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Scuola Superiore
Sant'Anna

Retis
Real-Time Systems Laboratory

Real-Time Multitasking in Arduino

Pasquale Buonocunto, Alessandro Biondi, Pietro Lorefice

Who I am

- **Pasquale Buonocunto**
  PhD Fellow at Scuola Superiore Sant'Anna
  - Graduated cum Laude (Oct 2012) in Computer Engineering at *University of Pisa*
  - Nov 2012 , now – PhD Fellow on Embedded Systems at TeCIP Institute, Scuola Superiore Sant'Anna, Pisa.

Research Interests

- Real-time operating systems: design and implementation;
- Real-time wireless communication
- Wearable, low power e-Health devices

Who I am

- **Alessandro Biondi**
  PhD Fellow at Scuola Superiore Sant'Anna

  - Graduated cum Laude in 2013 in Computer Engineering at *University of Pisa*, within the excellence program;

  - Aug 2011, Oct 2011 – Visiting student @ San Diego State University, California.

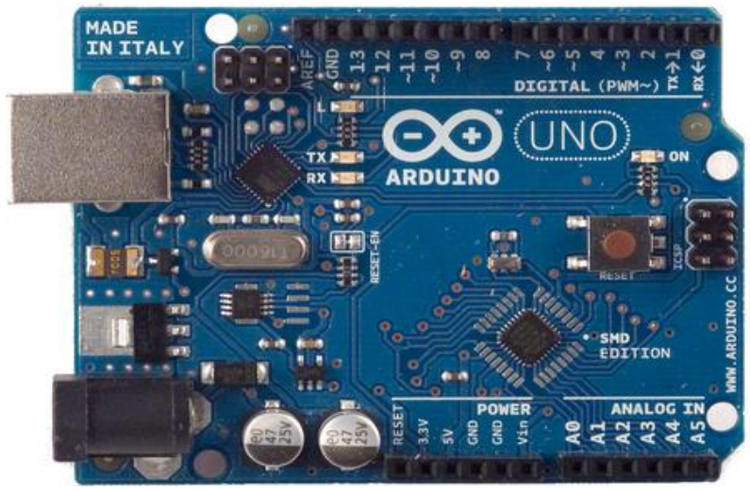
Research Interests

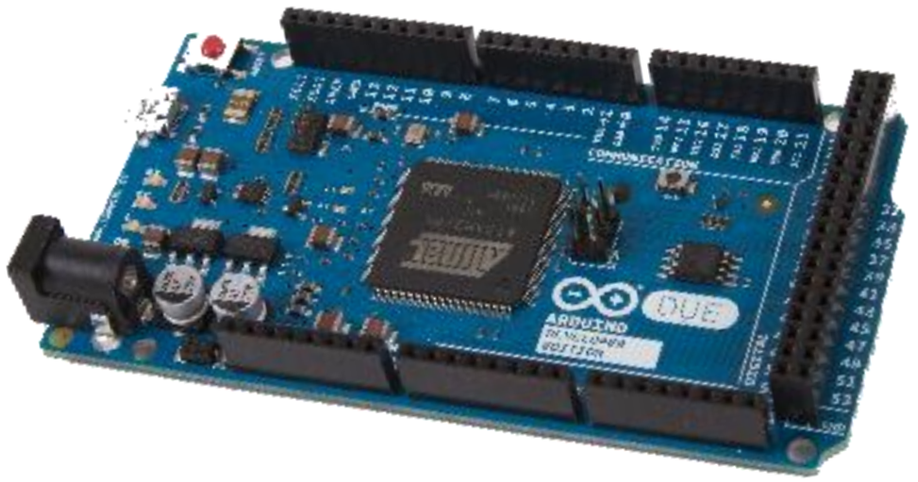
- Real-time operating systems: design and implementation;
- Real-time schedulability analysis;
- Hierarchical systems;
- Synchronization protocols.

Arduino Framework

"Arduino is a tool for making computers that can sense and control more of the physical world than your desktop computer."

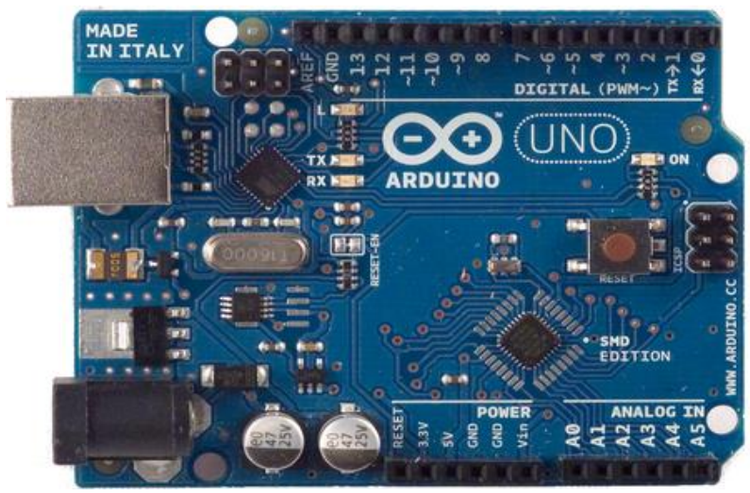
- **Very popular**
  - 2013: *700,000+ official boards were in users' hands (not counting unofficial clones…)*

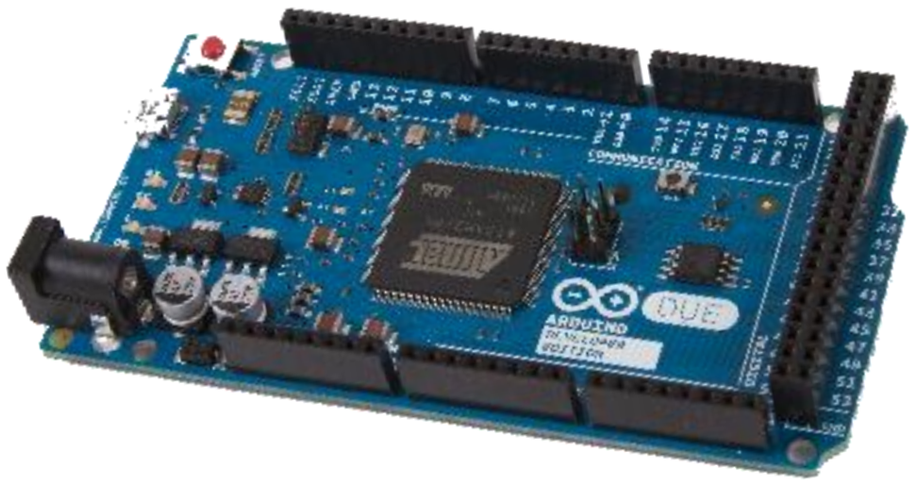




Arduino Framework

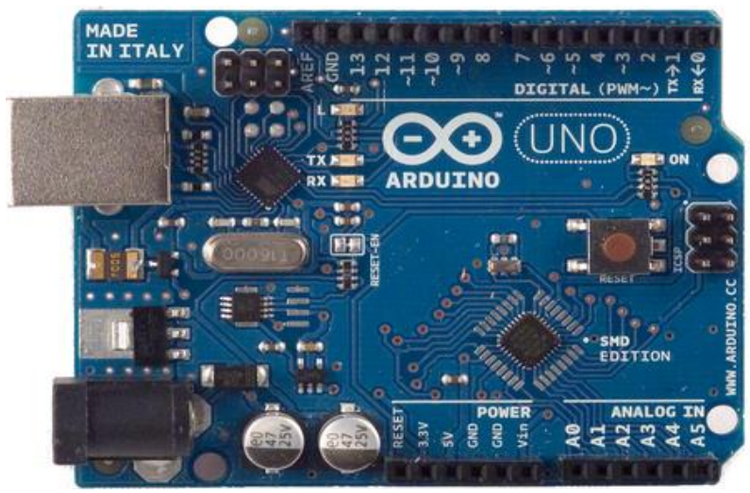
- **Very simple!**
  - Simple programming interface;
  - Easy firmware loading;

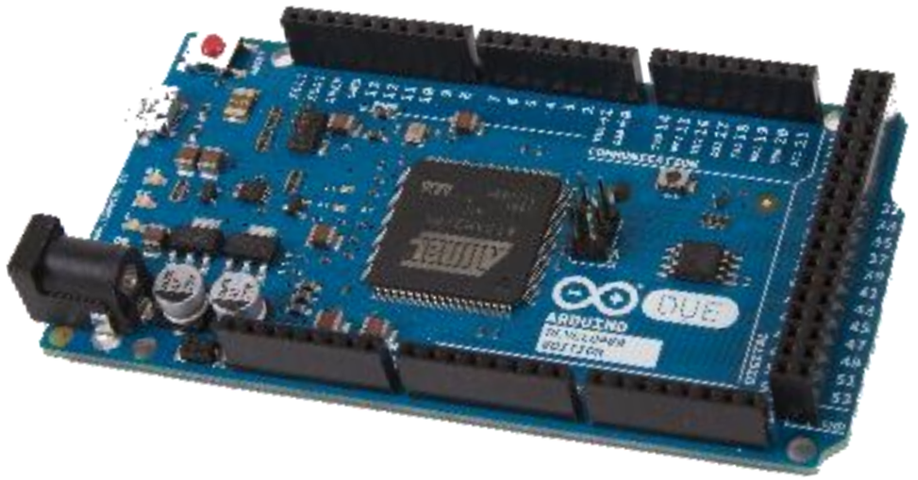




Arduino Framework

- **Low cost**
  - Arduino Uno ~20€;
  - Arduino Due ~35€.



