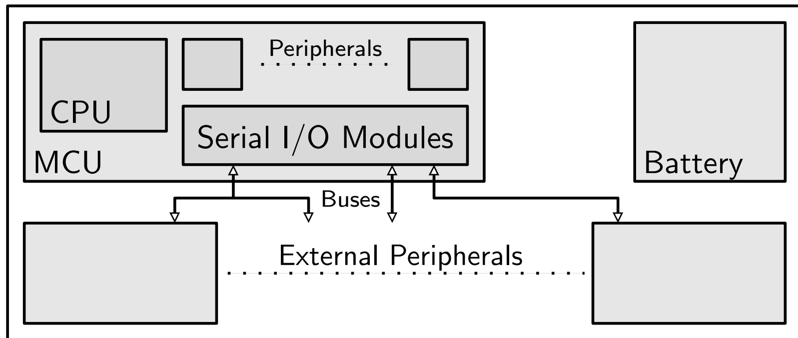
Synchronous Programming of Device Drivers for Global Resource Control in Embedded Operating Systems

Nicolas Berthier   Florence Maraninchi   Laurent Mounier

LCTES 2011 — April 13

The Need for Global Knowledge & Control

Typical Hardware Platform: Wireless Sensor Network Node



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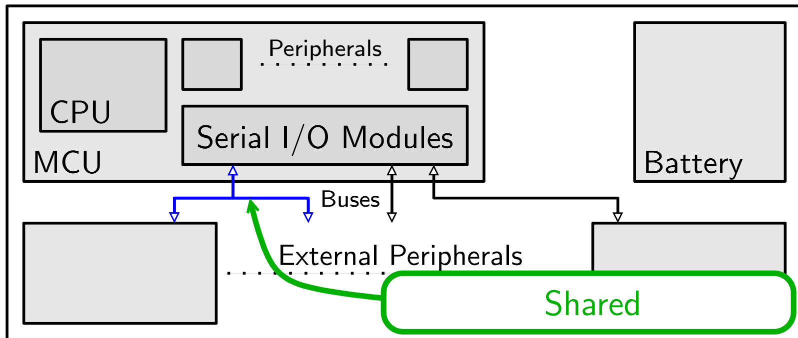

Problems

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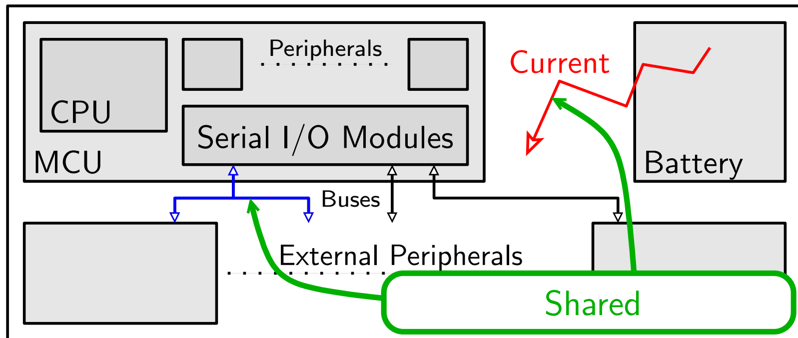
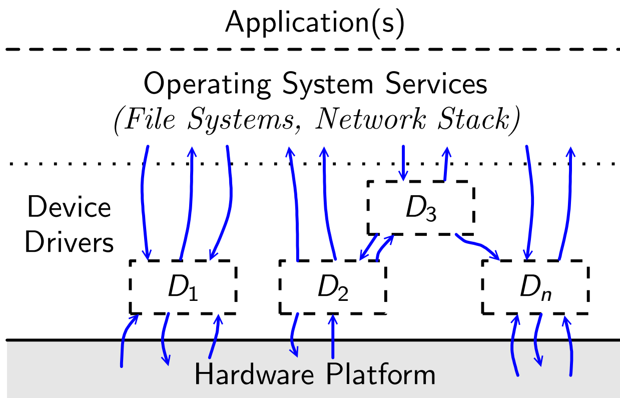


Problems

- Shared Resources (as usual — *e.g.*, Buses)
- Avoiding Consumption Peaks (*e.g.*, How to Forbid a Radio Transceiver and an ADC to be Simultaneously in their Highest Consuming State?)

