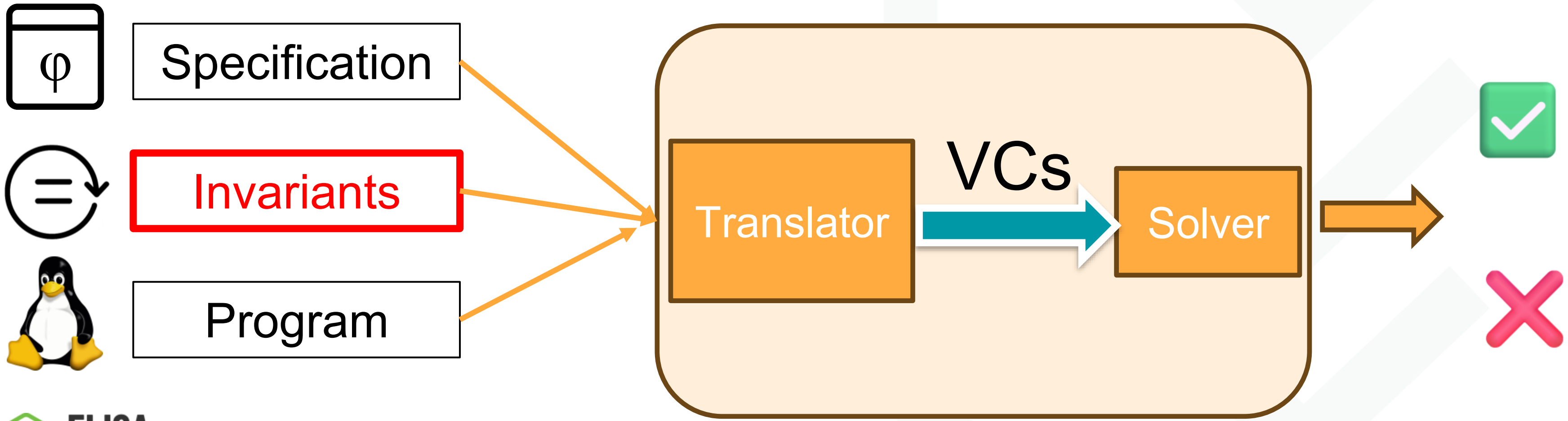
Pre-condition Post-condition

✅ `{ x > 1 } x := x+1 { x > 2 }`

✅ `{ x > 1 } x := x+1 { x > -10 }`

From Hoare Triple to Verification

- Verifiers translate a program and specifications to logical formulas:
  - If and only if the logical formulas hold (are satisfiable), the program is correct.
  - Such logical formulas are called verification conditions (VCs).



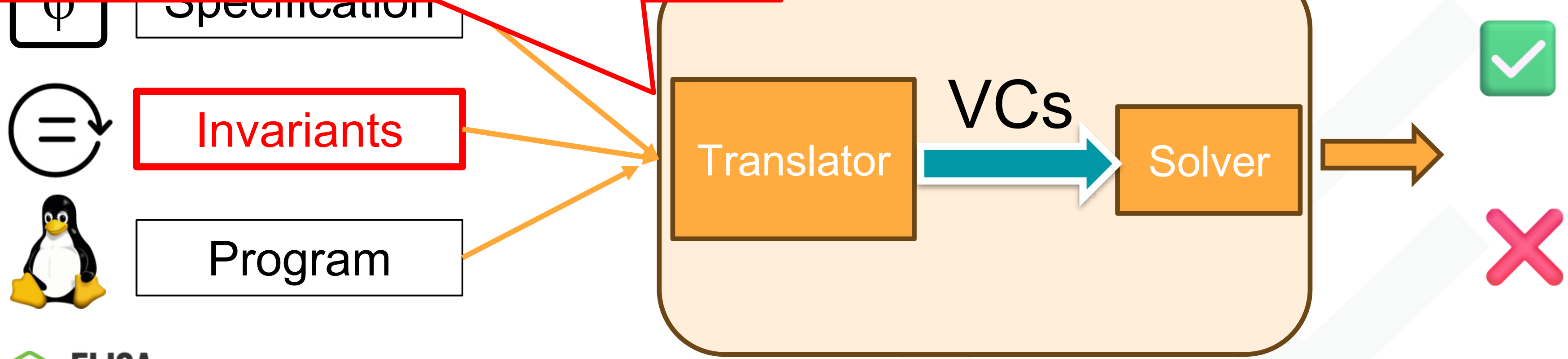
From Hoare Triple to Verification

Point 1: To generate VCs, the loops need to be annotated with invariants.

d specifications to logical formulas:

ld (are satisfiable), the program is correct.

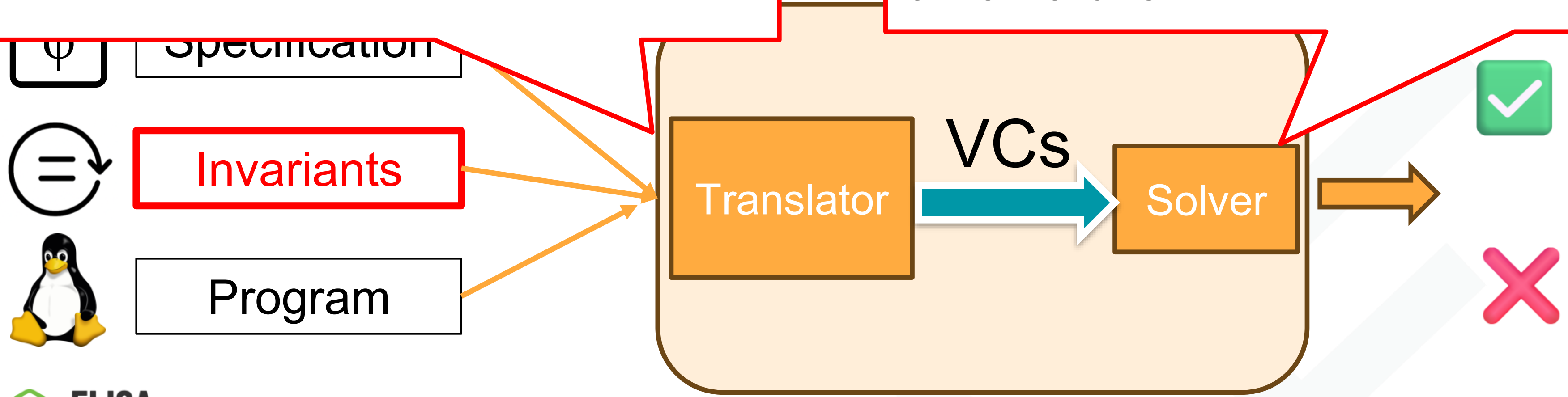
rification conditions (VCs).



From Hoare Triple to Verification

Point 1: To generate VCs, the loops need to be annotated with invariants.