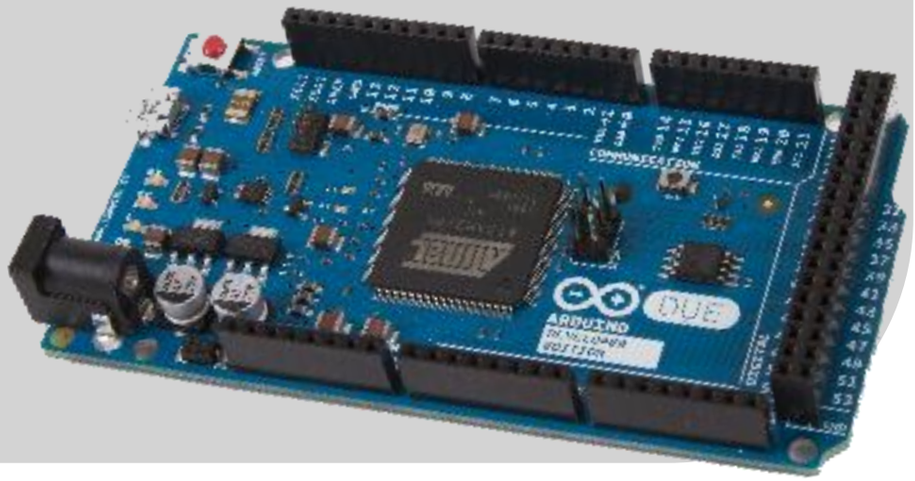


Arduino Framework

- **Very popular**
  - 2013: *700,000+ official boards were in users' hands*
- **Very simple!**
  - Simple
  - Easy fir
- **Low cost**

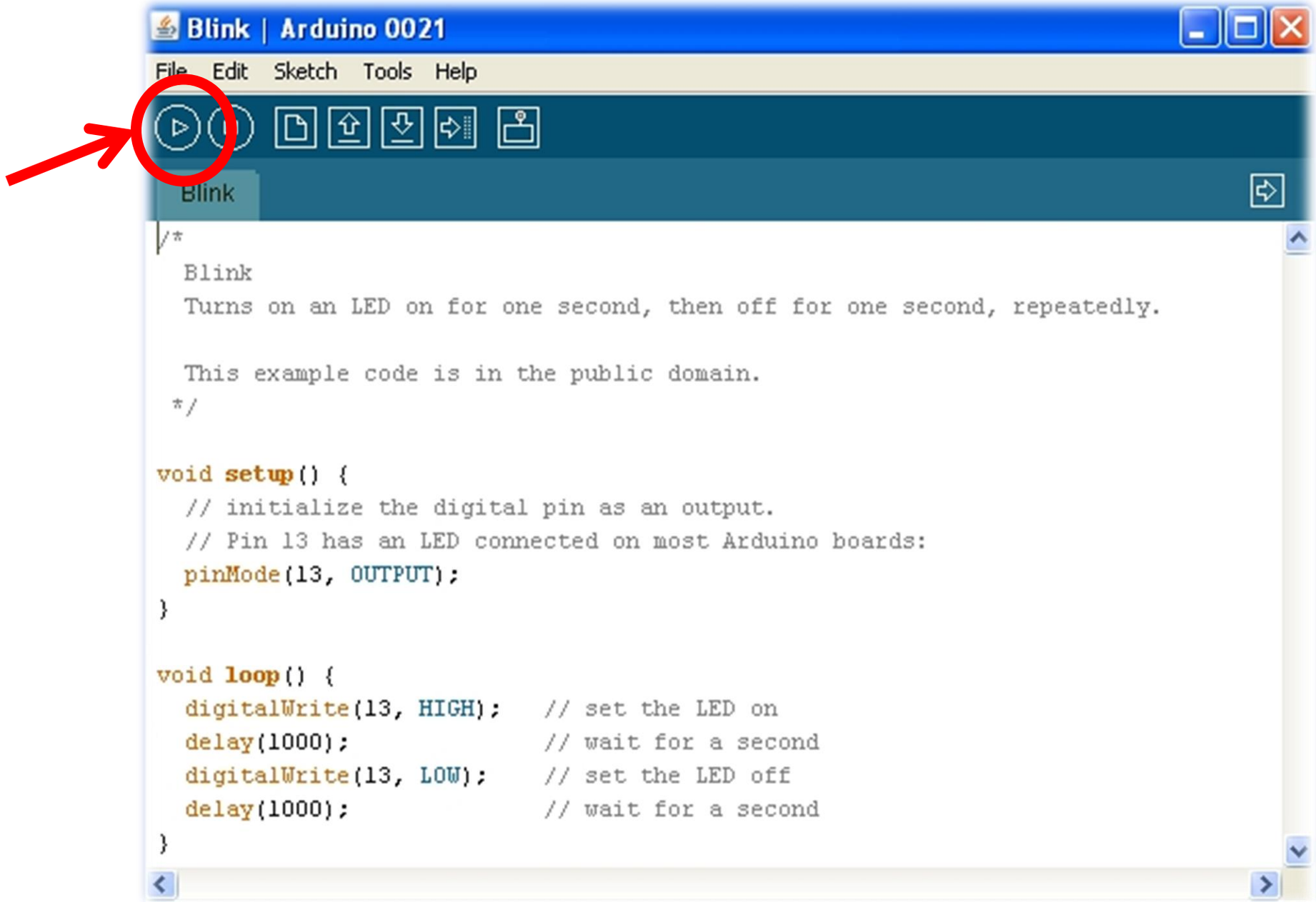
  ~20$ official

"Embedded system programming for everyone"



Arduino Framework

- …Very simple!



Arduino Framework

```
void setup() {

        <instructions here>
}


void loop() {

        <instructions here>
        delay(1000);

}
```

One-shot execution at startup

Cyclically executed "*until power off*"!

Arduino Framework

- A lot of libraries…

Standard Libraries

- EEPROM
- Ethernet
- GSM
- LiquidCrystal
- SD
- Servo
- SPI
- SoftwareSerial
- Stepper
- TFT
- WiFi
- Wire

Contributed Libraries

Messenger
NewSoftSerial
OneWire
PS2Keyboard
Simple Message System
SSerial2Mobile
Webduino
X10
XBee
SerialControl
Capacitive Sensing
Debounce
GLCD
Improved LCD
LedControl
LedDisplay
Matrix
PCD8544
Sprite
ST7735
FFT
Tone
TLC5940
DateTime
Metro
MsTimer2
PString
Streaming

Limitation of the Arduino Framework

- **No** support for concurrency;
- Execution limited to ***a single loop*** of instructions;
- **No** period can be expressed.

```
void loop() {

        <instructions here>
        delay(1000);

}
```

Existing Solutions

- **Scheduler Library**
  - Support for multiple "concurrent" loops;
  - Cooperative Scheduler: each task is responsible to "*pass the baton*";
  - No periodic activities can be expressed;
  - Experimental Library.

Existing Solutions

Scheduler Library

```
void setup() {
  Scheduler.startLoop(func1);
  Scheduler.startLoop(func2);
}

void func1() {
  digitalWrite(led2, HIGH);
  delay(100);
  digitalWrite(led2, LOW);
  delay(100);
}


void func2() {
  <instructions here>
    yield(); // Pass control to other tasks.
}
```

Pass the control to func2()

Pass the control to func1()

Existing Solutions

Scheduler Library

```
void setup() {
  Scheduler.startLoop(func1);
  Scheduler.startLoop(func2);
}

void func1() {
  digitalWrite(led2, HIGH);
  delay(100);
  digitalWrite(led2, LOW);
  delay(100);
}


void func2() {
  <instructions here>
    yield(); // Pass control to other tasks.
}
```

No Scheduling Policy

The scheduling pattern is established by *explicit* call to *yield()* or *delay()*

Existing Solutions

Scheduler Library

```
void setup() {
  Scheduler.startLoop(func1);
  Scheduler.startLoop(func2);
}

void func1() {
  digitalWrite(led2, HIGH);
  delay(100);
  digitalWrite(led2, LOW);
  delay(100);
}


void func2() {
  <instructions here>
    yield(); // Pass control to other tasks.
}
```

No Real-Time

No Periodic Activities

No Preemption

Existing Solutions

- **Other Solutions:**
  - Arduino Simple Task Scheduler;
  - Looper;
  - WrapOS;
  - …

