Ipanema:
Safe multicore scheduling in a Linux cluster environment

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Work in Progress!
Context: cluster computing

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- Multicore servers with dozens of cores
  - High cost of infrastructure, high energy consumption
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- Linux-based software stack
  - Low (license) cost, yet high reliability
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- Multicore servers with dozens of cores
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- Linux-based software stack
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- Challenge: don’t waste cycles!
  - Reduces infrastructure and energy costs
  - Improves bandwidth and latency
The problem: perf bugs in scheduler

- The Linux scheduler has performance bugs!
- Showed this last year @EuroSys
  « The Linux Scheduler: A Decade of Wasted Cores »
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- Work-conservation invariant not maintained:
  - Idle cores while several threads running on some cores
  - Situation lasts for a long time (several seconds, sometimes forever)
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- Work-conservation invariant not maintained:
  - Idle cores while several threads running on some cores
  - Situation lasts for a long time (several seconds, sometimes forever)

- Consequences:
  - Wasted energy, infrastructure resources, lower bandwidth, higher latency...
  - Lack of predictability: harder to scale-out!
The problem: perf bugs in scheduler

- Work-conservation invariant not maintained: four bugs described in the paper « The Linux Scheduler: A Decade of Wasted Cores »
- Bug 1: problem with the way load is calculated
The problem: perf bugs in scheduler

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- Idea: the scheduler thinks the load is balanced if nodes have same average load
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- Work-conservation invariant not maintained: four bugs described in the paper « The Linux Scheduler: A Decade of Wasted Cores »
- Bug 1: problem with the way load is calculated
  - Idea: the scheduler thinks the load is balanced if nodes have same average load
  - Not necessarily the case!

Load 1 = \( \text{avg}(R \text{ thread with high load} + \text{a few make threads with low load}) \)

Load 2 = \( \text{avg}(\text{many make threads with low load}) \)

Load 1 = Load 2: the scheduler thinks the load is balanced!
The problem: perf bugs in scheduler

- **Work-conservation invariant not maintained**: four bugs described in the paper «The Linux Scheduler: A Decade of Wasted Cores»
- **Bugs 2 & 3**: problem with the way the hierarchy is built
The problem: perf bugs in scheduler

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- **E.g., idea of bug 2:** at the last level (connected nodes), one node in both groups
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- **Bugs 2 & 3**: problem with the way the hierarchy is built

- **E.g., idea of bug 2**: at the last level (connected nodes), one node in both groups

- **Threads on that core never balanced**: load of both groups equal
The problem: perf bugs in scheduler

- Work-conservation invariant not maintained: four bugs described in the paper « The Linux Scheduler: A Decade of Wasted Cores »
- Bug 4: problem with « smart » wakeups
The problem: perf bugs in scheduler

- **Work-conservation invariant not maintained:** four bugs described in the paper « *The Linux Scheduler: A Decade of Wasted Cores* »
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- **Idea of bug 4:** periodic load balancing global, « smart » wakeups on local node
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- **Work-conservation invariant not maintained**: four bugs described in the paper « The Linux Scheduler: A Decade of Wasted Cores »
- **Bug 4**: problem with « smart » wakeups
- **Idea of bug 4**: periodic load balancing global, « smart » wakeups on local node
- **One makes mistakes the other can’t fix!**
Analysis: Linux scheduler too complex!

- Linux used for many classes of applications
  - Cloud hosting, database, n-tier services, HPC...
  - Interactive applications
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- Multicore architectures increasingly diverse and complex!
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- Result: a very complex monolithic scheduler, supposed to work in all situations!
  - Many heuristics interact in complex, unpredictable ways
  - Some features greatly complexify, e.g., load balancing (tasksets, cgroups/autogroups...)
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- Keeps getting worse!
  - E.g., task_struct: 163 fields in Linux 3.0 (07/2011), 215 fields in 4.6 (05/2016)
  - 20,000 lines of C!
Analysis: Linux scheduler too complex!

For instance, `fair.c`:

- **# lines of code**
  - Actual code
  - Comments

- **# functions**
  - Non-static
  - Static

- **# variables**
  - Non-static
  - Static
- **A solution: prove scheduler implementation correct?**
  - Way too much code for current technology
  - We’d need to detect high-level abstractions from low-level C: a challenge!
- **A solution: prove scheduler implementation correct?**
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- **Supposing we managed this feat through hard work...**
  - How do we keep up with updates?
  - The code keeps evolving with new architectures and application needs...
- **A solution:** prove scheduler implementation correct?
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- **Supposing we managed this feat through hard work...**
  - How do we keep up with updates?
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- **Not doable! We need another approach...**
Our solution: Ipanema

- A scheduler is tailored to a (class of) parallel application(s)
  - Specific thread election criterion
    - *E.g., more preemption for more interactive applications...*
  - Specific load balancing criterion
    - *EDF for real-time apps, locality-aware balancing...*
  - Event-based state machine (new, block, unblock, terminate, tick, balance)...