Point 2: Some options to discharge VCs are available.



Generating Verification Conditions

```
{ x > 10 }

x = x + 1

{ x > 0 }
```

Idea: Finding the weakest preconditions by reasoning in the backward direction

The weakest preconditions: `x > -1`

VC: `x > -1` $\Rightarrow$ `x > 10`

Weakest Precondition   Given Precondition

Generating Verification Conditions

```
{ x > 10 }

  while(c)
    loop-body

{ x > 0 }
```

~~Idea: Finding the weakest preconditions by reasoning in the backward direction~~

How many iterations?

Does it terminate?

In general, automatically finding such conditions is impossible.

Manual Annotation for Loop Invariants

- With specifications, loop invariants also need to be specified.
- The loop invariants holds at both the beginning and the end of a loop

```
{ Precondition }
    while(c)
        { Invariant }
        loop-body
        { Invariant }
{ Postcondition }
```

One needs to find conditions that hold before and after the body.

VCs

$$\text{Precondition} \Rightarrow \text{Invariant}$$

$$\text{Invariant} \;\&\&\; !c \Rightarrow \text{Postcondition}$$

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Manual Annotation for Loop Invariants

- With specifications, loop invariants also need to be specified.
- The loop invariants holds at both the beginning and the end of a loop

```
i = 0;
while (i<=10) {
      a[i] = 0;
      i++;
}
```

```
∀j, 0 <= j < i ⇒ a[j] == 0
&&
0 <= i <= 10
```

```
∀j, 0 <= j < i ⇒ a[j] == 0
&&
0 <= i <= 10
```

Manual Annotation for Loop Invariants

- Writing invariants for every loops in a function to be verified can be a major stumbling block in verification.

- For practical verification of the Linux kernel, some degree of automation is needed and doable; we will see it later.

Handling Verification Conditions

- How to discharge verification conditions?

Example

$$\forall j,\ 0 <= j < i \Rightarrow a[j] == 0$$
$$\&\&$$
$$0 <= i <= 10$$

- Options:
  - Pen & paper proof
  - Manually writing proof in interactive theorem provers.
  - Automatically discharging VCs using SMT solvers.

Handling Verification Conditions

- How to discharge verification conditions?

Example

```
∀j, 0 <= j < i ⇒ a[j] == 0
            &&
      0 <= i <= 10
```

😊 Flexibility
😞 Needs expertise and effort.

- Options:
  - ~~Pen & paper proof~~
  - Manually writing proof in interactive theorem provers.
  - Automatically discharging VCs using SMT solvers.

Handling Verification Conditions

- How to discharge verification conditions?

Example

```
∀j, 0 <= j < i ⇒ a[j] == 0
            &&
     0 <= i <= 10
```

- Options:
    - ~~Pen & paper proof~~
    - Manually writing proof in interactive theorem provers.
    - Automatically discharging VCs using SMT solvers.

😊 Automation
😞 No guarantee of success

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Deductive Program Verification: Verifiers

- There are multiple available verifiers for C.
  - Frama-C
  - Verifast
  - CN
  - RefinedC
  - VerifiableC
  - etc.

Design Spaces:

- How to verify Hoare triples (or a similar approach)?
- Utilizing SMT solvers or interactive theorem provers?
- What kind of specifications?
- Maturity?
- …

Deductive Program Verification: Verifiers

- There are multiple available verifiers for C.
  - Frama-C
  - Verifast
  - CN
  - RefinedC
  - VerifiableC
  - etc.

Our research group uses Frama-C:

- Relatively limited support for pointers
- Using SMT solvers
- Expressive specifications

)?
ers?

- What kind of specifications?
- Maturity?
- …

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Outline

- Overview: What is verification?
- Case Study: Applying verification to a small function, is_core_idle()
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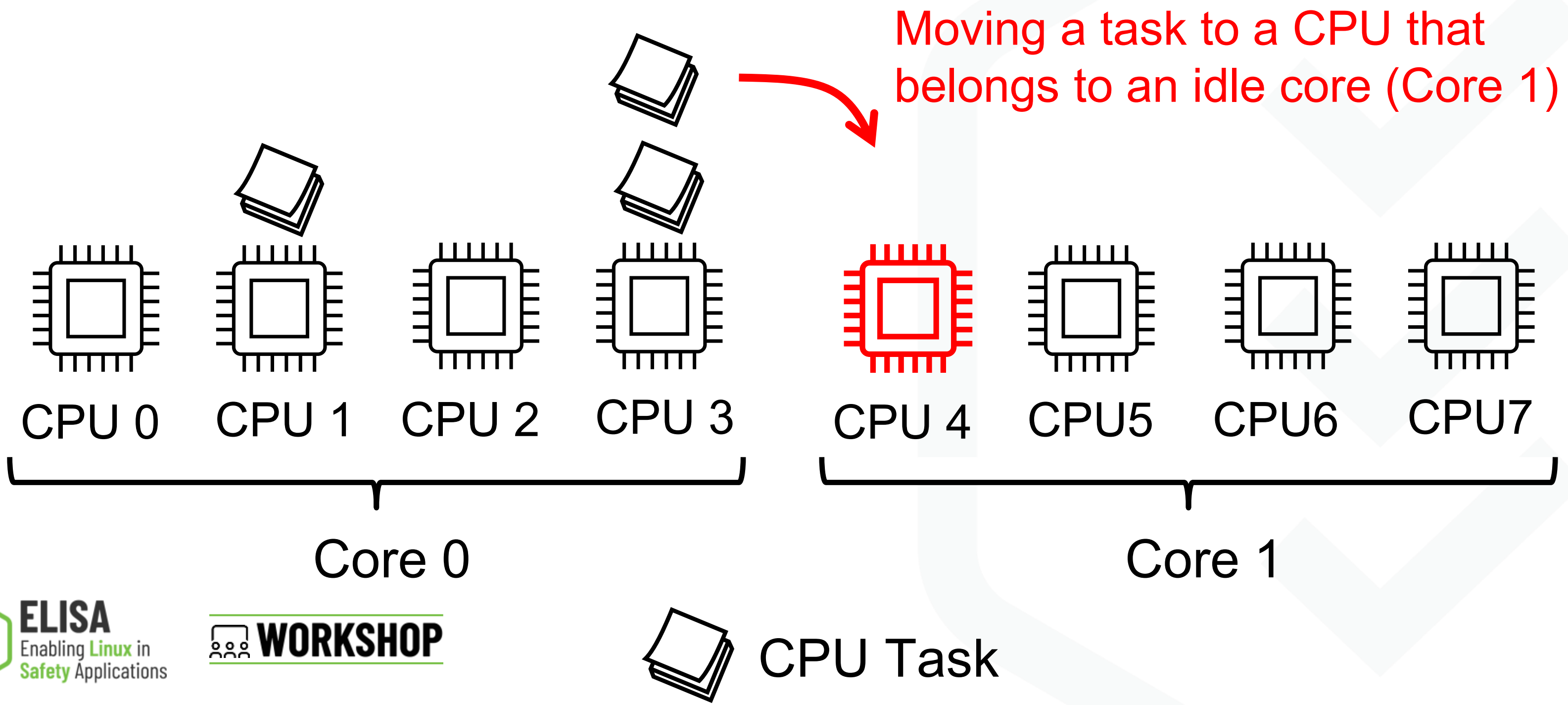
Background: Task Scheduling in the Kernel

- The task scheduler load-balances tasks among CPUs and cores.