Existing Solutions

```
scheduler.createSchedule(7*20*4, -1, false, put_leds
uint32_t pid = scheduler.createSchedule(50, -1, false
scheduler.beginProfiling(pid);
scheduler.stopProfiling(pid);
scheduler.clearProfilingData(pid);

char * temp = dumpProfilingData(void);
if (temp != NULL) {
  Serial.println(temp);
  free(temp);
}

/* Fires callback_function() after 790ms, and then cle
scheduler.createSchedule(790, 0, true, callback_fun

/* Blinks an LED for (20*9)ms. */
scheduler.createSchedule(20, 9, true, toggle_led);

/* Makes a 500Hz beep that lasts for 0.5 seconds. */
scheduler.createSchedule(1, 1000, true, toggle_spea

void put_leds_into_cycle() {
  // Pulse all the LEDs in sequence...
  scheduler.createSchedule(20, 7, true, toggle_02_o
  scheduler.delaySchedule(scheduler.createSchedul
toggle_04_oclock_led_r), 7*20);
  scheduler.delaySchedule(scheduler.createSchedul
toggle_08_oclock_led_r), 7*20*2);
  scheduler.delaySchedule(scheduler.createSchedul
toggle_10_oclock_led_r), 7*20*3);
}
```

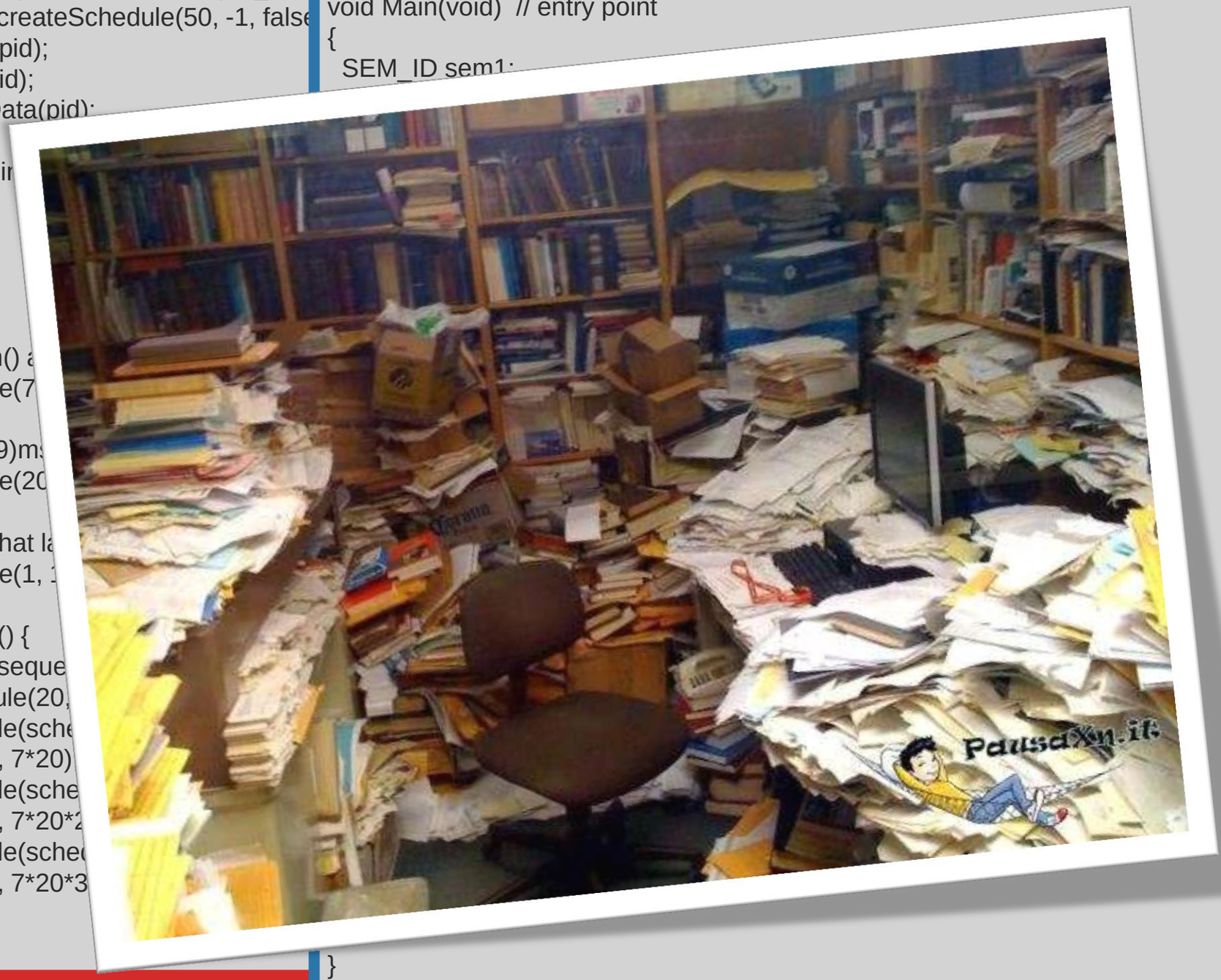
```
void Main(void)  // entry point
{
  SEM_ID sem1;
  MSGQ_ID msgQ1;

  semCreate(sem1);  //  initial it.
  msgQCreate(msgQ1, 100, 10);

  // create and start tasks.
  taskCreate("task1", 240, 0x7fff, (FUNCPTR)task1);
  taskCreate("task2", 250, 0x7fff, (FUNCPTR)task2);
}

void task1(void)
{

  while (!done) { // main loop
    semTake(sem1, 10);  //  wait for the semaphore

    //  Do task1 stuff here
  }
}

void task2(void)
{
  while(!done) {  // main loop
    //  wait for a message to come.
    msgQReceive(msgQ1, buf, size, WAIT_FOREVER);

    //  Do task2 stuff here.
  }
}
```

```
1000);
```

Existing Solutions

```
scheduler.createSchedule(7*20*4, -1, false, put_leds
uint32_t pid = scheduler.createSchedule(50, -1, false
scheduler.beginProfiling(pid);
scheduler.stopProfiling(pid);
scheduler.clearProfilingData(pid);

char * temp = dumpProfilin
if (temp != NULL) {
  Serial.println(temp);
  free(temp);
}

/* Fires callback_function() a
scheduler.createSchedule(7

/* Blinks an LED for (20*9)ms
scheduler.createSchedule(20

/* Makes a 500Hz beep that la
scheduler.createSchedule(1, 1

void put_leds_into_cycle() {
  // Pulse all the LEDs in seque
  scheduler.createSchedule(20,
  scheduler.delaySchedule(sche
toggle_04_oclock_led_r), 7*20)
  scheduler.delaySchedule(sche
toggle_08_oclock_led_r), 7*20*2
  scheduler.delaySchedule(sche
toggle_10_oclock_led_r), 7*20*3
}
```

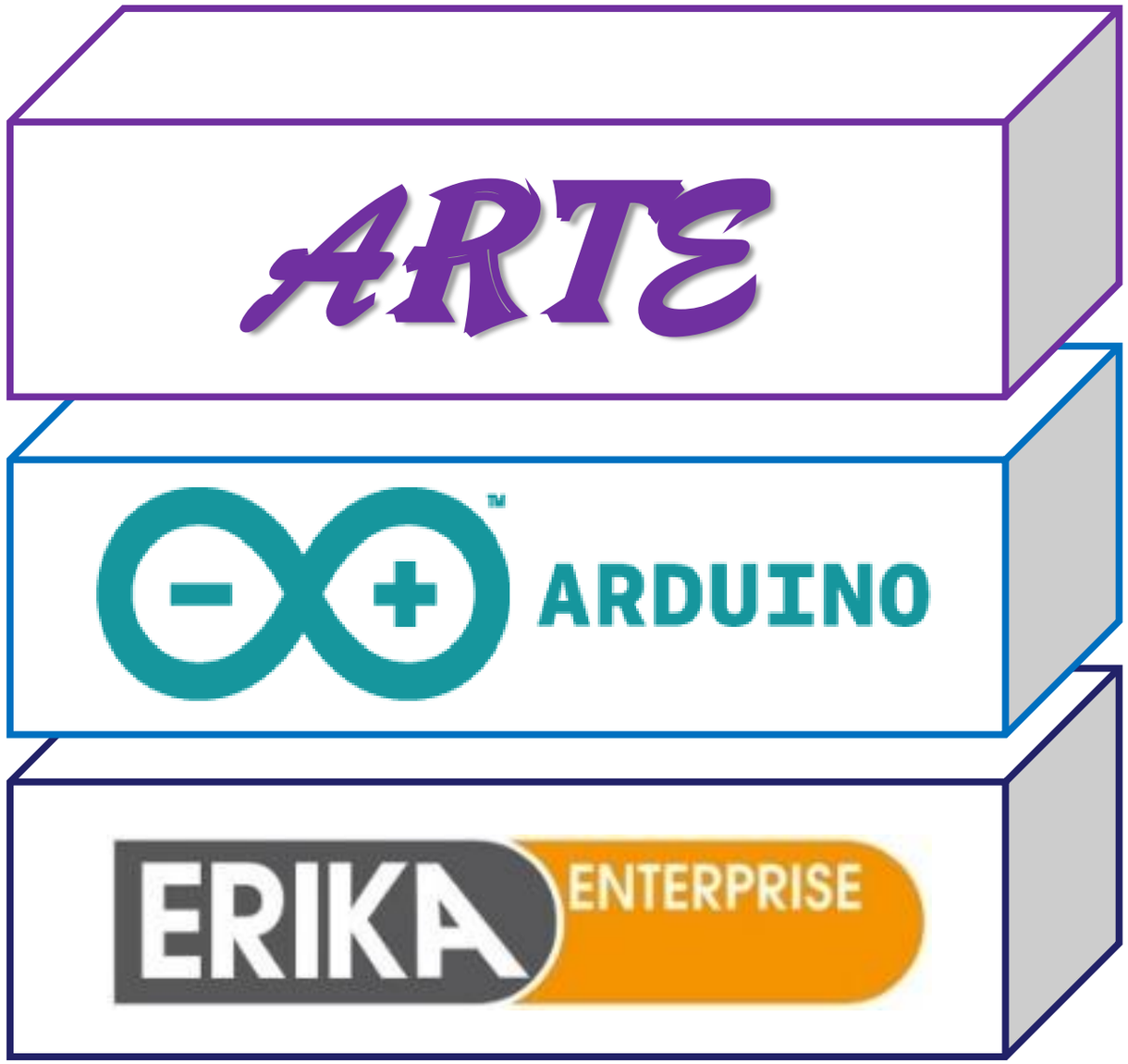
```
void Main(void)  // entry point
{
  SEM_ID sem1;
```




```
1000);
```

```
}
```