Usual Programming Practice (with an OS)



- Device Drivers Designed Independently of Each Other

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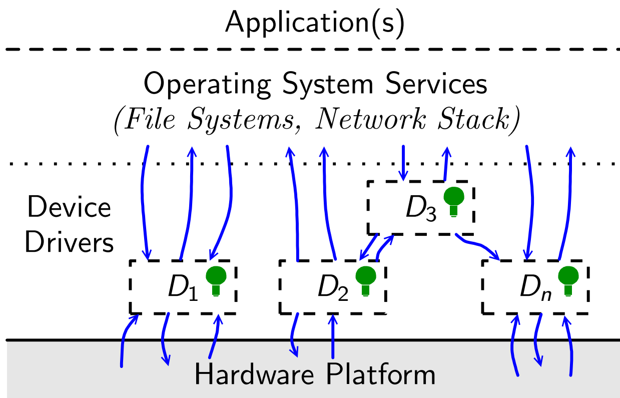

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$\rightsquigarrow$ **Decentralized Knowledge!**

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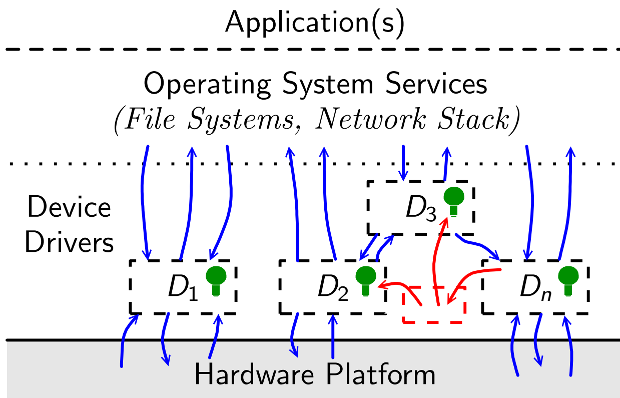

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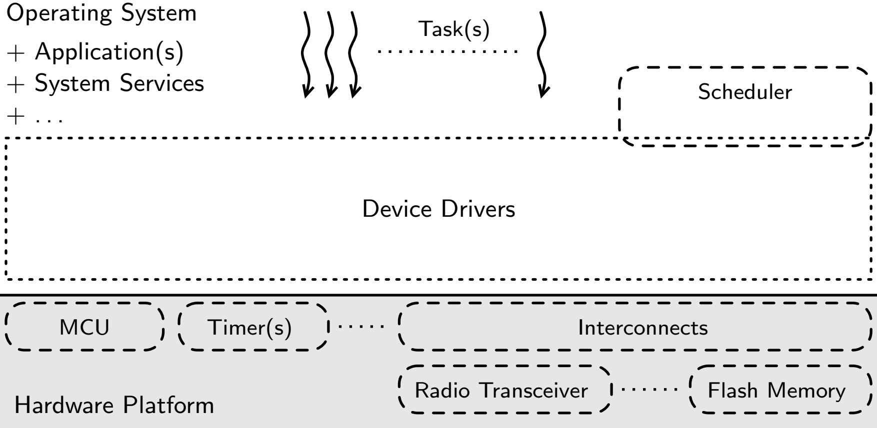
- Ad hoc Solutions for Resource & Power Management

Idea of the Solution



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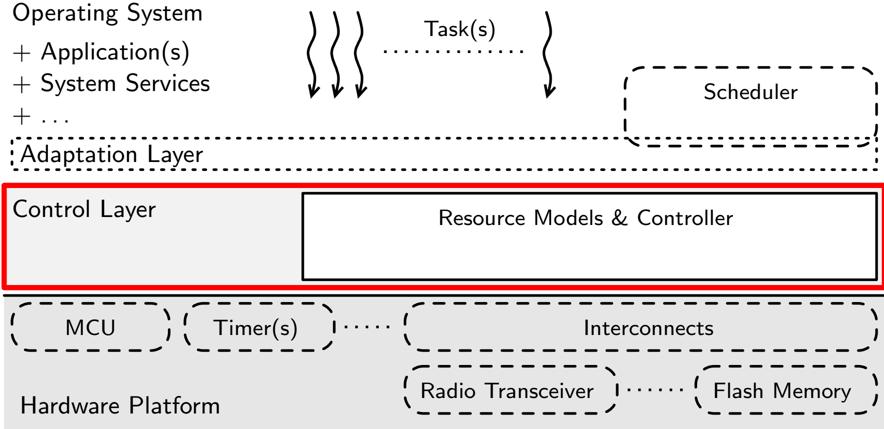

Outline

- Context
- Synchronous Programming in a Nutshell
- Proposal
- Evaluation
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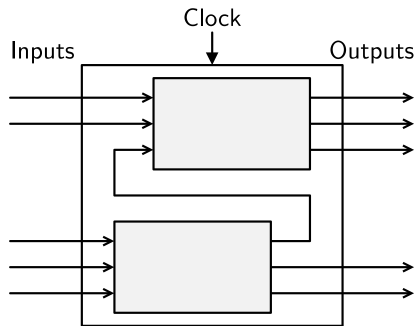
Synchronous Programming in a Nutshell