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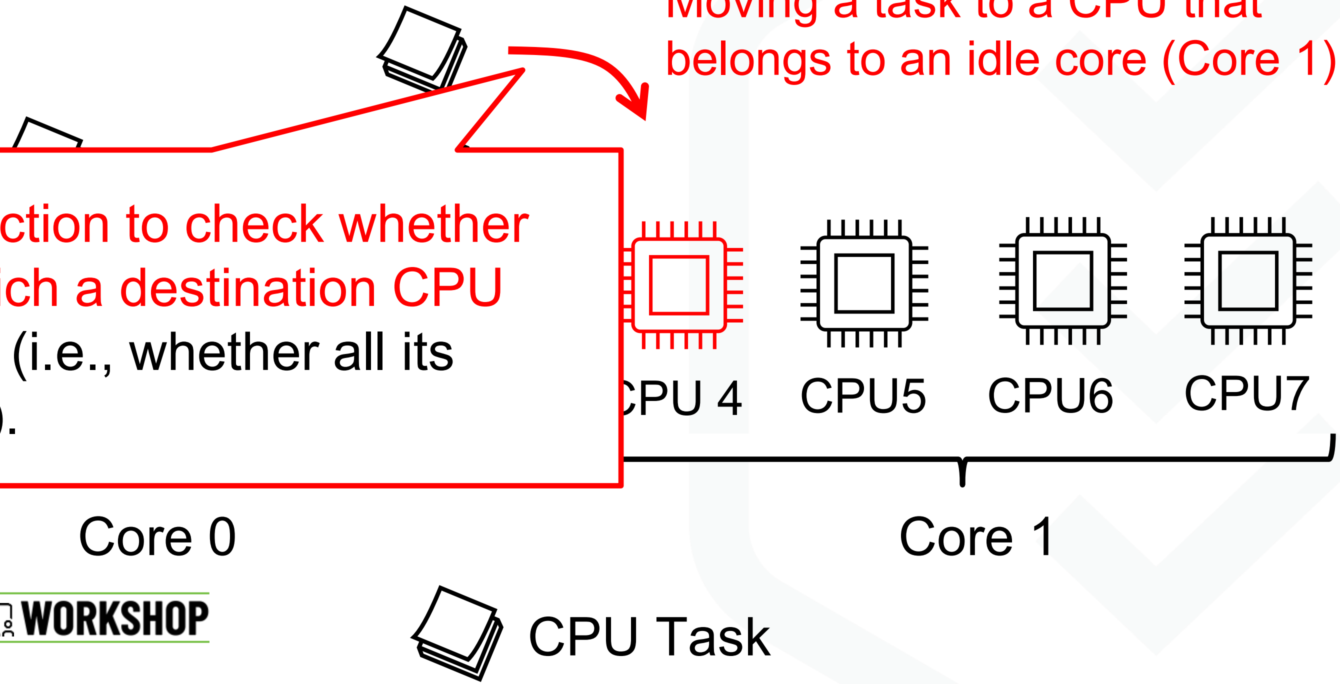
Background: Task Scheduling in the Kernel

- The task scheduler load-balances tasks among CPUs and cores.

Moving a task to a CPU that belongs to an idle core (Core 1)

We want a function to check whether the core to which a destination CPU belongs is idle (i.e., whether all its CPUs are idle).



Example: Verification of is_core_idle()

- We verify the function is_core_idle()
  - A function defined in the task scheduler (kernel/sched/fair.c)
  - A predicate that determines whether the core where the CPU belongs is idle.
    - Input: a CPU ID
    - Output: true iff the core is idle

```c
static inline bool is_core_idle(int cpu)
{
#ifdef CONFIG_SCHED_SMT
	int sibling;

	for_each_cpu(sibling, cpu_smt_mask(cpu)) {
		if (cpu == sibling)
			continue;

		if (!idle_cpu(sibling))
			return false;
	}
#endif

	return true;
}
```

Example: Verification of is_core_idle()

- is_core_idle() checks if all CPUs are idle.
  - This iterates over CPU IDs in a cpumask (a set of CPUs).
  - Once a non-idle CPU is found, it returns false immediately.
  - If all CPUs are idle, it returns true.

```
static inline bool is_core_idle(int cpu)
{
#ifdef CONFIG_SCHED_SMT
	int sibling;

	for_each_cpu(sibling, cpu_smt_mask(cpu)) {
		if (cpu == sibling)
			continue;

		if (!idle_cpu(sibling))
			return false;
	}
#endif

	return true;
}
```

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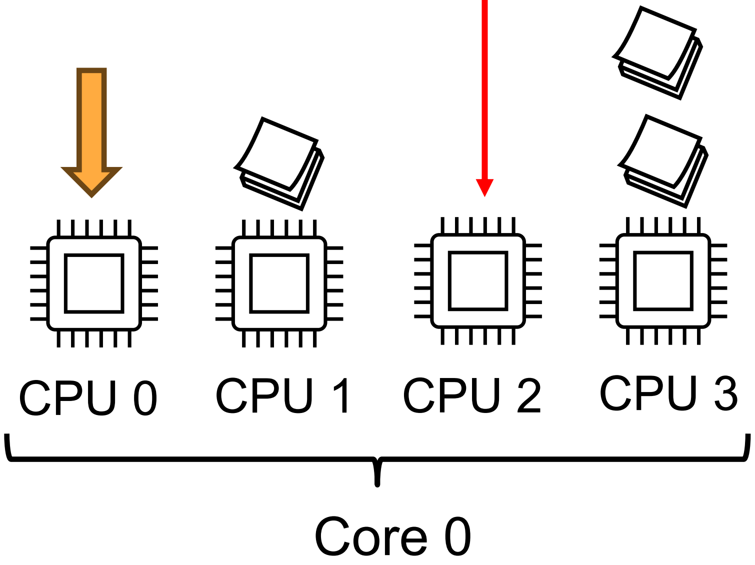
Example: Verification of is_core_idle()