ARTE: Arduino Real-Time Extension

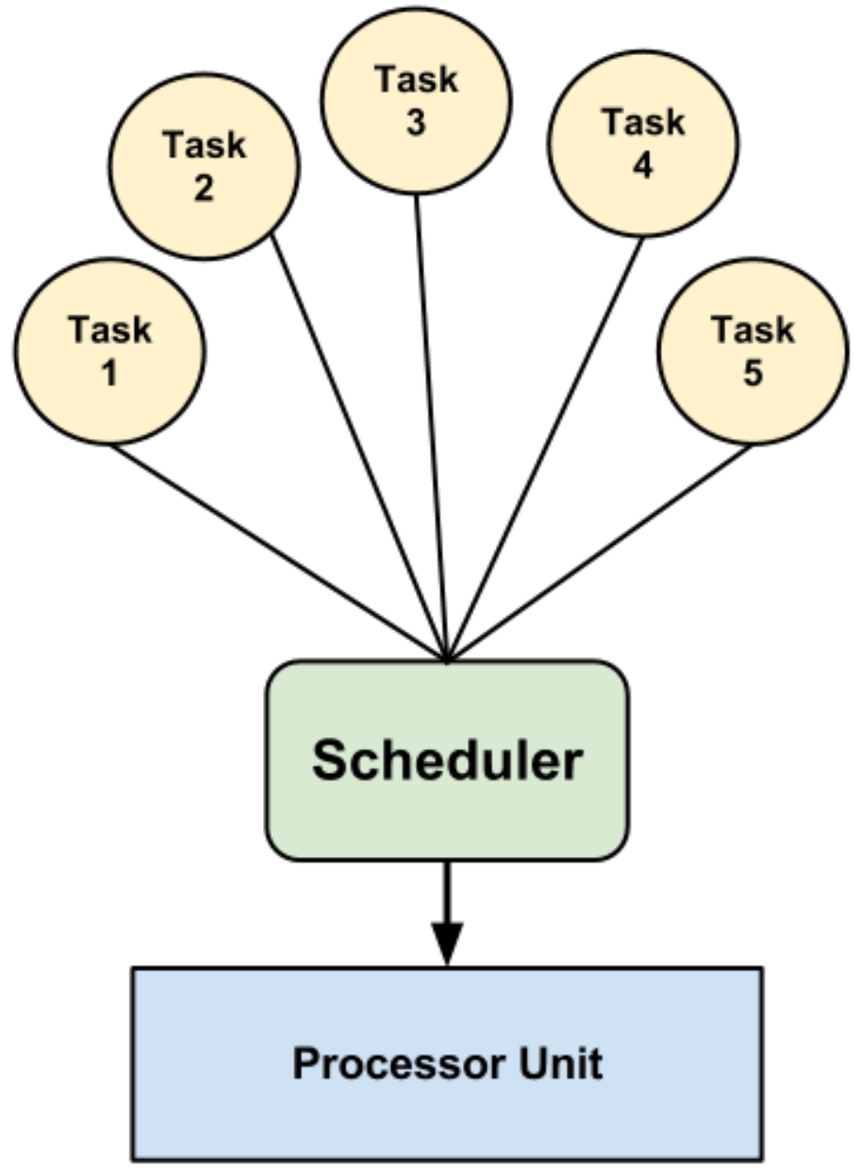


ARTE: Arduino Real-Time Extension

- Support for **real-time multitasking** and **periodic activities**;
- Maintain a **very simple programming interface** compliant with the Arduino philosophy;
- **Minimum amount of differences** with respect to the original Arduino programming model.

What is Real-Time Multitasking?

- **Scheduling Algorithm**: Rules dictating the task that needs to be executed on the CPU at each time instant

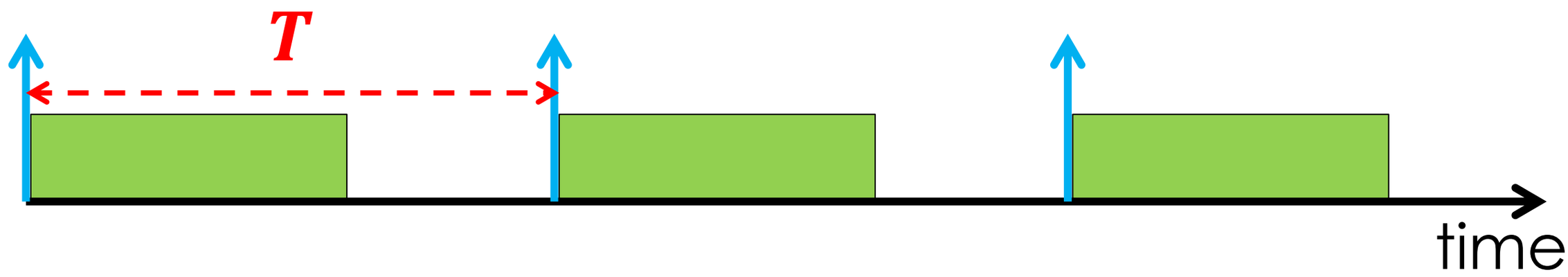


What is Real-Time Multitasking?

- **Preemptive** & **Priority driven** scheduling
  - Task have **priorities** (static);
  - At each time, the **highest priority** task is executed ;
  - **Preemption**: the execution of the running task can be interrupted by an *higher priority task*, and the CPU given to the new task.

What is Real-Time Multitasking?

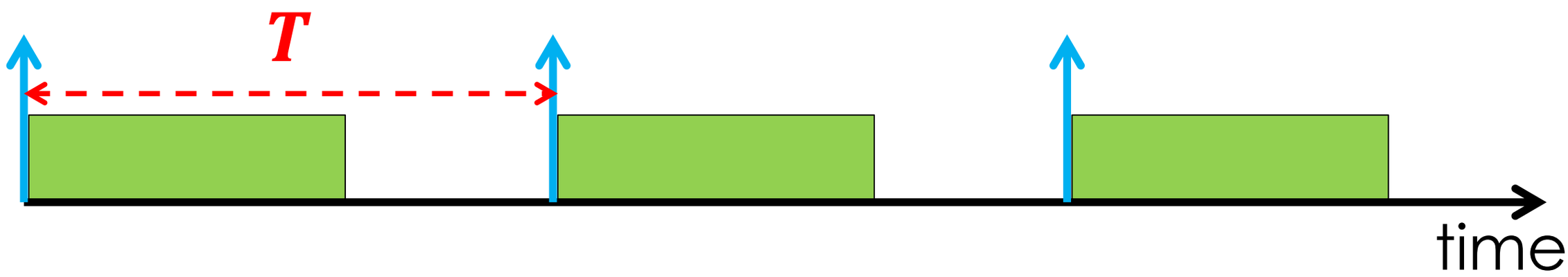
- **Periodic Activities**



- Standard Real-time programming model:
  - Periodic activities without explicit delay/suspensions;
  - Be predictable: polling preferred to event reaction.

What is Real-Time Multitasking?