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- Machine partitioned into sets of cores that run ≠ schedulers
- Scheduler deployed together with an application on a partition
1. Implementing scheduling policies must be simple enough to be doable by an application developer (not a Linux kernel expert)
Scientific challenges

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2. Scheduling policies must be proven safe so that they do not hang or crash the kernel
3. Scheduling policies must be proven free of the recently identified performance bugs
1. Implementing **scheduling policies must be simple enough** to be doable by an application developer (not a Linux kernel expert)

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5. The approach **should not introduce a performance penalty**
Challenge 1: ease of implementation

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  - Testing/debugging time-consuming, tedious!
  - Not all stack trace info easily available...

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  - Testing/debugging time-consuming, tedious!
  - Not all stack trace info easily available...
- No clear framework for writing schedulers ⇒ unclear interactions, synchro. issues!
- More issues, e.g., optimizations hinder code maintenance
  - Target-specific implementation of mechanisms ⇒ policy obfuscated!

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Challenge 1: solution

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Solution: capture kernel expertise into a Domain-Specific Language (DSL)!
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DSL: A programming language dedicated to a family of programs that offers specific abstractions and notations.
Challenge 1: solution

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Solution: capture kernel expertise into a Domain-Specific Language (DSL)!

**DSL:** A programming language dedicated to a family of programs that offers specific abstractions and notations.

- Trade expressiveness for expertise/knowledge:
  - **Productivity:** easier and safer programming
  - **Robustness:** (static) verification of properties
  - **Performance:** efficient compilation

Jean-Pierre Lozi
- **Ten years ago: Bossa**

- **Idea:** enrich an existing kernel with a scheduling-specific event interface

- **Framework and rules for developing a scheduler**
- **Ten years ago: Bossa**

  Existing bossa-ified kernel

  Event Interface

  Compiled policy (kernel module)

  DSL policy

  Bossa compiler/verifier

- **Idea:** enrich an existing kernel with a scheduling-specific event interface
- **Framework and rules for developing a scheduler**
- **Used for teaching scheduling**
- **Ten years ago: Bossa**
  
  - **Idea:** enrich an existing kernel with a scheduling-specific event interface
  - Framework and rules for developing a scheduler
  - Used for teaching scheduling
  - Related publications [ASE 2003, EW 2004, HASE 2006]
- **Ten years ago: Bossa**

- **Idea:** enrich an existing kernel with a scheduling-specific event interface
- Framework and rules for developing a scheduler
- Used for teaching scheduling
- Related publications [ASE 2003, EW 2004, HASE 2006]
- **Target:** single-core systems only!
Bossa provides: 1, 2, and 5

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  - Co-design of the proofs with the design of the DSL abstractions
  - Translation into the Leon program verifier
- Abstractions inherited from the Bossa DSL
- Abstractions dedicated to multicore architectures
  - Objective: no explicit synchronization
- Verification of properties
  - Co-design of the proofs with the design of the DSL abstractions
  - Translation into the Leon program verifier
- Properties checked with Leon:
  - Load-balancing is work-conserving (can ensure it on « reasonable » policies)
  - Load is balanced in finite number of rounds of load-balancing (assuming « stable » system)
  - Load-balancing hierarchy is valid:
    - Top level contains all cores
    - No core in two groups at same level
Scientific challenges

Ipanema also provides: 3 and 4

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What’s inherited from Bossa?
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- **Abstractions:**
  - Thread attributes
  - Ordering criteria
  - Thread states
  - Event handlers
  - A few more things (interface functions...)

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What’s inherited from Bossa?

- **Abstractions:**
  - Thread attributes
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  - A few more things (interface functions...)

- **Properties (mandatory):**
  - Termination of events, bounded loops
  - Valid state transitions
  - No loss of a thread
The Ipanema DSL: a very basic example

Process/thread and core-local abstractions:

```cpp
process = {
  int quanta;
  int load;
}

core = {
  processes = {
    RUNNING process current;
    shared READY set<process> ready : order = {lowest quanta};

    BLOCKED set<process> blocked;
    TERMINATED terminated;
  }
  ...
}
```
Process/thread and core-local abstractions:

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Process/thread-local variables.
Number of quanta the process has been running for.
Core-local, process-related variables.

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- **Process/thread-local variables.**
- **Core-local, process-related variables.**
- Number of quanta the process has been running for.
- Process currently running on the core.
- List of processes, ordered by quantum (lazy evaluation), can be accessed by other processes (**shared** keyword).
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**Core-local, process-related variables.**

- Process currently running on the core.
- List of processes, ordered by quantum (lazy evaluation), can be accessed by other processes (shared keyword).
- List of blocked processes (on an I/O, a lock).
- No reference kept (pseudo-state).