cpu == 2

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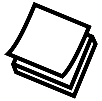
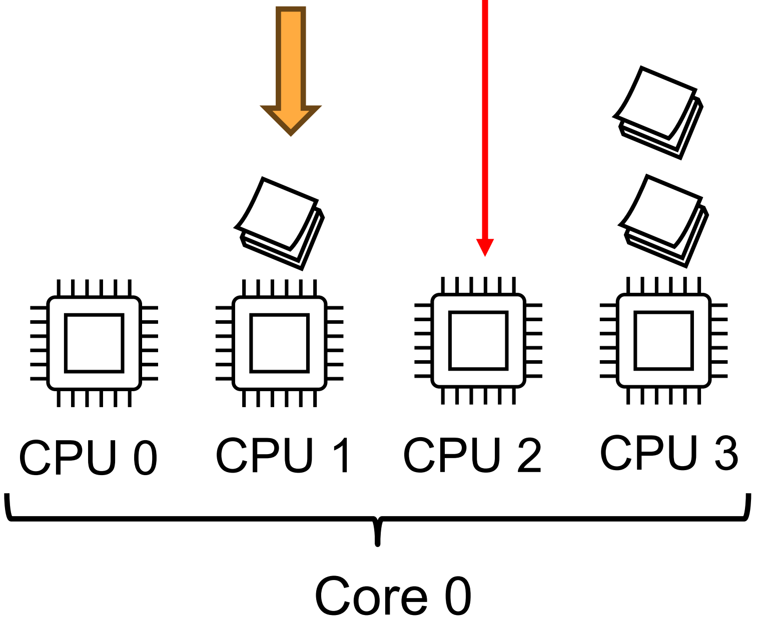
        return true;
}
```


CPU Task

Example: Verification of is_core_idle()

cpu == 2

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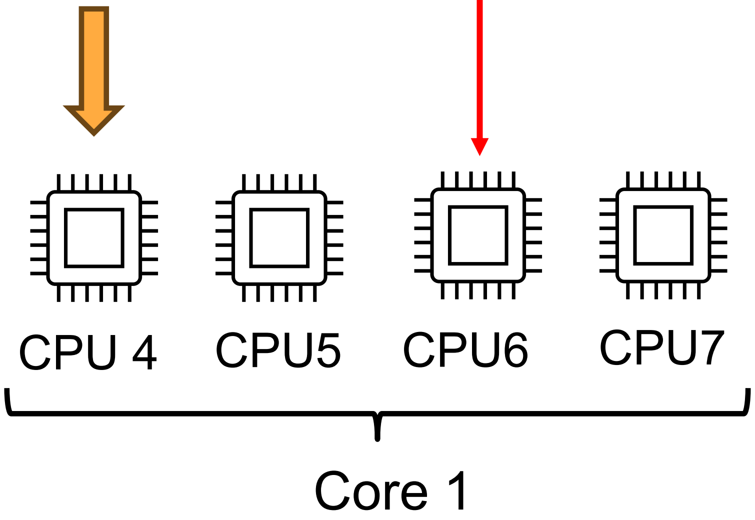
#endif

	return true;
}
```

CPU Task

Example: Verification of is_core_idle()

cpu == 6

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{
#ifdef CONFIG_SCHED_SMT
	int sibling;

	for_each_cpu(sibling, cpu_smt_mask(cpu)) {
		if (cpu == sibling)
			continue;

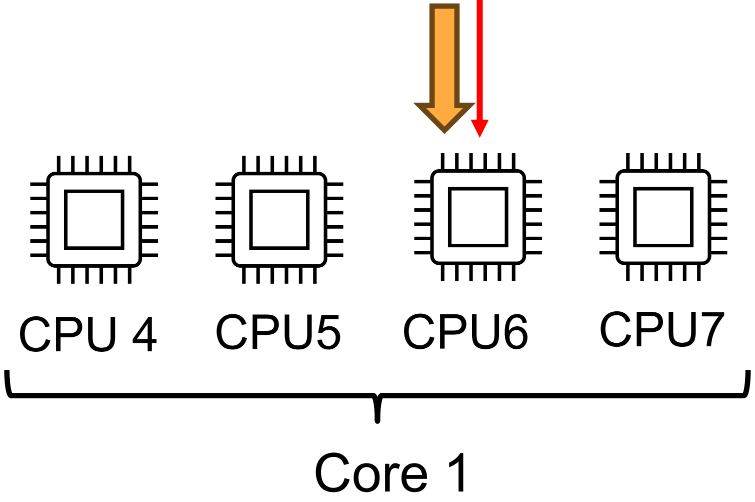
		if (!idle_cpu(sibling))
			return false;
	}
#endif

	return true;
}
```

CPU Task

Example: Verification of is_core_idle()

cpu == 6

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                        return false;
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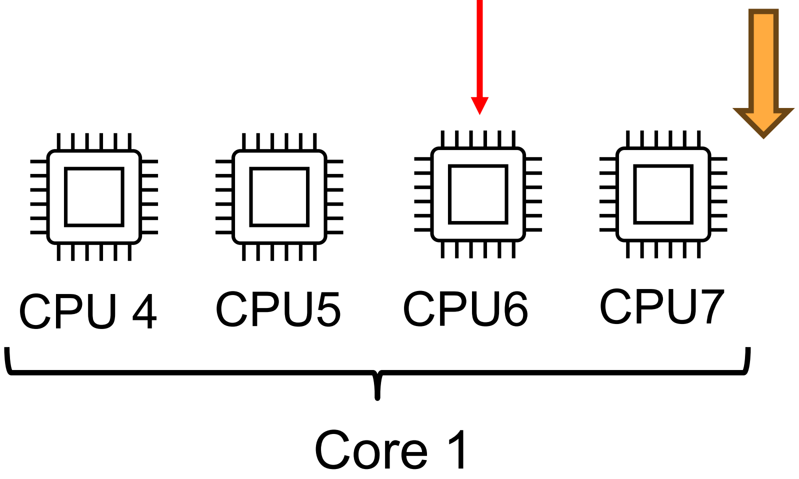
        return true;
}
```

CPU Task

Example: Verification of is_core_idle()

cpu == 6

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                        continue;

                if (!idle_cpu(sibling))
                        return false;
        }
#endif

        return true;
}
```

CPU Task

Example: Verification of is_core_idle()

How can we apply verification in practice?