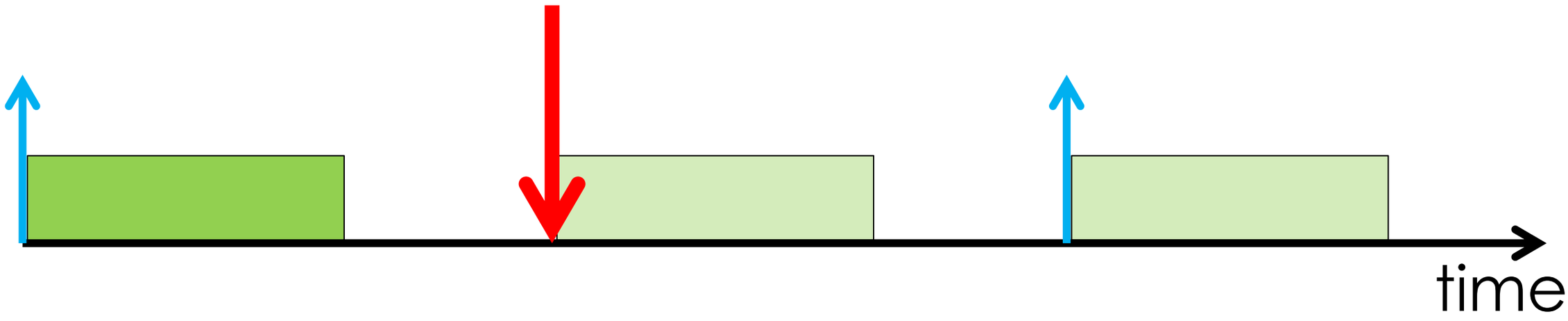
- **Periodic Activities**



- Typical Real-Time Applications:
  - Sampling sensors and actuating (e.g., control loop,…);
  - Multimedia and transmissions;

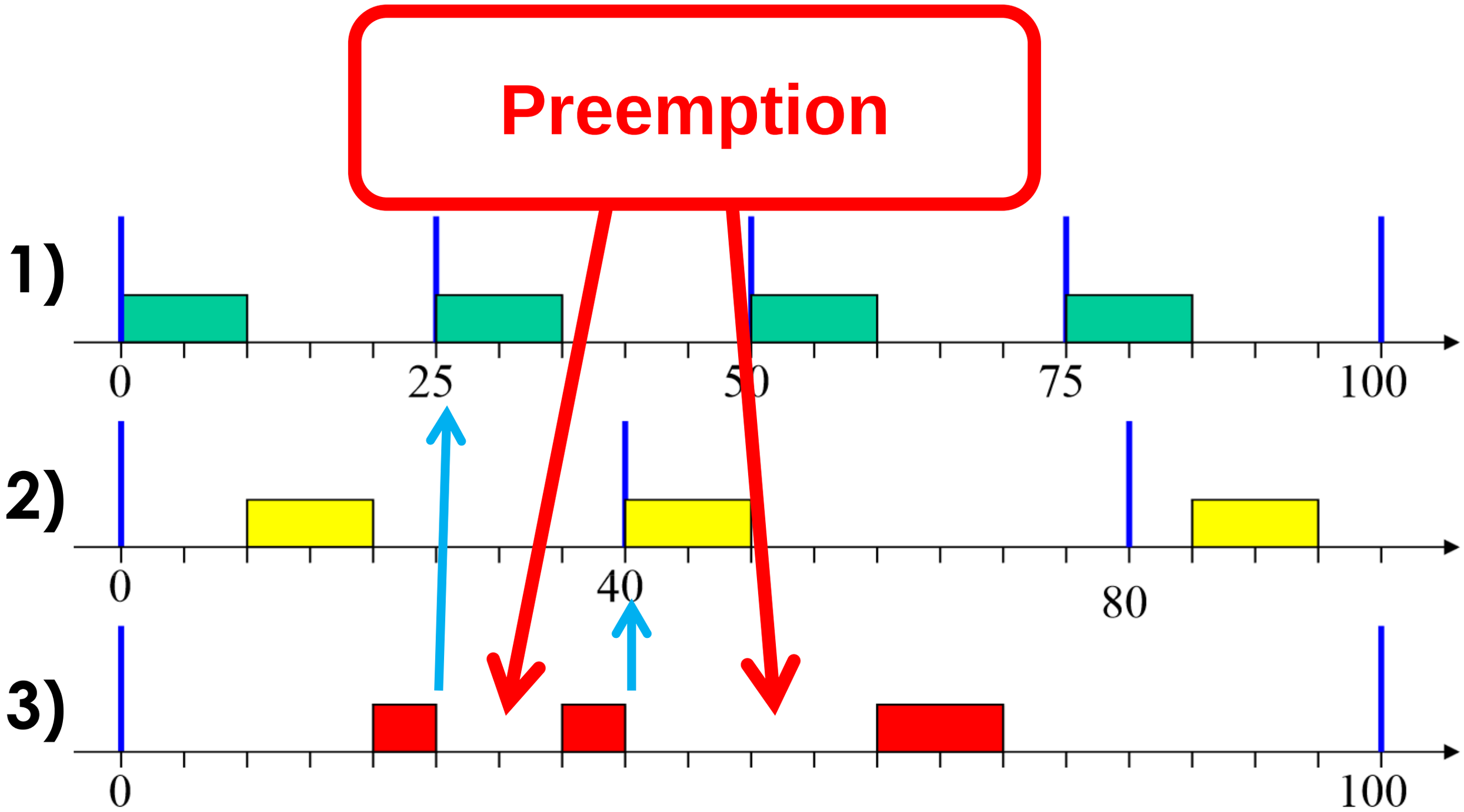
What is Real-Time Multitasking?

- **Periodic Activities**



- **Deadline**: we want the task finishing before the next activation.

What is Real-Time Multitasking?



Real-Time Multitasking and Arduino

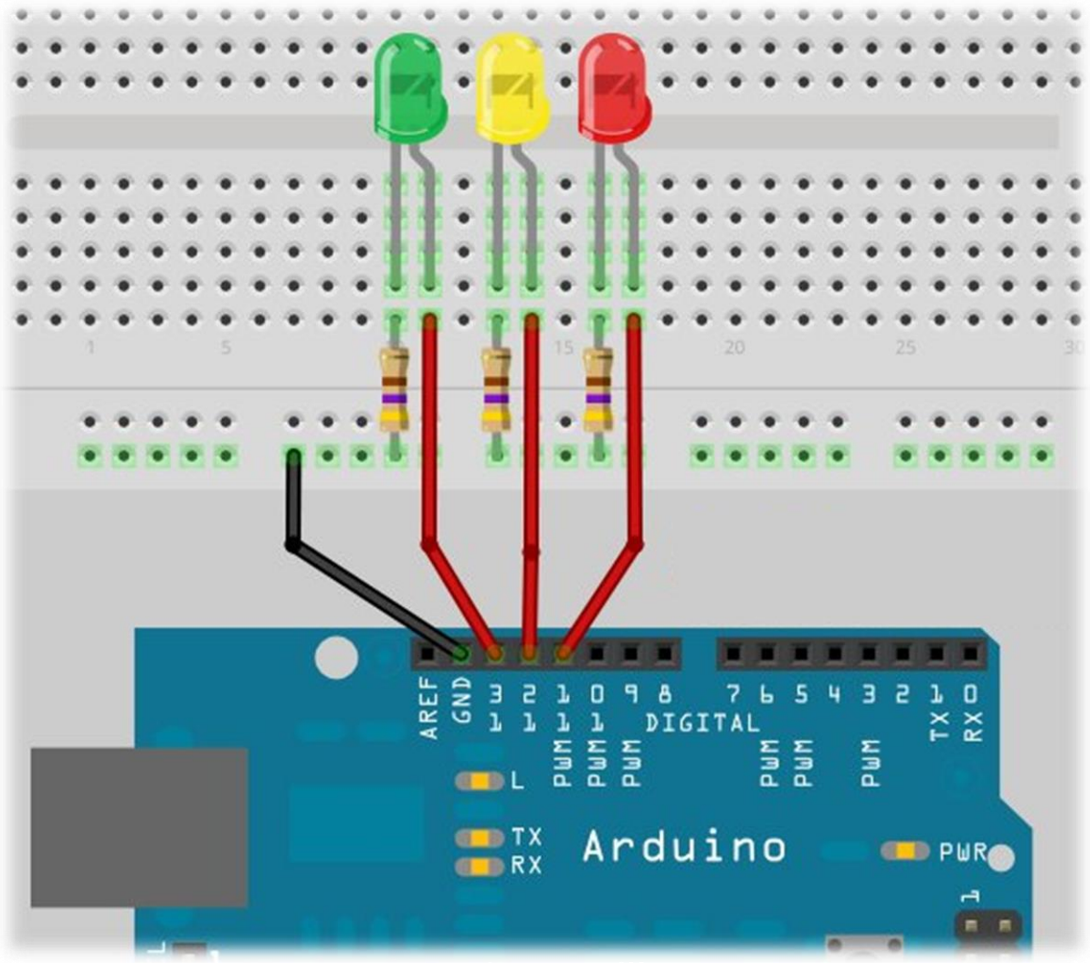
- **Idea**: Exploit the power of Real-Time Multitasking with the simple and effective Arduino Programming Model;
- Extension to the Arduino Framework allowing concurrent, multiple, loops each one scheduled with a **Real-Time OS**

Erika Enterprise

- ERIKA Enterprise is an **OSEK/VDX** certified RTOS;
- ERIKA Enterprise implements an API inspired by the **AUTOSAR OS API**;
- Offers a suitable **open-source** license allowing the static linking of closed source code;
- Typical footprint around **2-4KB** Flash;
- Used by several automotive/white goods companies.