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The Ipanema DSL: a very basic example

Process events:

```plaintext
handler (process_event e) {
    on tick {
        e.target.quanta++;
        if (e.target.quanta % 5 == 0) {
            e.target => ready;
        }
    }
    on yield {
        e.target => ready;
    }
    on block {
        e.target => blocked;
    }
    on unblock {
        e.target => ready;
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    on schedule {
        first(ready) => current;
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Handlers for all events regarding a process (or thread).

Context switch (will trigger schedule). Implicit list management.
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- **Handlers for all events regarding a process (or thread).**
- **Context switch (will trigger schedule). Implicit list management.**
- **Uses ready’s ordering criterion.**
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Handlers for all events regarding a process (or thread).
Context switch (will trigger schedule). Implicit list management.
Valid state transitions checked at compile-time.
Uses ready's ordering criterion.
What’s new? Mostly multicore stuff.
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- **Abstractions:**
  - Core attributes
  - Load criteria
  - Groups of cores
  - Core handlers
  - Load balancing functions
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- **Abstractions:**
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- **Performance/synchronization properties:**
  - Locking/synchronization handled by the framework
  - Mostly trylocks: if unable to lock a runqueue, give up on stealing thread (best effort)
  - Ensure no performance bugs
Multicore abstractions:

domain = {
    set<group> groups;
}

group = {
    set<core> cores;
    lazy int load = sum(cores.load);
    int capacity = count(cores);

    lazy bool is_stealable = or(cores.is_stealable);
}
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Scheduling hierarchy: works like in Linux, i.e. tree where at each level a domain contains groups, themselves being domains of lower level.
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**Scheduling hierarchy:** works like in Linux, i.e. tree where at each level a domain contains groups, themselves being domains of lower level.

**Evaluated when value is read (lazy).**

Stealing from this group won’t cause load conservation issues.

**Group stealable iff one of its cores is.**
Core abstractions:

core = {

... 

system int id;
lazy int load = sum(current.load, ready.load);
lazy bool is_stealable = count(current, ready) > 1;
set<domain> scheduling_domains;

domains (core self) to scheduling_domains = {
    foreach (dist in distances starting_at 1) {
        domain (c | distance(c, self) <= dist) to groups = {
            group (c1,c2 | distance(c1, c2) <= dist - 1) to cores;
        }
    }
}

]
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    domains (core self) to scheduling_domains = {
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            domain (c | distance(c, self) <= dist) to groups = {
                group (c1,c2 | distance(c1, c2) <= dist - 1) to cores;
            }
        }
    }
}
```

Obtained from the kernel.

Be work-conserving (basic).
The Ipanema DSL: a very basic example

Core abstractions:

core = {
    ...
    system int id;
    lazy int load = sum(current.load, ready.load);
    lazy bool is_stealable = count(current, ready) > 1;
    set<domain> scheduling_domains;

    domains (core self) to scheduling_domains = {
        foreach (dist in distances starting_at 1) {
            domain (c | distance(c, self) <= dist) to groups = {
                group (c1,c2 | distance(c1, c2) <= dist - 1) to cores;
            }
        }
    }
}

Obtained from the kernel.

Be work-conserving (basic).

Hierarchy-building functions co-designed with proofs: Leon code checks good properties (top domain contains all cores, no core in two groups at the same level...).
Load balancing: who steals whom?

```java
handler (core_event e) {
    on balancing_select {
        foreach (sd in e.target.scheduling_domains) {
            group busiest = max(sd.groups order = { highest load / capacity } filter = { is_stealable });
            if (valid(busiest)) {
                core busiest_core = max(busiest.core order = { highest load } filter = { ready.size >= 1 });
                balancing_steal(e.target, busiest_core);
            }
        }
    }
}
```

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The Ipanema DSL: a very basic example

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}
```

Load-balancing logic similar to Linux (simplified).
The Ipanema DSL: a very basic example

Load balancing: stealing processes

```cpp
try void balancing_steal(core self, core busiest) {
    int imbalance = (busiest.load - self.load) / 2;
    if (imbalance <= 0)
        return;

    foreach (p in busiest.ready) {
        if (imbalance < p.load)
            continue;

        p => self.ready;
        imbalance -= p.load;
        if (imbalance <= 0)
            break;
    }
}
```
Load balancing: stealing processes

```c
try void balancing_steal(core self, core busiest) {
    int imbalance = (busiest.load - self.load) / 2;
    if (imbalance <= 0)
        return;

    foreach (p in busiest.ready) {
        if (imbalance < p.load)
            continue;

        p => self.ready;
        imbalance -= p.load;
        if (imbalance <= 0)
            break;
    }
}
```

Acquires locks automatically and may quietly fail (best effort).
- Makes programming multicore scheduling policies possible for non-kernel experts
Ipanema: to conclude

- Makes programming multicore scheduling policies possible for non-kernel experts
- Ensures safety and performance properties:
  - Valid state transitions, bounded loops, terminating events, no loss of process
  - Work-conservation, eventual balancing, valid hierarchy
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Ipanema: to conclude

- Makes programming multicore scheduling policies possible for non-kernel experts
- Ensures **safety** and **performance properties**:
  - Valid state transitions, bounded loops, terminating events, no loss of process
  - Work-conservation, eventual balancing, valid hierarchy
- **Useful for research, teaching, and real-world scenarios**
- **Current status:**
  - DSL nearly completed, verification of static properties
  - Basic versions of the Ipanema runtime and compiler
  - Manual verifications of multicore properties with Leon
- Makes programming multicore scheduling policies possible for non-kernel experts

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