```
static inline bool is_core_idle(int cpu)
{
#ifdef CONFIG_SCHED_SMT
	int sibling;

	for_each_cpu(sibling, cpu_smt_mask(cpu)) {
		if (cpu == sibling)
			continue;

		if (!idle_cpu(sibling))
			return false;
	}
#endif

	return true;
}
```

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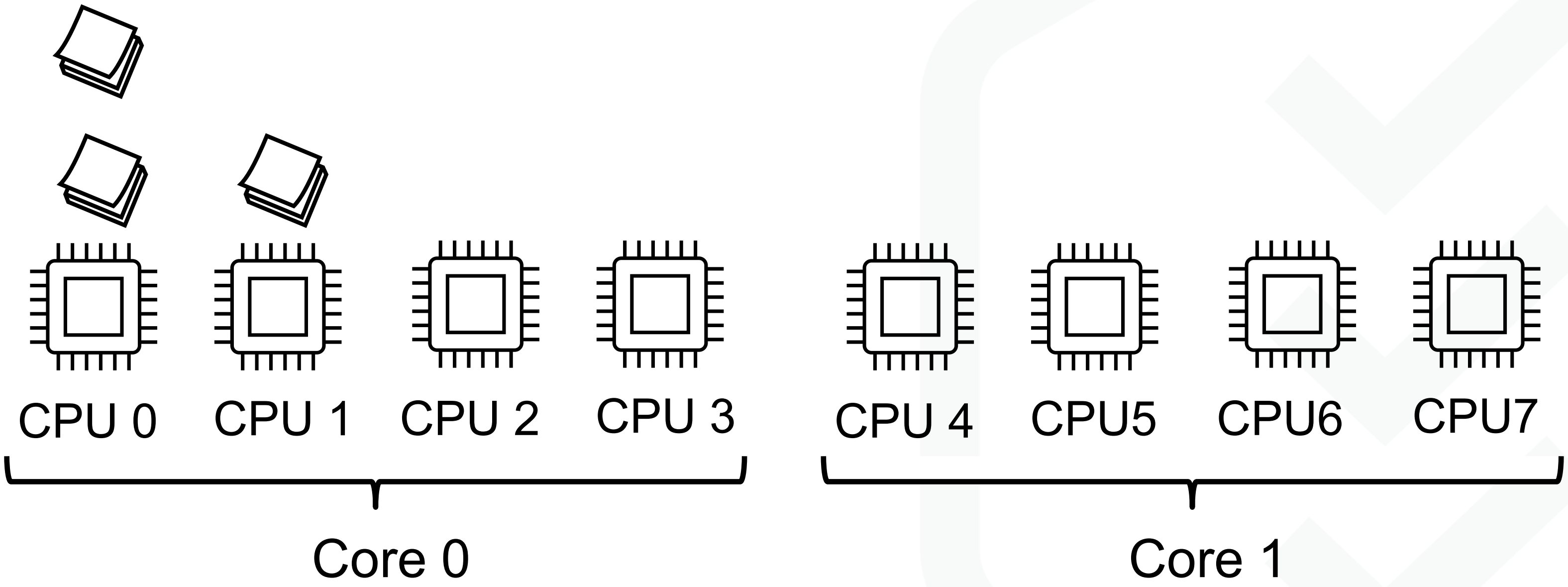
Define Specifications 1/3

The first step: model CPU states

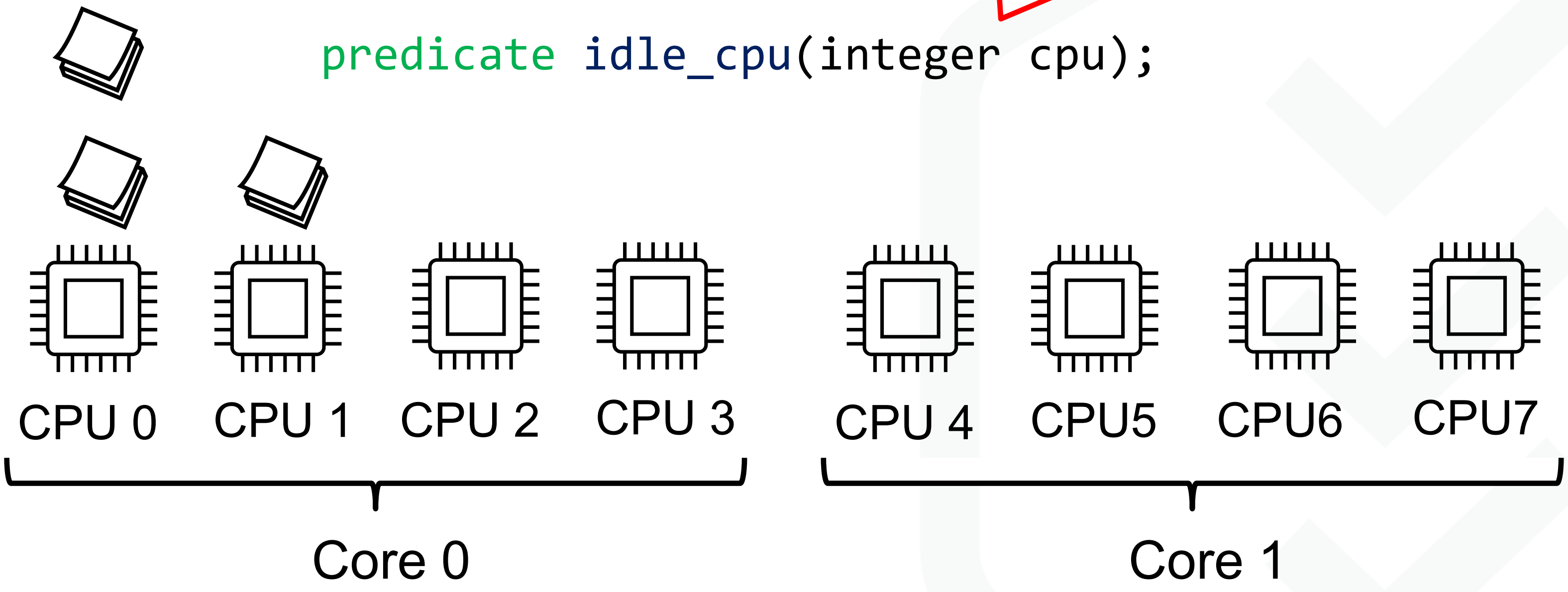


Define Specifications 1/3

Deciding if a CPU is idle.

The first step: model CPU states