Program ≈ Synchronous Circuit

- High-level Description of Parallelism
- Compiled into Sequential Code
- Various Programming Styles



Languages

- LUSTRE, ARGOS, ESTEREL ...
- Easy Integration with C Code
  - Import of C Function
  - Export to C Module

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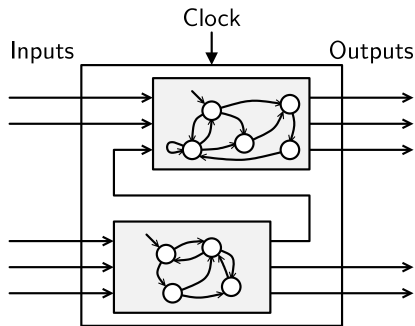

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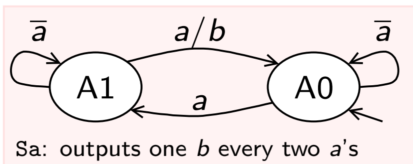
Synchronous Programs as Boolean Mealy Machines

One Boolean Mealy Machine



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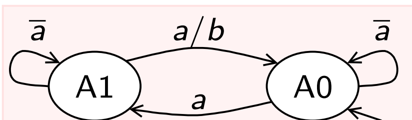
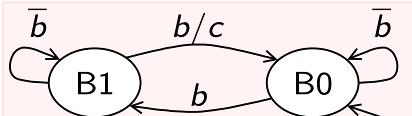
Synchronous Product





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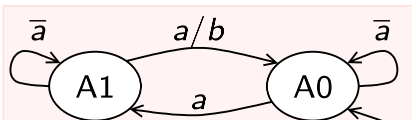
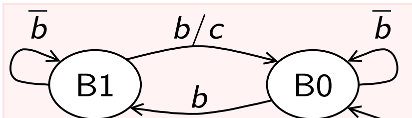
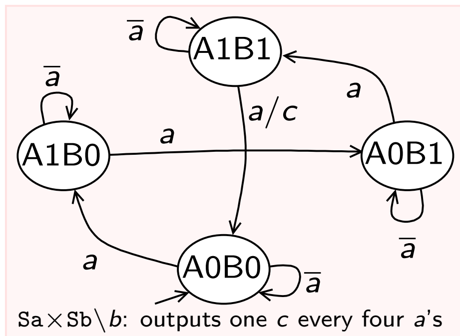
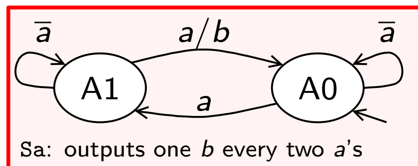


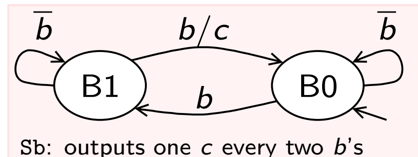


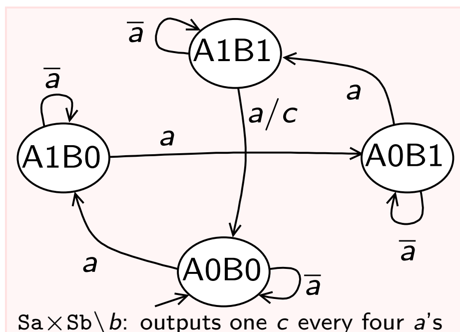


Synchronous Programs as Boolean Mealy Machines

In Lustre



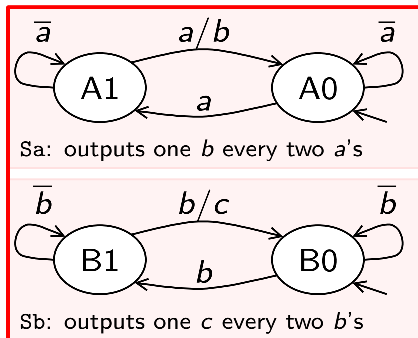


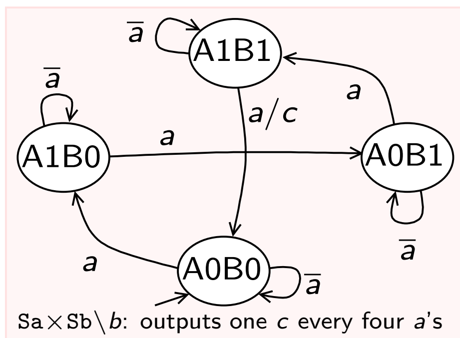



```
node Sa (a: bool) returns (b: bool);
var inA0, inA1, m_A0, A0: bool;
let
  inA1 = not m_A0;      inA0 = m_A0;      b = a and inA1;

  A0 = not a and inA0 or a and inA1; m_A0 = true -> pre A0;

tel;
```

