# *Transparent Standby for Low-Power, Resource-Constrained Embedded Systems*

## *A Programming Language-Based Approach*


www.ceu-lang.org



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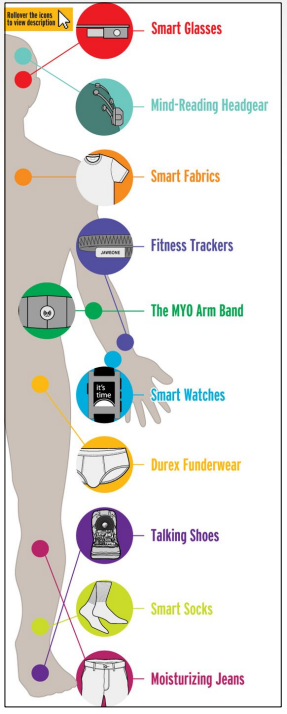
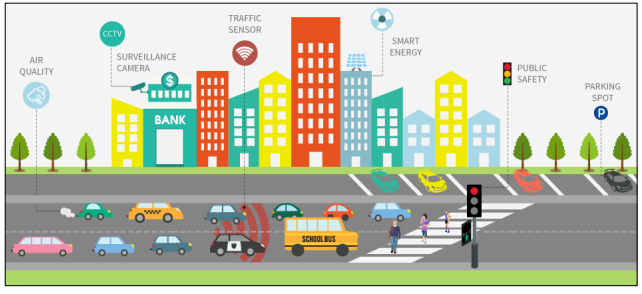
# From “Traditional” Internet to “IoT”

- Today: 15 billion devices

- Tomorrow: 50 billion devices (2020)







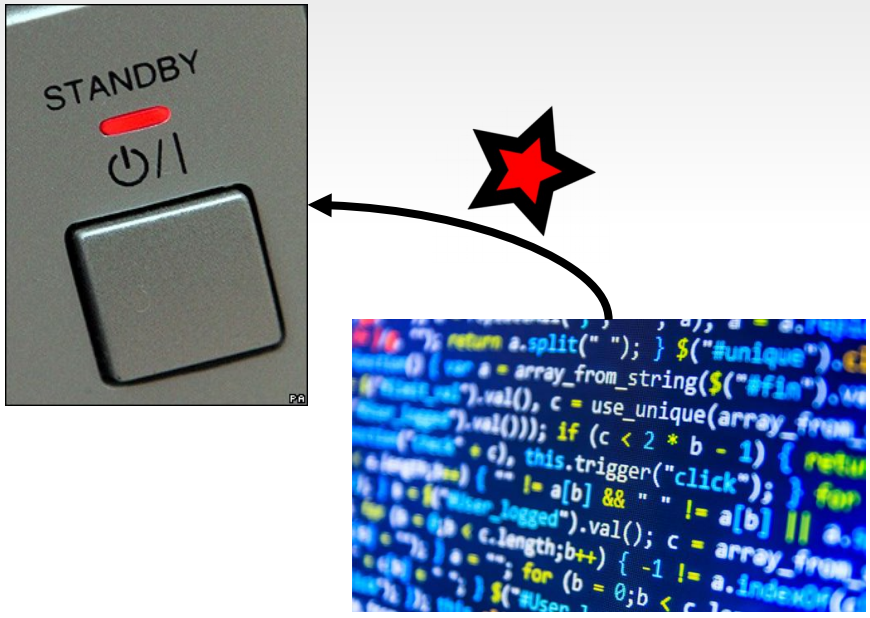
# Energy Efficiency for the IoT

- Challenges: Pollution, Autonomy

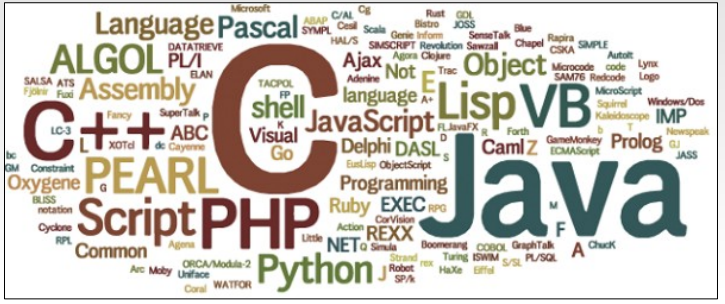

- Opportunity: Effective “standby”


**30-50% economy with existing technologies**

All smart devices have software...




… which is written in a language




Current languages have not been designed with energy efficiency in mind!

# Our Research Goals

1. Address energy efficiency through rigorous use of **standby**.
2. Target **constrained** embedded architectures that form the IoT.
3. Provide standby mechanisms at the **programming language** level that scale to all applications.
4. Support **transparent**/non-intrusive standby mechanisms that reduce barriers of adoption.