```
predicate idle_cpu(integer cpu);
```



Define Specifications 1/3

The first step: model CPU states

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predicate idle_cpu(integer cpu);
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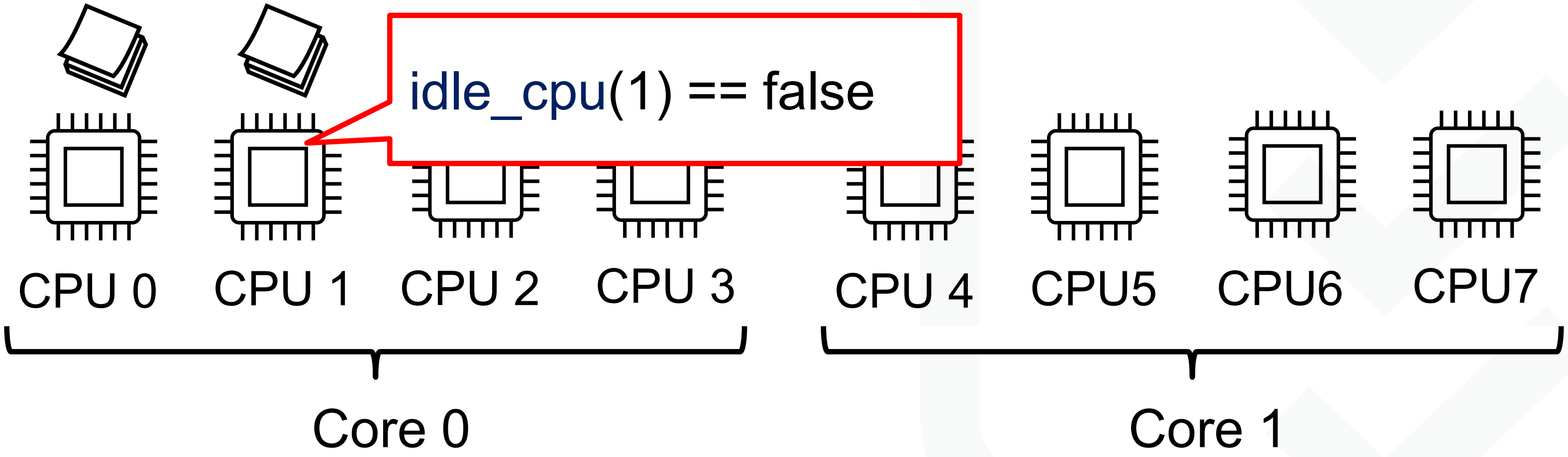
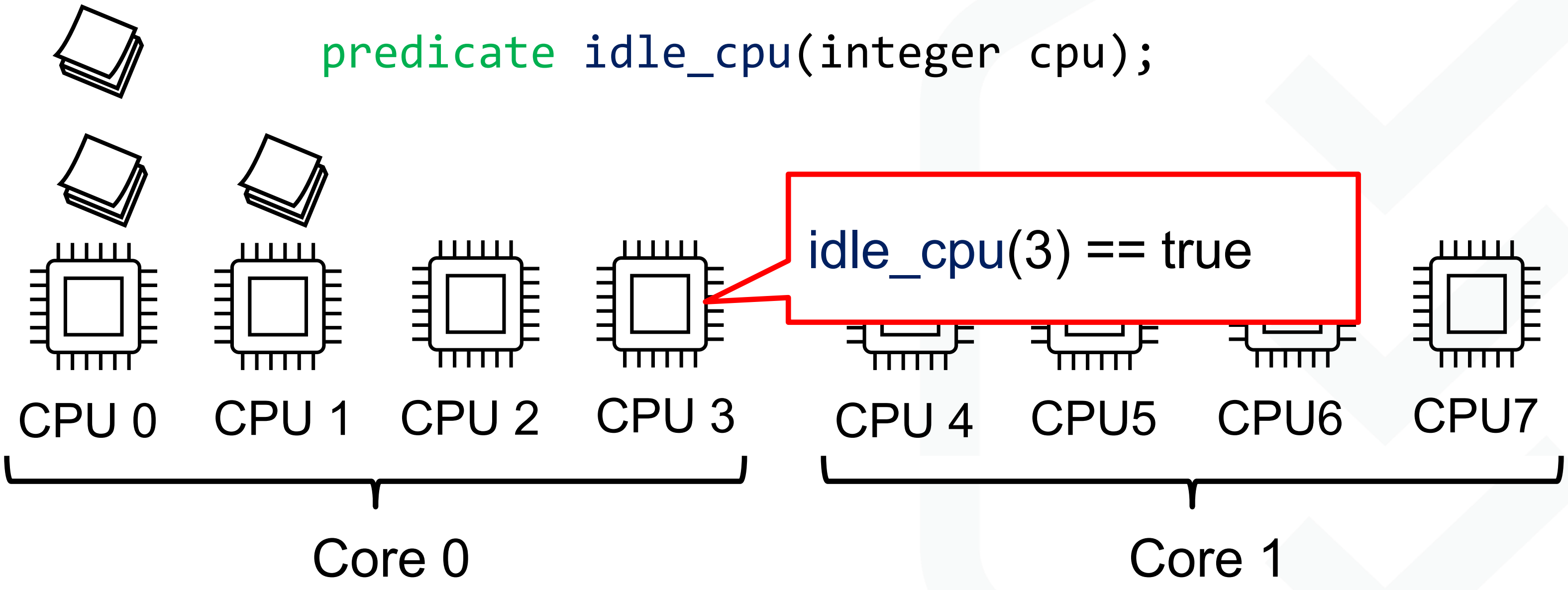


Define Specifications 1/3

The first step: model CPU states

```
predicate idle_cpu(integer cpu);
```



Define Specifications 1/3

Mapping CPU IDs and Cores

The first step: model CPU states

```
logic integer get_core(integer cpu);
```

A function for specifications that returns an integer (Core ID).

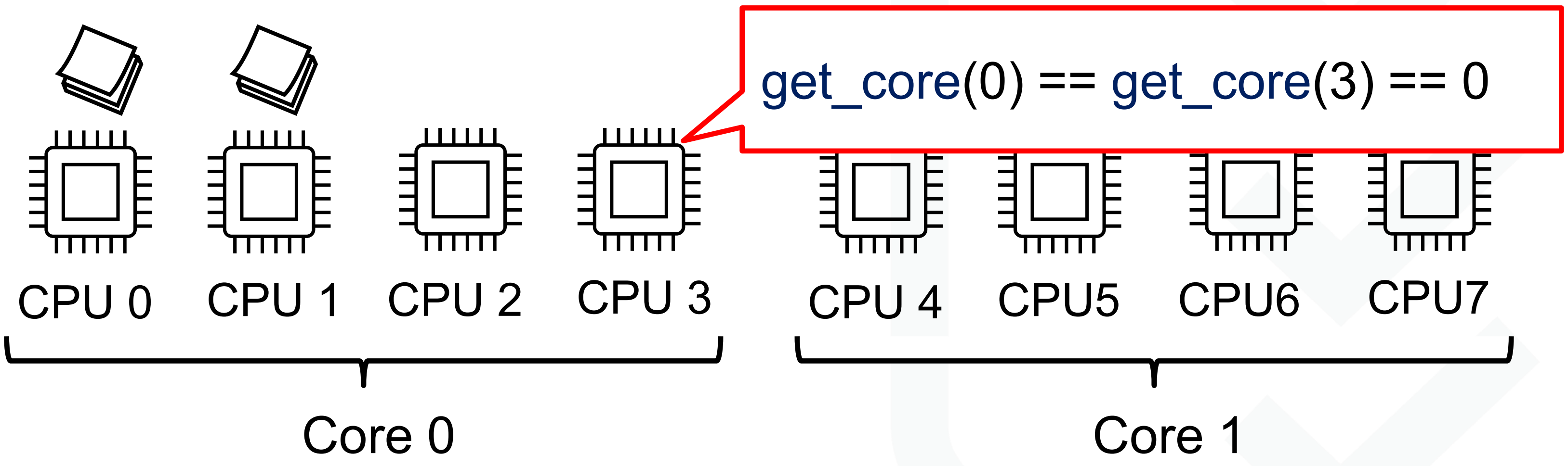
CPU 0 CPU 1 CPU 2 CPU 3 CPU 4 CPU5 CPU6 CPU7

Core 0 Core 1

Define Specifications 1/3

The first step: model CPU states