Example

- Make blinking three different leds, each one at a different frequency.
  - **Led1**: *3s*
  - **Led2**: *7s*
  - **Led3**: *11s*



Robotmill.com

Example

With *classical* **Arduino** programming model

Led1 *3s*

Led2 *7s*

Led2 *11s*

```
int led1 = 13;
int led2 = 14;
int led3 = 15;
int count = 0;

void loop() {
        if (count%3 == 0)
                digitalToggle(led1);

        if (count%7 == 0)
                digitalToggle(led2);

        if (count%11 == 0)
                digitalToggle(led3);

        if (count == 3*7*11)
                count = 0;
        count++;
        delay(1000);
}
```

Example

ARTE

With **Arduino**
Real-Time
Extension

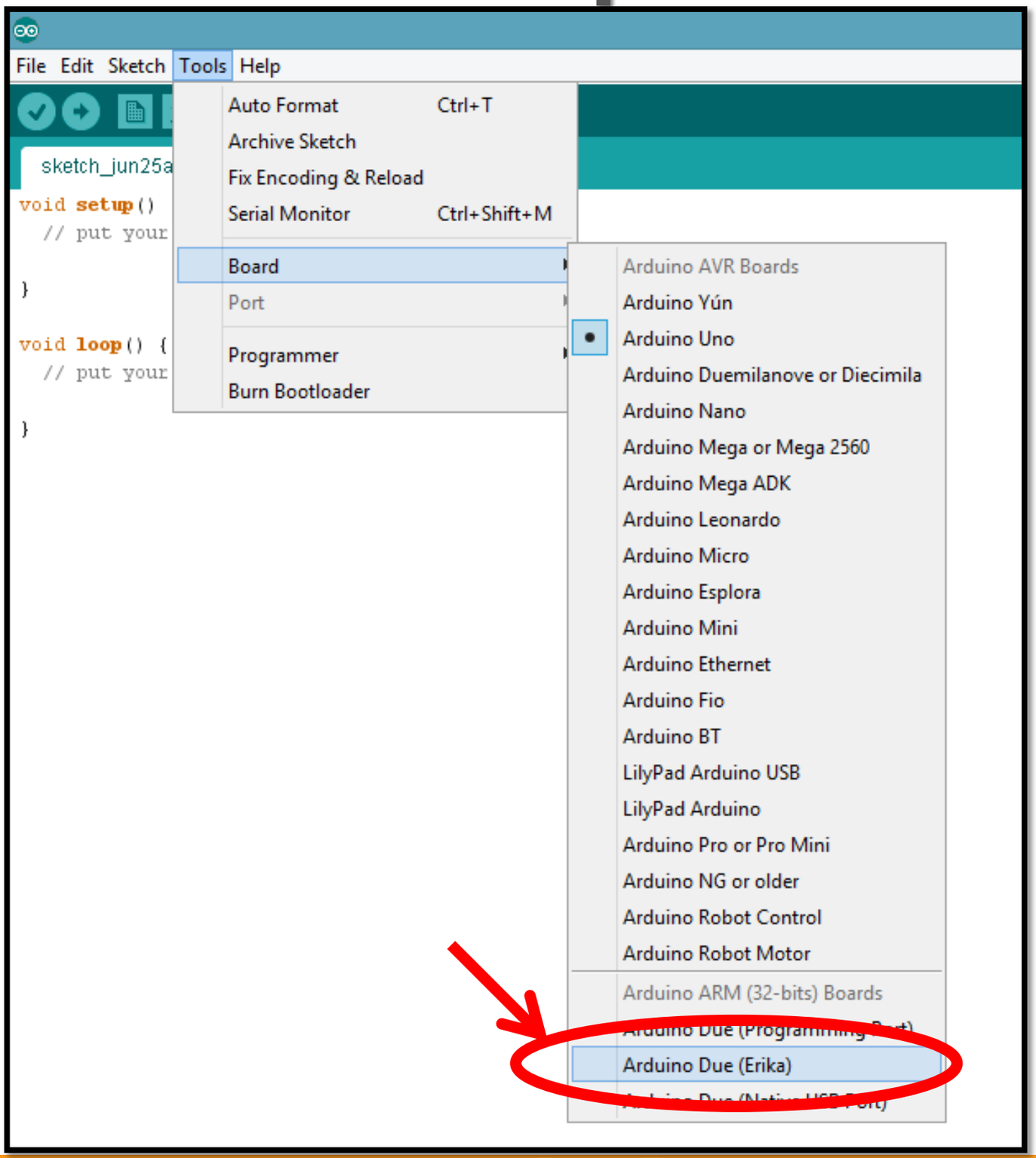
Led1 *3s*

Led2 *7s*

Led2 *11s*

```
int led1 = 13;
int led2 = 14;
int led3 = 15;

void loop1(3000) {
        digitalToggle(led1);
}

void loop2(7000) {
        digitalToggle(led2);
}

void loop3(11000) {
        digitalToggle(led3);
}
```

Example


File Edit Sketch Tools Help
sketch_jun25a
void setup()
// put your
}
void loop() {
// put your
}
Auto Format Ctrl+T
Archive Sketch
Fix Encoding & Reload
Serial Monitor Ctrl+Shift+M
Board
Port
Programmer
Burn Bootloader
Arduino AVR Boards
Arduino Yún
Arduino Uno
Arduino Duemilanove or Diecimila
Arduino Nano
Arduino Mega or Mega 2560
Arduino Mega ADK
Arduino Leonardo
Arduino Micro
Arduino Esplora
Arduino Mini
Arduino Ethernet
Arduino Fio
Arduino BT
LilyPad Arduino USB
LilyPad Arduino
Arduino Pro or Pro Mini
Arduino NG or older
Arduino Robot Control
Arduino Robot Motor
Arduino ARM (32-bits) Boards
Arduino Due (Erika)

Arduino Real-Time Extension

- *ARTE* is a real extension to the **Arduino IDE**, not an external library!
  - It provides a code pre/post-processor that avoids *tiring* and *error-prone* user configurations;
  - **Automatic generation** of the application configuration and skeleton code;
  - The user is focused on the application logic.

Arduino Real-Time Extension

- *ARTE* has a **real** RTOS *under the hood*

Example

```
int led1 = 13;
int led2 = 14;
int led3 = 15;

void loop1(3000) {
        digitalToggle(led1);
}

void loop2(7000) {
        digitalToggle(led2);
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void loop3(11000) {
        digitalToggle(led3);
}
```
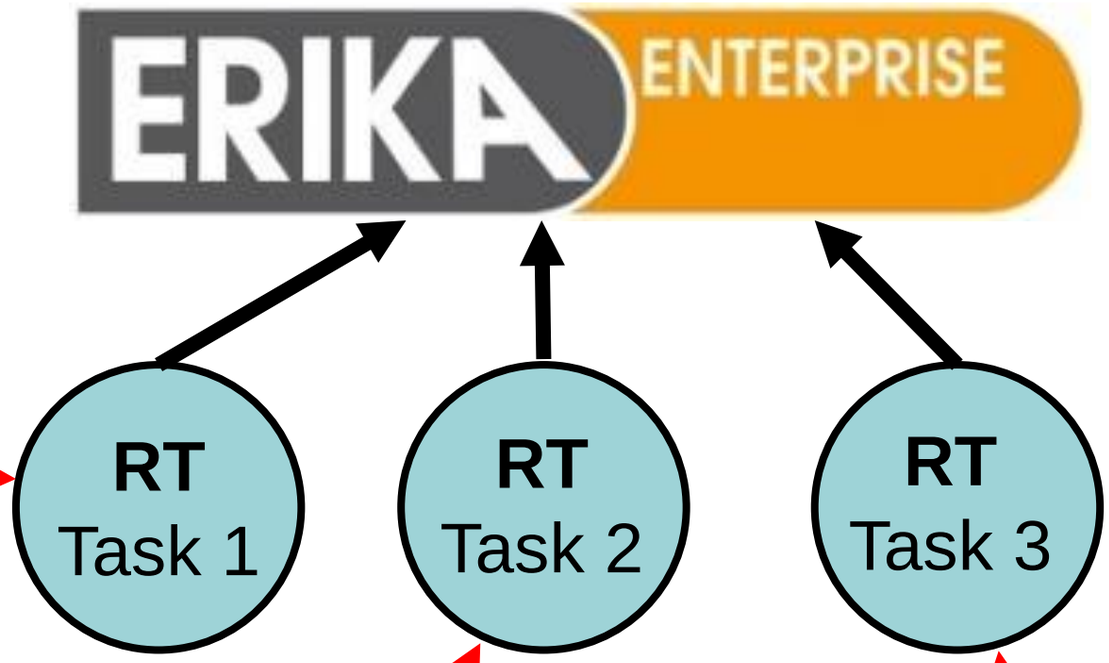



Erika Enterprise

- ERIKA Enterprise is a **static** RTOS:
  - All the RTOS configuration (*tasks, resources, counters, hardware configuration*) is decided at compiling time;
  - **Minimal** impact on the RAM;
  - **OIL** language is used to configure the RTOS.