Synchronous Programs as Boolean Mealy Machines

In Lustre






```
node SE (a: bool) returns (c: bool);
var inA0, inA1, m_A0, A0, inB0, inB1, m_B0, B0, b: bool;
let
  inA1 = not m_A0;      inA0 = m_A0;      b = a and inA1;
  inB1 = not m_B0;      inB0 = m_B0;      c = b and inB1;
  A0 = not a and inA0 or a and inA1; m_A0 = true -> pre A0;
  B0 = not b and inB0 or b and inB1; m_B0 = true -> pre B0;
tel;
```

Synchronous Programs as C Code

The Compilation Produces a Reactive Kernel in C

```
bool M1, M2, INIT;              // state variables
void init () { INIT = 1; } // initialization

void run_step (bool a) {
  bool L1, L2, L3, L4, L5, L6;
  L2 = INIT | M1;    L5 = INIT | M2;
  L4 = ~L5 &  a;     L1 = ~L2 &  L4;
  L6 =  L5 & ~a;     L3 =  L2 & ~L4;
  main_O_c (L1);
  M1 = L3 | L1;      M2 = L6 | L4;
  INIT = 0;
}
```

- One Call to `run_step()` = One Transition in the Product

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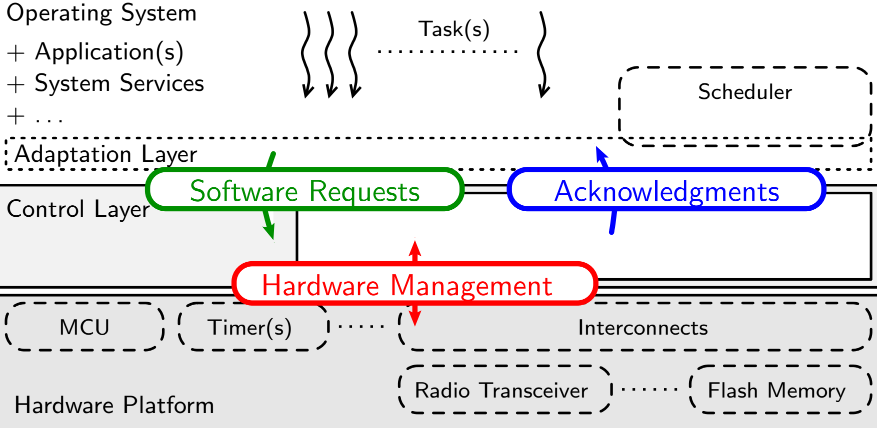
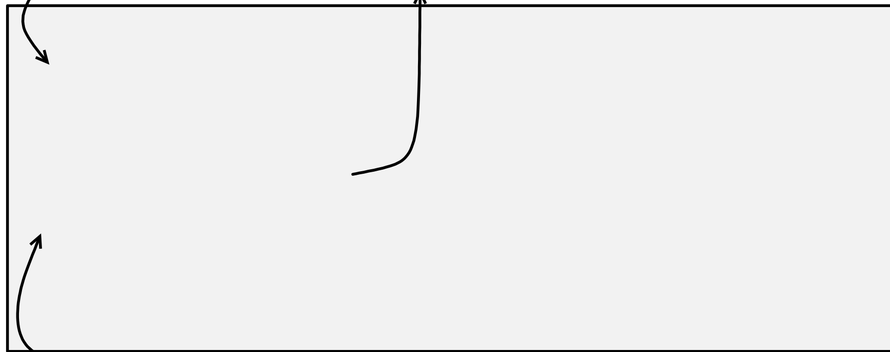
Principles of the Solution



Architecture: Control Layer



“function call”   push / pop request

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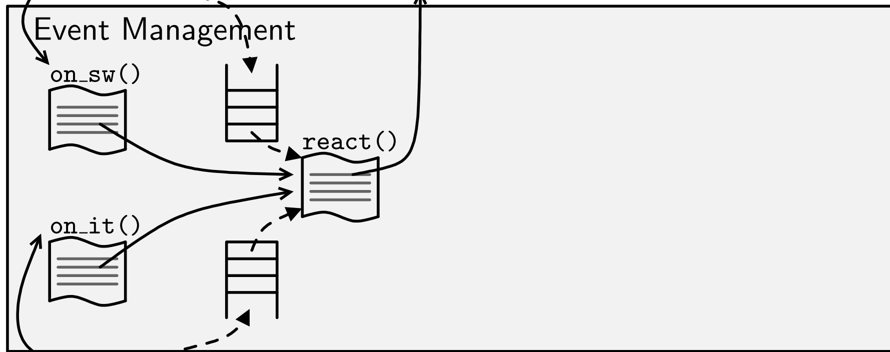