# Research Non-Goals

- Adaptive Computing
  - QoS (e.g., resolution, frame rate, accuracy)
  - Behavior (e.g., switch UI, disable functionalities)
  - ***Don't take advantage of standby modes (goal 1)***
- Energy-Aware Network Protocols
  - Low-power listening
  - Small periods of duty cycles
  - ***Only for networked parts, not automatic (goals 3 & 4)***
- Complex Hardware Architectures
  - Microprocessors, MMU, OS-based, Smartphones
  - ***Not constrained embedded platforms (goal 2)***

# General Approach

## (standby, constrained, programming language, transparent)

- Enforce idle states of execution
- Infer deepest sleeping mode
- Put device to sleep
- Only awake from interrupts

# A Motivating Example

*Every second, read sensor value and broadcast it.*

- Arduino

```
while (1) {
  delay(1000);
  int v = analogRead();
  radioWrite(v);
}
```

- Céu

```
loop do
  await 1s;
  int v = await AnalogRead();
  await RadioWrite(v);
end
```

# Let's add concurrency...

*Every second, read sensor value and broadcast it.*

***Stop immediately as soon as a message arrives.***

- Arduino

```
uint32_t prv = millis();
while (1) {
  if (radioAvail())
    break;
  uint32_t cur = millis();
  if (cur > prv+1000) {
    prv = cur;
    int v = analogRead();
    radioWrite(v);
  }
}
```

```
while (1) {
  delay(1000);
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}
```

- Céu

```
par/or do
  await RadioAvail();
with
  loop do
    await 1s;
    int v = await AnalogRead();
    await RadioWrite(v);
  end
end
```

# Standby Considerations

*Every second, read sensor value and broadcast it.*

***Stop immediately as soon as a message arrives.***

- Arduino

```
uint32_t prv = millis();
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- Céu

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par/or do
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  end
end
```

# Céu in a Nutshell

- Reactive
  - environment in control: *events*
- Imperative
  - sequences, loops, assignments
- Concurrent
  - multiple lines of execution: *trails*
- Synchronous (based on Esterel)
  - trails synchronize at each external event
  - **trails are always awaiting**
- Deterministic
  - always yields the same outcome for a given timeline

# In Practice...

- Hardware infrastructure
  - Off-the-shelf Arduinos (ATMega328, Cortex-M0)
- Software infrastructure
  - Implement an energy-aware runtime for Céu
  - Rewrite device drivers in Céu (timers, ADC, Radio)
- Applications
  - Rewrite existing IoT applications in Céu
    - Time to rewrite, Coding “aesthetics”, Energy consumption

```
par/or do
  await RadioAvail();
with
  loop do
    await 1s;
    int v = await AnalogRead();
    await RadioWrite(v);
  end
end
```

```
output void ADC_REQUEST do
   ADMUX = 0x40|(A0&0x07);
   bitSet(ADCSRA, ADIE);
   bitSet(ADCSRA, ADSC);
end
```

```
input ADC_vect_num do
  bitClear(ADCSRA, ADIE);
  emit ADC_DONE(ADC);
end
```

```
code AnalogRead (void) -> int do
  PM_SET(PM_ADC, 1);
  do finalize with
    PM_SET(PM_ADC, 0);
  end
  emit ADC_REQUEST;
  int value = await ADC_DONE;
  escape value;
end
```

```
par/or do
  await RadioAvail();
with
  loop do
    await 1s;
    int v = await AnalogRead();
    await RadioWrite(v);
  end
end
```

```
void pm_sleep (void) {
  if (PM_GET(PM_TIMER1)) {
      sleep_1(<...>)
    } else if (PM_GET(PM_ADC)) {
      sleep_2(<...>);
    } else {
      sleep_3(<...>);
    }
  }
}
```

```
output void ADC_REQUEST do
   ADMUX = 0x40|(A0&0x07);
   bitSet(ADCSRA, ADIE);
   bitSet(ADCSRA, ADSC);
end
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input ADC_vect_num do
  bitClear(ADCSRA, ADIE);
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    PM_SET(PM_ADC, 0);
  end
  emit ADC_REQUEST;
  int value = await ADC_DONE;
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input ADC_vect_num do
  bitClear(ADCSRA, ADIE);
  emit ADC_DONE(ADC);
end
```

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code AnalogRead (void) -> int do
  PM_SET(PM_ADC, 1);
  do finalize with
    PM_SET(PM_ADC, 0);
  end
  emit ADC_REQUEST;
  int value = await ADC_DONE;
  escape value;
end
```

# General Approach

## (standby, constrained, programming language, transparent)

- Enforce idle states of execution
  - Céu enforces a reactive model of execution
- Infer deepest sleeping mode
  - Céu has a semantics amenable to analysis
- Put device to sleep
  - Céu has an energy-aware runtime
- Only awake from interrupts
  - Céu provides interrupt service routines (ISRs)

```
par/or do
  await RadioAvail();
with
  loop do
    await 1s;
    int v = await AnalogRead();
    await RadioWrite(v);
  end
end
```

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# Standby Efficiency for IoT

- 15 billion “traditional” network-connected devices in 2015 (e.g., mobile phones & smart TVs).
- 75 billion by 2025 with the IoT (e.g., smart bulbs & fitness wearables). [2016]
- **Most energy consumed in standby mode.**
- Network standby is one of the six fronts on IEA/G20's Energy Efficiency Action Plan
    - https://www.iea-4e.org/projects/g20

# Related Publications

- SenSys'13, ACM Embedded Networked Sensor Systems
  - *Safe System-level Concurrency on Resource-Constrained Nodes*
- TECS'17, ACM Transactions on Embedded Computing Systems
  - *The Design and Implementation of the Synchronous Language Céu*
- LCTES'18, ACM Conference on Languages, Compilers, and Tools for Embedded Systems
  - *A Memory-Bounded, Deterministic and Terminating Semantics for the Synchronous Programming Language Céu*
- LCTES'18, ACM Conference on Languages, Compilers, and Tools for Embedded Systems
  - *WIP: Transparent Standby for Low-Power, Resource-Constrained*

# Cooperation Opportunities

- Hardware infrastructure
  - Off-the-shelf Arduinos (ATMega328, Cortex-M0)
- Software infrastructure
  - Implement an energy-aware runtime for Céu
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