Example

- Mapping to an **OSEK** application

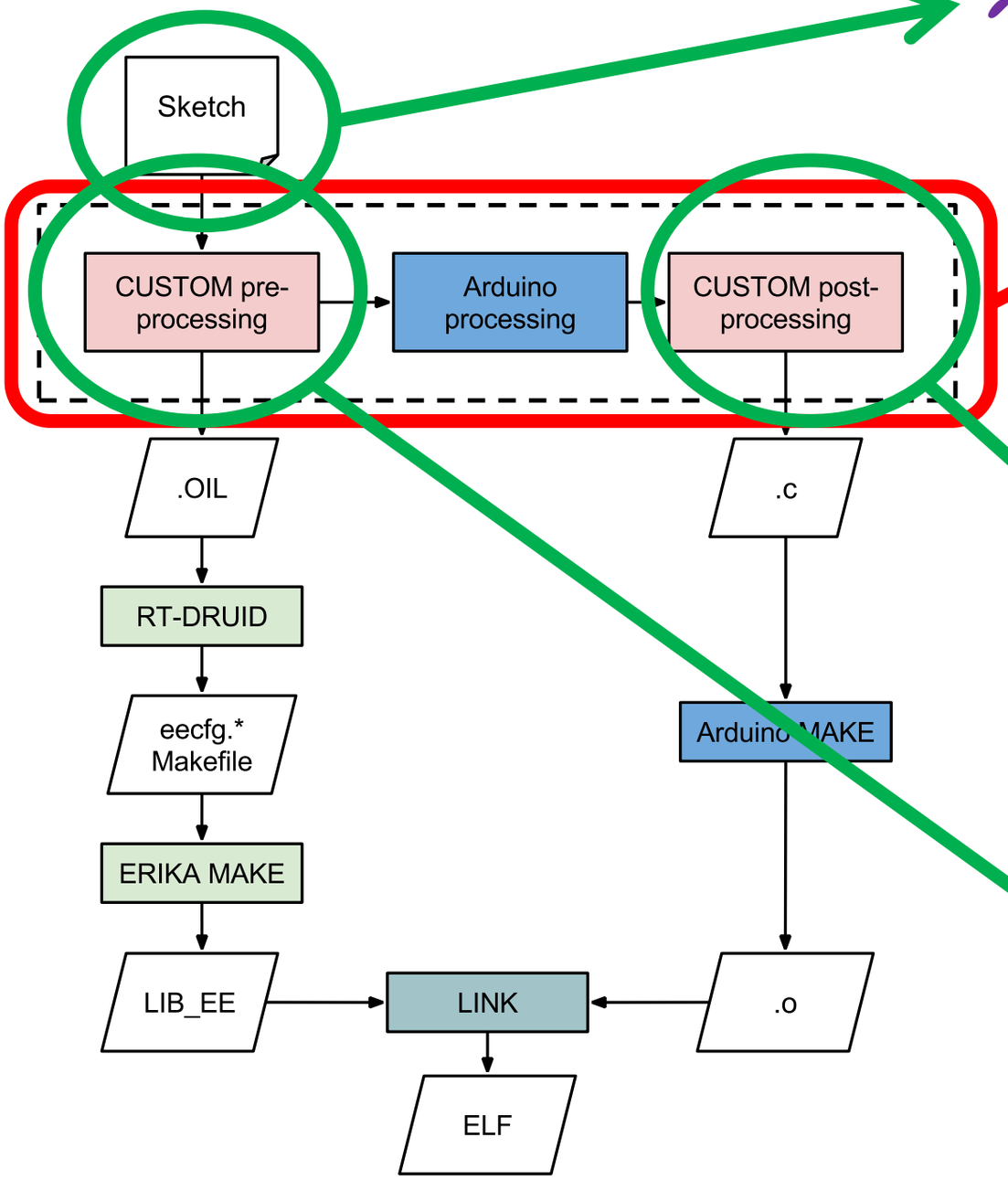
```
int led1 = 13;
int led2 = 14;
int led3 = 15;

void loop1(3000) {
        digitalToggle(led1);
}

void loop2(7000) {
        digitalToggle(led2);
}

void loop3(11000) {
        digitalToggle(led3);
}
```

OIL

```
TASK loop1 {
  PRIORITY = 0x01;
  SCHEDULE = FULL;
  STACK = SHARED;
};
ALARM Alarmloop1 {
  COUNTER = TaskCounter;
  ACTION = ACTIVATETASK {
             TASK = loop1;
};};

TASK loop2 {
  PRIORITY = 0x02;
  SCHEDULE = FULL;
  STACK = SHARED;
};
ALARM Alarmloop2 {
  COUNTER = TaskCounter;
  ACTION = ACTIVATETASK {
             TASK = loop2;
};};

TASK loop3 {
  PRIORITY = 0x03;
  SCHEDULE = FULL;
  STACK = SHARED;
};
ALARM Alarmloop3 {
  COUNTER = TaskCounter;
  ACTION = ACTIVATETASK {
             TASK = loop3;
};};
```