`react()`: Combines Software and Hardware Requests to be Submitted to the Reactive Part

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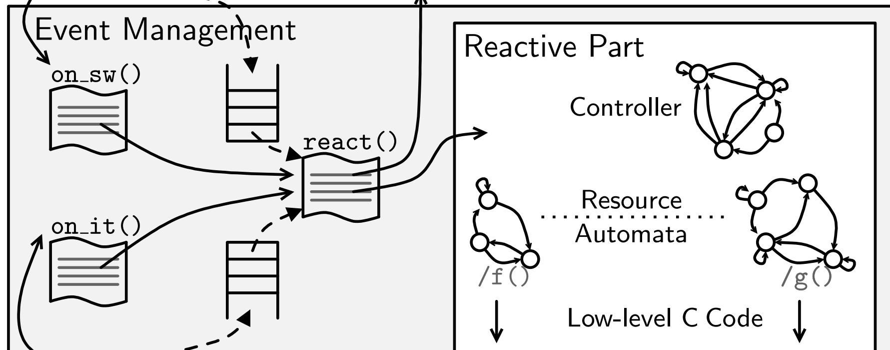

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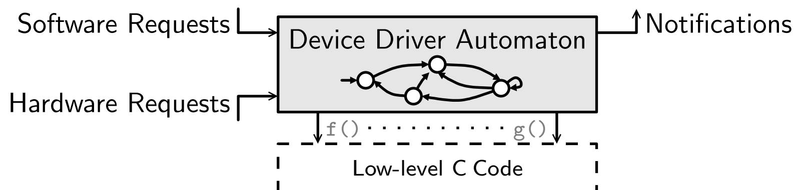
Automata Involved

One Driver Automaton per Device



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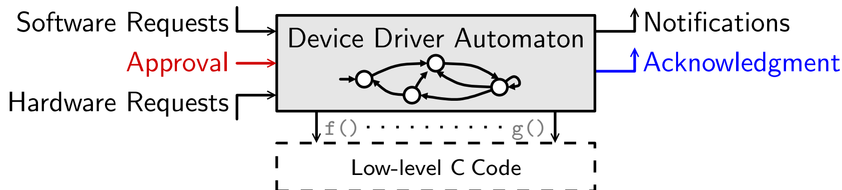

- Can be made Controllable

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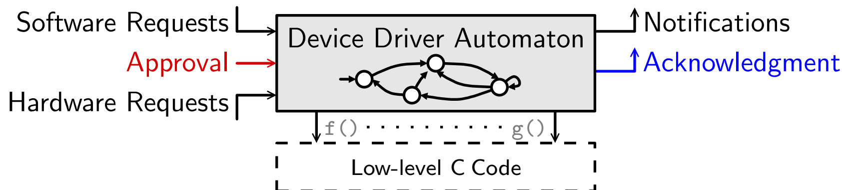
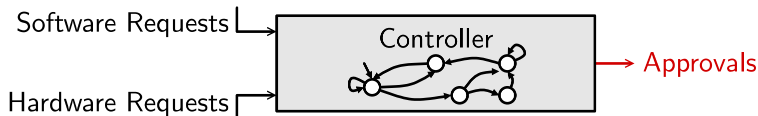