```
logic integer get_core(integer cpu);
```

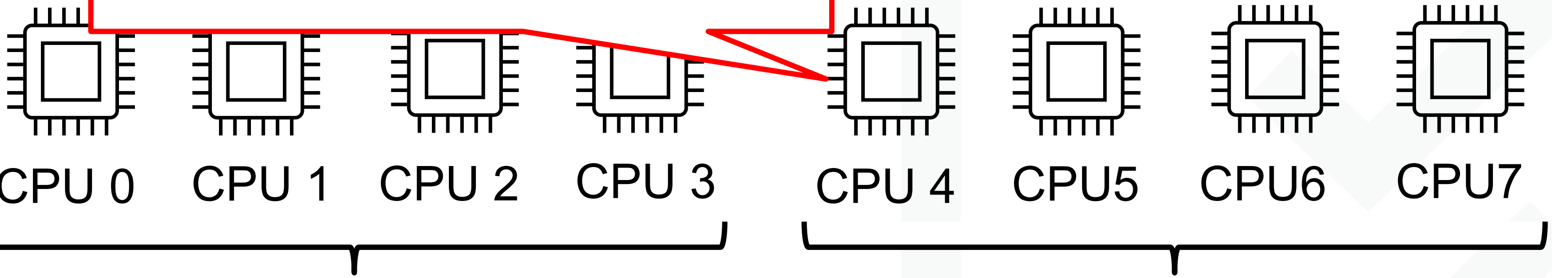


Define Specifications 1/3

The first step: model CPU states

```
logic integer get_core(integer cpu);
```

get_core(0) != get_core(4)



Define Specifications 1/3

The first step: model CPU states

```
axiomatic schedule_cpumask {
  predicate idle_cpu(integer cpu);
  logic integer get_core(integer cpu);

  predicate idle_core(integer cpu) =
    \forall integer i; 0 <= i < NR_CPUS ==>
    get_core(i) == get_core(cpu) ==> idle_cpu(i);
}
```

```
static inline bool is_core_idle(int cpu)
{
#ifdef CONFIG_SCHED_SMT
	int sibling;

	for_each_cpu(sibling, cpu_smt_mask(cpu)) {
		if (cpu == sibling)
			continue;

		if (!idle_cpu(sibling))
			return false;
	}
#endif

	return true;
}
```

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```
static inline bool is_core_idle(int cpu)
{
#ifdef CONFIG_SCHED_SMT
	int sibling;

	for_each_cpu(sibling, cpu_smt_mask(cpu)) {
		if (cpu == sibling)
			continue;

		if (!idle_cpu(sibling))
			return false;

	true;
```

Define Specifications 1/3

The first step: model CPU states

```
axiomatic sc
  predicate i
  logic integ

  predicate idle_core(integer cpu) =
    \forall integer i; 0 <= i < NR_CPUS ==>
    get_core(i) == get_core(cpu) ==> idle_cpu(i);
}
```

This predicate defines the idleness of a core that a CPU (cpu) belongs to.

Define Specifications 1/3

```c
static inline bool is_core_idle(int cpu)
{
#ifdef CONFIG_SCHED_SMT
	int sibling;

	for_each_cpu(sibling, cpu_smt_mask(cpu)) {
		if (cpu == sibling)
			continue;

		if (!idle_cpu(sibling))
			return false;
	}
#endif

	return true;
}
```

The first step: model CPU states

```
axiomatic schedule_cpumask {
  predicate idle_cpu(integer cpu);
  logic integer get_core(integer cpu);

  predicate idle_core(integer cpu) =
    \forall integer i; 0 <= i < NR_CPUS ==>
    get_core(i) == get_core(cpu) ==> idle_cpu(i);
}
```

If CPU i belongs to the same core...

Define Specifications 1/3

The first step: model CPU states

```
axiomatic schedule_cpumask {
  predicate idle_cpu(integer cpu);
  logic integer get_core(integer cpu);

  predicate idle_core(integer cpu) =
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    get_core(i) == get_core(cpu) ==> idle_cpu(i);
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```

```
static inline bool is_core_idle(int cpu)
{
#ifdef CONFIG_SCHED_SMT
	int sibling;

	for_each_cpu(sibling, cpu_smt_mask(cpu)) {
		if (cpu == sibling)
			continue;

		if (!idle_cpu(sibling))
			return false;
	}
#endif

	return true;
}
```

Such CPUs must be idle

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Define Specifications 2/3

The second step: model the dependencies (the callee functions)

```
/*@
requires 0 <= cpu < NR_CPUS;
assigns \nothing;
ensures \result <==> idle_cpu(cpu);
*/
bool idle_cpu(int cpu);
```

Define Specifications 2/3

The second step: model the dependencies (the callee functions)

```
/*@
requires 0 <= cpu < NR_CPUS;
assigns \nothing;
ensures \result <==> idle_cpu(cpu);
*/
bool idle_cpu(int cpu);
```

“requires” represents the preconditions

“ensures” represents the postconditions

Define Specifications 2/3

The second step: model the dependencies (the callee functions)

```
/*@
requires 0 <= cpu <          s;
assigns \nothing;
ensures \result <==> idle_cpu(cpu);
*/
bool idle_cpu(int cpu);
```

means no side effects.

Define Specifications 2/3

The second step: model the dependencies (the callee functions)

```
/*@
requires 0 <= cpu < NR_CPUS;
assigns \nothing;
ensures \result == cpu_smt_mask(cpu);
ensures cpu_smt_mask(cpu)->bits[cpu];
ensures \forall integer i; 0 <= i < NR_CPUS ==>
  (cpu_smt_mask(cpu)->bits[i] <==> get_core(i) == get_core(cpu));
*/
static inline struct cpumask *cpu_smt_mask(int cpu);
```

Define Specifications 2/3

The second step: model the dependencies (the callee functions)

```
/*@
requires 0 <= cpu < NR_CPU
assigns \nothing;
ensures \result == cpu_sm
ensures cpu_smt_mask(cpu)
ensures \forall integer i
  (cpu_smt_mask(cpu)->bits[i] <=              e(i) == get_core(cpu));
*/
static inline struct cpumask *cpu_smt_mask(int cpu);
```

This function returns a cpumask that represents the CPU set contained in a core, where the CPU *cpu* belongs.

Define Specifications 2/3

The second step: model the dependencies (the callee functions)