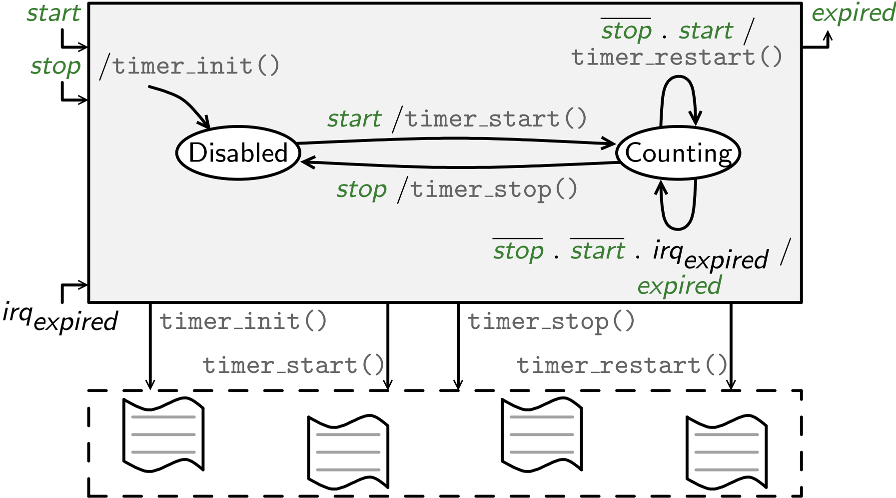
- Can be made Controllable

One Controller Makes Decisions



Example of Uncontrollable Driver Automaton

Timer



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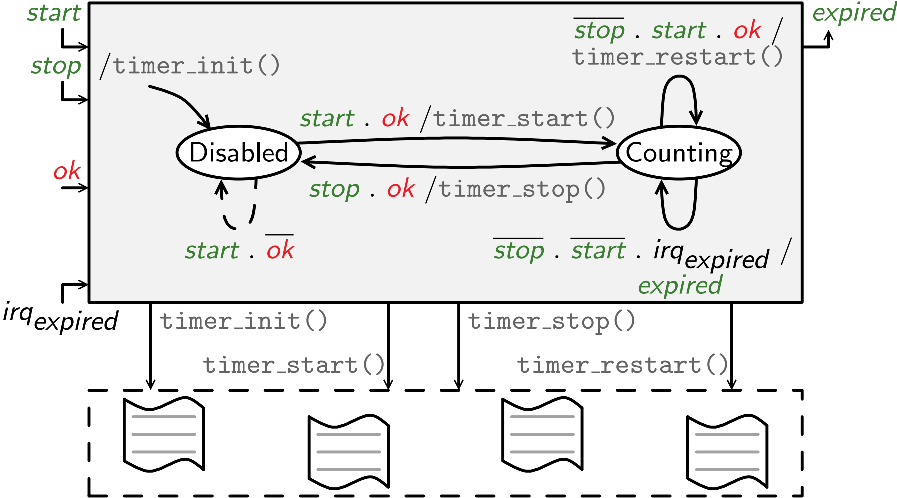

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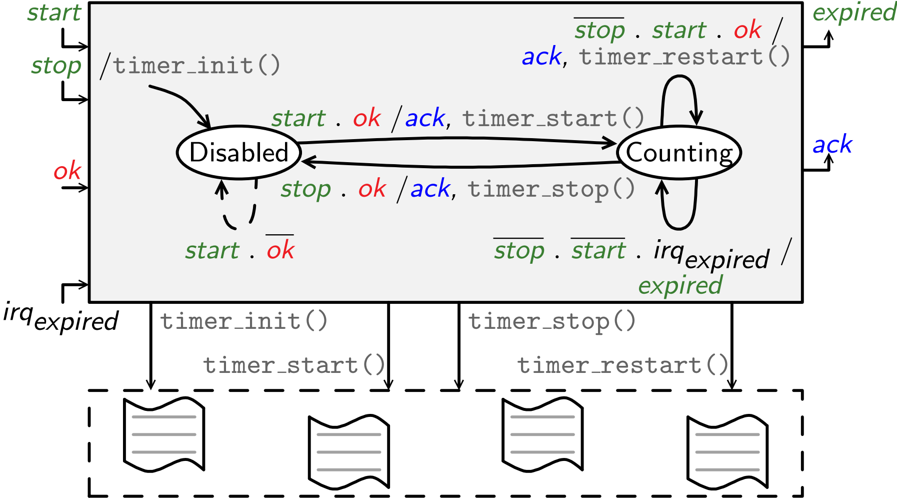
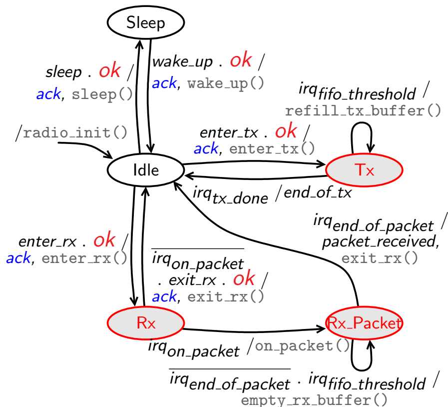
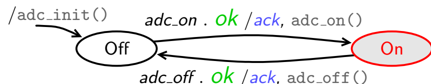


Exclusion of Energy-greedy States: Example

Radio Transceiver



ADC



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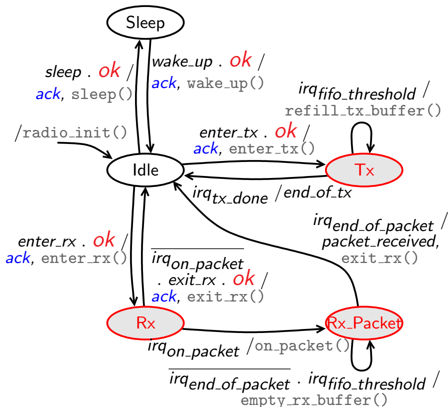
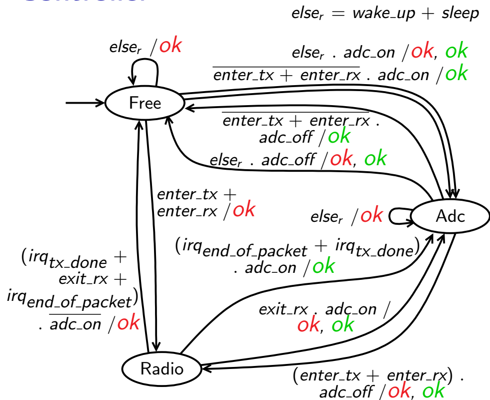


Controller



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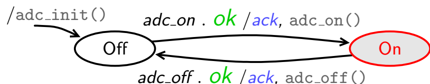
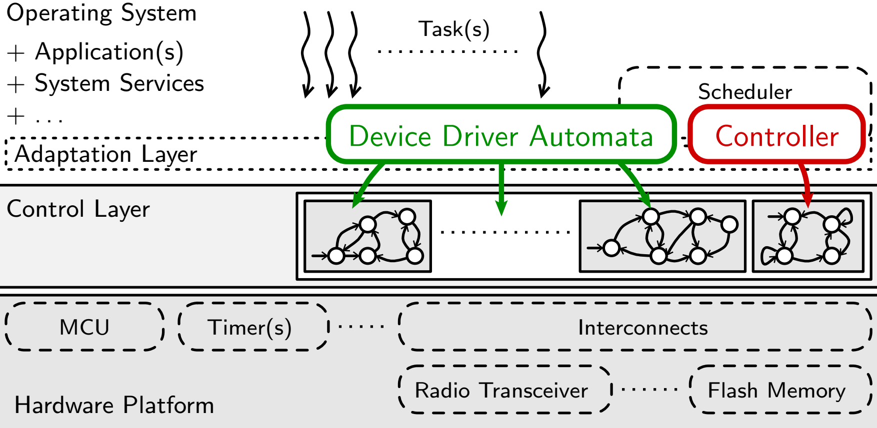


Guarantee:

- States Tx×On, Rx×On and Rx_Packet×On are Unreachable

Putting it All Together



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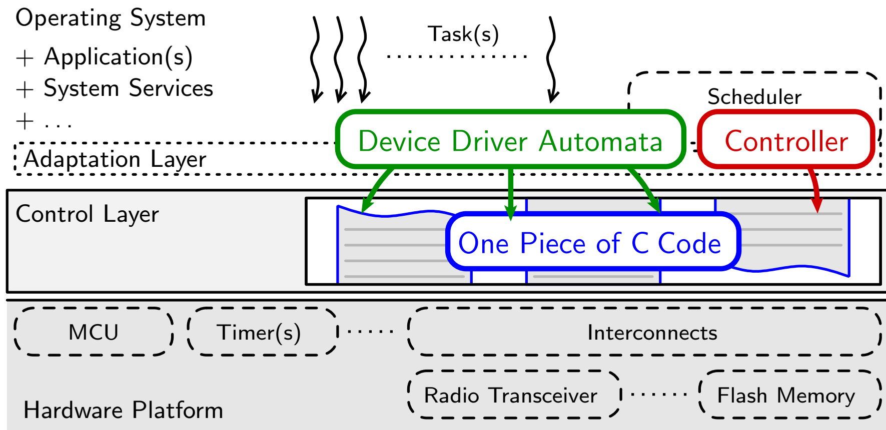

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Evaluation

Proof-of-Concept Implementation

- Targeting Wireless Sensor Network Nodes (Wsn430)
- Device Drivers & Controller Encoded in ARGOS ($\leadsto$ LUSTRE)
    - $\sim$ 10 Device Drivers
- Adapted Operating Systems:
    - Home-made Multithreaded
    - CONTIKI

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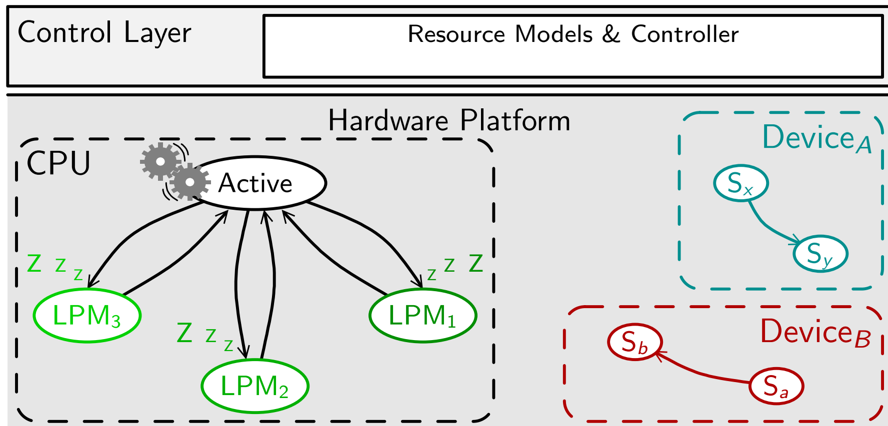
Results