```
/*@
requires 0 <= cpu < NR_CPUS;
assigns \nothing;
ensures \result == cpu_smt_mask(cpu);
ensures cpu_smt_mask(cpu)->bits[cpu];
ensures \forall integer i; 0 <= i < NR_CPUS ==>
  (cpu_smt_mask(cpu)->bits[i] <==> get_core(i) == get_core(cpu));
*/
static inline struct cpumask *cpu_smt_mask(int cpu);
```

The CPU *cpu* is included in the cpumask.

Define Specifications 2/3

The second step: model the dependencies (the callee functions)

```
/*@
requires 0 <= cpu < NR_CPUS;
assigns \nothing;
ensures \result == cpu_smt_mask(cpu);
ensures cpu_smt_mask(cpu)->bits[cpu];
ensures \forall integer i; 0 <= i < NR_CPUS ==>
  (cpu_smt_mask(cpu)->bits[i] <==> get_core(i) == get_core(cpu));
*/
static inline struct cpumask *cpu_smt_mask(int cpu);
```

The other CPUs sharing the same core are also included.

Define Specifications 3/3

The third step: model the function behavior.

```
requires 0 <= cpu < NR_CPUS;
requires idle_cpu(cpu);

ensures \result <==> idle_core(cpu);
```

```c
static inline bool is_core_idle(int cpu)
{
#ifdef CONFIG_SCHED_SMT
	int sibling;

	for_each_cpu(sibling, cpu_smt_mask(cpu)) {
		if (cpu == sibling)
			continue;

		if (!idle_cpu(sibling))
			return false;
	}
#endif

	return true;
}
```

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Define Specifications 3/3

The third step: model the function behavior.

```
requires 0 <= cpu < NR_CPUS;
requires idle_cpu(cpu);

ensures \result <==> idle_core(cpu);
```

```c
static inline bool is_core_idle(int cpu)
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		if (cpu == sibling)
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	}
#endif

	return true;
}
```

Applying the Verifier

```
static inline bool is_core_idle(int cpu)
{
#ifdef CONFIG_SCHED_SMT
	int sibling;

	for_each_cpu(sibling, cpu_smt_mask(cpu)) {
		if (cpu == sibling)
			continue;

		if (!idle_cpu(sibling))
			return false;
	}
#endif

	return true;
}
```

Recall: a loop requires its invariants

- Iterates over the CPU IDs in the given core.
- Skips the idleness check for the given CPU that is supposed to be idle.
- Otherwise, it checks the idleness. If it is not idle, return early.

Applying the Verifier

```c
static inline bool is_core_idle(int cpu)
{
#ifdef CONFIG_SCHED_SMT
	int sibling;

	for_each_cpu(sibling, cpu_smt_mask(cpu)) {
		if (cpu == sibling)
			continue;

		if (!idle_cpu(sibling))
			return false;
	}
#endif

	return true;
}
```

```
loop invariant 0 <= sibling <= NR_CPUS;
loop invariant \forall integer j; 0 <= j < sibling ==>
 cpu_smt_mask(cpu)->bits[j] ==> idle_cpu(j);
```

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Applying the Verifier

```c
static inline bool is_core_idle(int cpu)
{
#ifdef CONFIG_SCHED_SMT
	int sibling;

	for_each_cpu(sibling, cpu_smt_mask(cpu)) {
		if (cpu == sibling)
			continue;

		if (!idle_cpu(sibling))
			return false;
	}
#endif

	return true;
}
```

```
loop invariant 0 <= sibling <= NR_CPUS;
loop invariant \forall integer j; 0 <= j < sibling ==>
 cpu_smt_mask(cpu)->bits[j] ==> idle_cpu(j);
```

Some degree of automation is possible?

Outline

- Overview: What is verification?
- Case Study: Applying verification to a small function, is_core_idle()
- Towards practical verification of the Linux kernel

Inferring Loop Invariants for the Kernel

- Adapting to the Linux kernel may allow for a practical solution to infer invariants.
- Insight: there are idiomatic usage patterns in the kernel.
    - In the case of *for_each_cpu()*, there are more than 400 loop instances that perform similar operations to a certain extent.
    - Our current work: automatic invariant inference for specific contexts in the kernel.

```
for_each_cpu(sibling, cpu_smt_mask(cpu)) {
        if (cpu == sibling)
                continue;

        if (!idle_cpu(sibling))
                return false;
}
```

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WORKSHOP

Ideal Verification Workflow for the Kernel

1. Select a function of interest
2. Write a specification
3. Write loop invariants
4. Verify your code

Ideal Verification Workflow for the Kernel

1. Select a function of interest
2. Write a specification

   This is not a simple task…
3. Write loop invariants
4. Verify your code

Preparation of Verifiable Code

- What should an input file of a verifier be?
- One can use the source file by adding spec. directly, but:
  - The file contains a lot of irrelevant code.

```
$frama-c -wp kernel/sched/fair.i
[kernel] Parsing kernel/sched/fair.i (no preprocessing)
[kernel] include/uapi/linux/types.h:17: User Error:
  __int128 is currently unsupported by Frama-C.
[kernel] Frama-C aborted: invalid user input.
```

  - There are many dependencies located in other files.
  - Some dependencies irrelevant to the specifications hinder verification (e.g., pr_info() has side effects and may be semantically irrelevant).

Preparation of Verifiable Code

- Our solution: Automatic preparation of verification code
    - Extracting target functions and dependencies into a minimal but self-contained (compilable) file.
    - Replacing dependencies (types, macros, etc.) with ones suitable for verification based on user-defined instructions.

Preparation of Verifiable Code

- Our solution: Automatic preparation of verification code

- Example: is_core_idle() defined in kernel/sched/fair.c
  - Code Size:
    - fair.c (original code): 13742 lines of code
    - fair.i (macro extended code): 103053 lines of code
    - Our extracted code: 66 lines of code

Preparation of Verifiable Code

- Our solution: Automatic preparation of verification code
- Example
  - Code S
    - fai
    - fai.i (macro e ... lines of code
    - Our extracted code: 66 lines of code

- 9 macros, 4 callees, etc.
- The dependencies are declared/defined across 10 files

Manual preparation is time-consuming and error-prone.

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Other Challenges Towards Practical Usages

- Lack of formalized specifications
  - We do not know the specifications of most functions in the kernel.
  - How strict should specifications be…?

- Limitations of automation (SMT solvers)
  - Even if a program is correct, there is no guarantee that the verification succeeds, especially due to quantifiers (forall and exists).
  - One can guide SMT solvers with hints, but doing so requires expertise.

Summary

- Deductive Program Verification
  - Pre/Post conditions-based specifications
  - Requirement of manual annotation of loop invariants
  - SMT solvers-based automation

- Towards practical applications:
  - Automating the preparation of verification code and inference of loop invariants **(our current work)**
  - Good specifications and better automation

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