- Extra Memory Footprint: 1.5 to 2.5 KB
- Timing Overhead:

	TINYOS (ICEM) with n Arbiters & m Power Managers	One Execution of Our Reactive Kernel
CPU Cycles	$\lesssim 350n + 400m$	$\approx 1,600$

Other Controllable Properties

Selecting the Best Low-Power Mode



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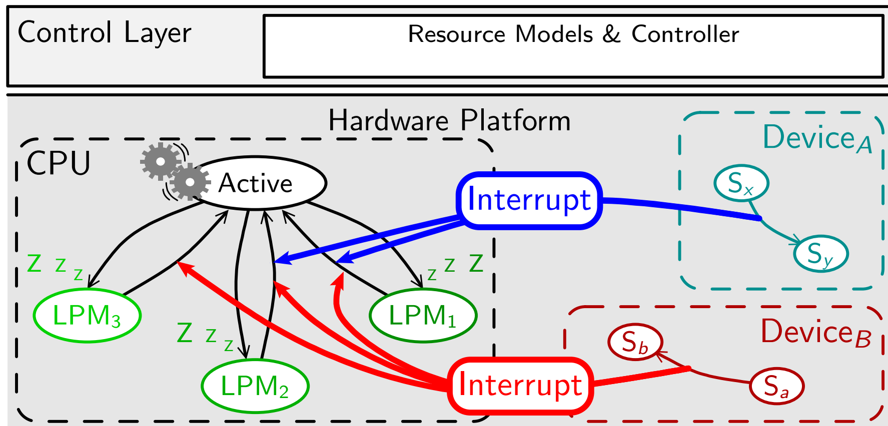
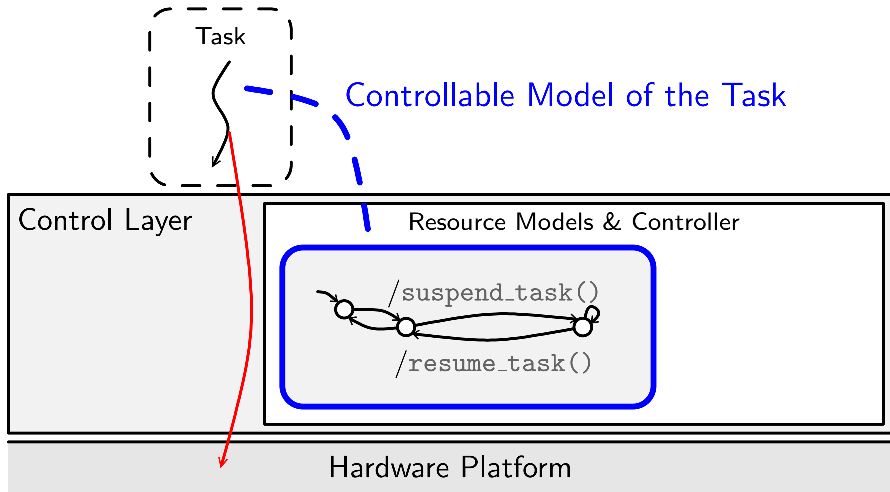


- Wake-up Guarantee (*e.g.*, State LPM$_3$ Should not be Reachable if Device$_B$ is not in State S$_a$)

Other Controllable Properties *(cont'd)*

Allowing Direct Access to the Devices



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Global Resource Control

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- Para-Virtualizaton Concept $\rightsquigarrow$ Flexible Framework
- Many Possible Extensions $\rightsquigarrow$ Powerful

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- Practicable
- Device Drivers Revealed "*easier*" to Develop

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Prospects

- Efficiency to Reduce Power Consumption? (in the Senslab Testbed)
- Automation: Using Controller Synthesis (by using SIGALI)

Thank You!

Outline

- **Adaptation Layer**
- **Example Execution**

Architecture: Adaptation Layer

Modified Part of the Operating System

- Simplified Device Drivers

Interacts with the Control Layer

- Emitting Software Requests to the Control Layer
  - Using on_sw()
- Receiving Outputs from the Control Layer
  - Notifications (Hardware Events, Acknowledgments)

```
turn_adc_on ()
  if (on_sw (adc_on) = ack_a)
    return success;
  timer_wait (some time);    // Consider we can
  turn_adc_on ();            // try again later
```

  - Callbacks (Virtual IRQs)

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- **Example Execution**

Example Execution