ERIKA ENTERPRISE

Build Process



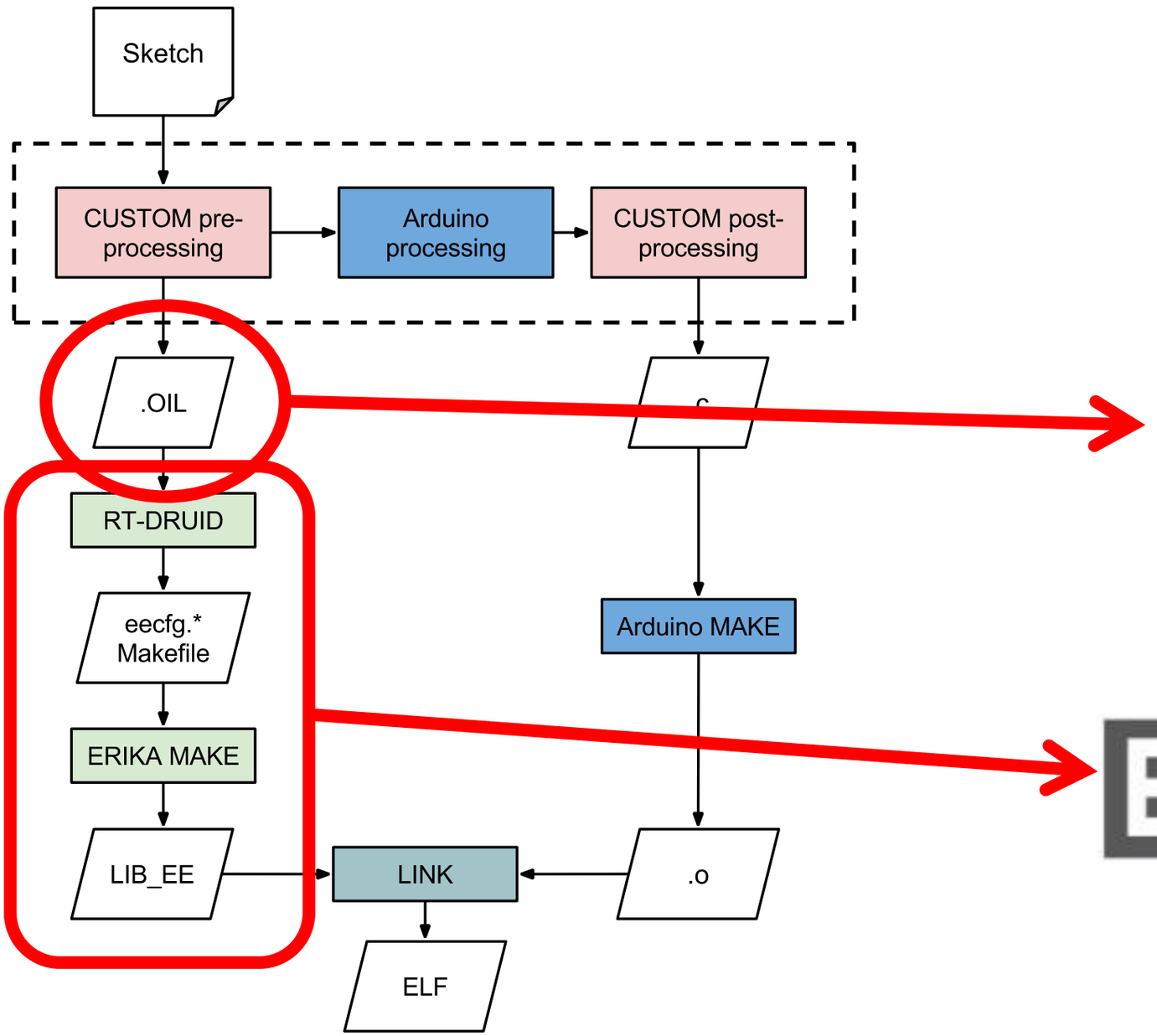
ARTE application

Core of the Arduino Real-Time Extension

Generates an ERIKA application code starting from the Arduino code

Parse the sketch an automatically generates the RTOS configuration

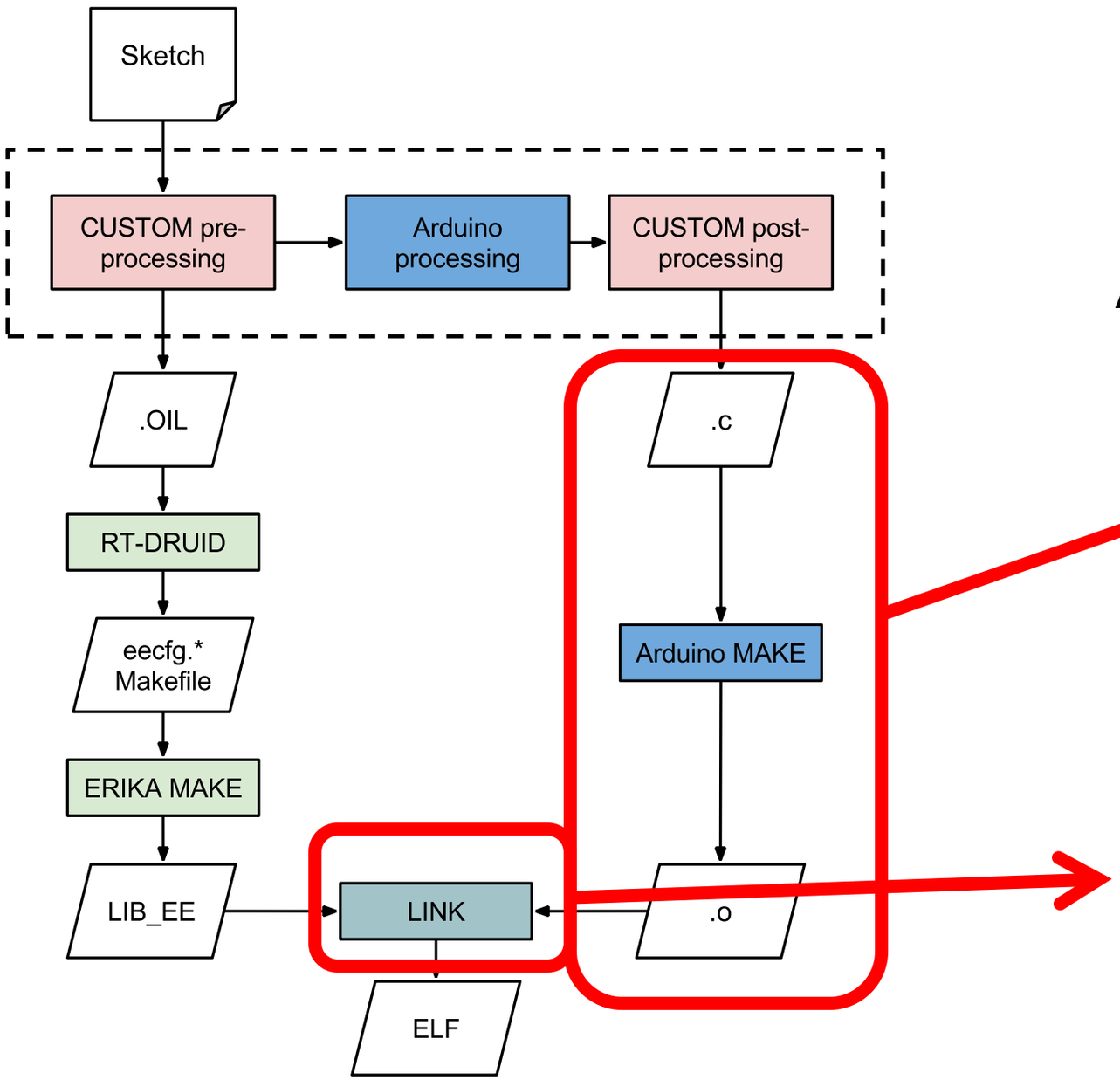
Build Process



OIL (OSEK Implementation Language)

ERIKA ENTERPRISE

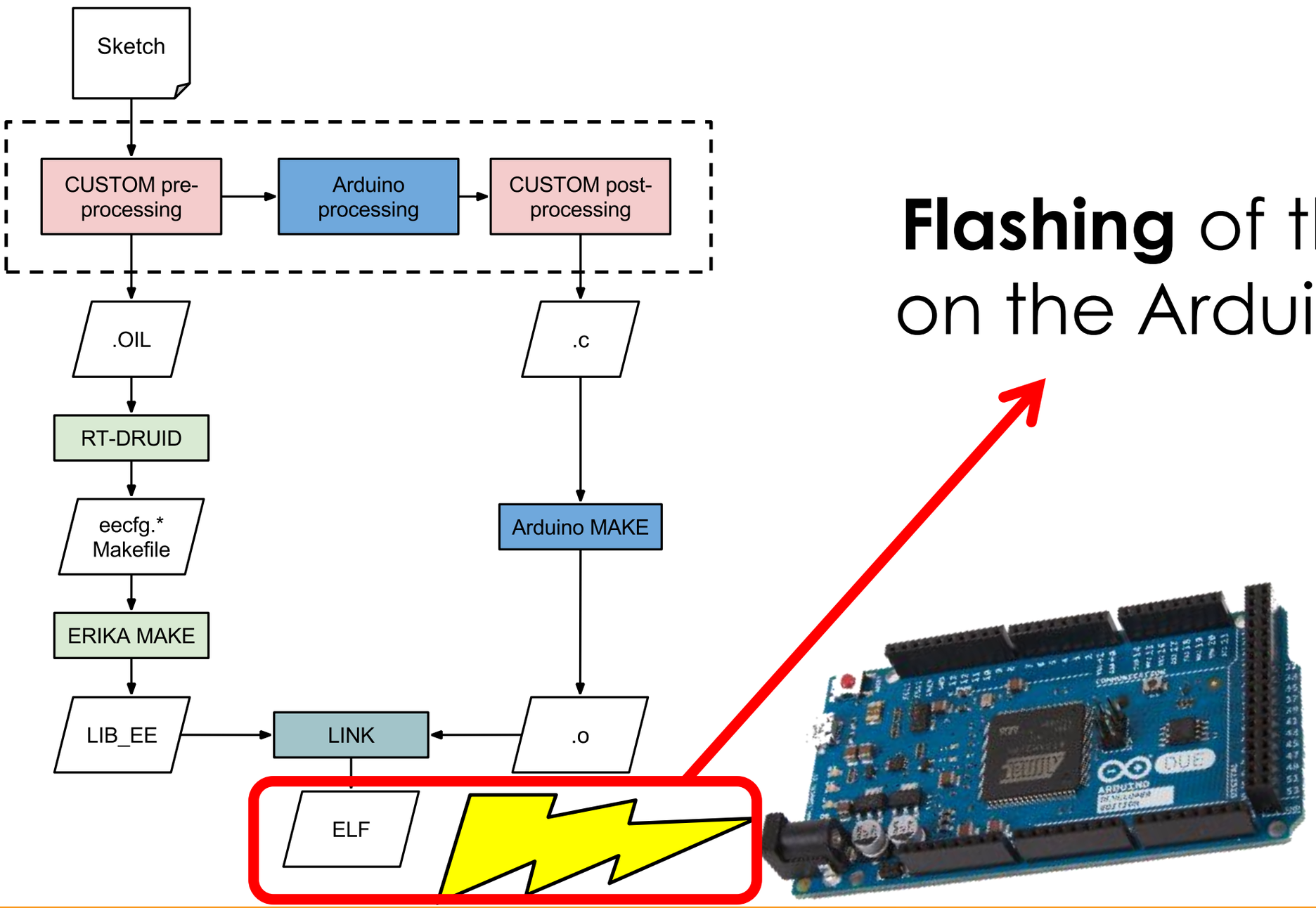
Build Process



Arduino build process as **ERIKA** application

Link all together!

Build Process



Flashing of the binary on the Arduino board

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Real-Time Systems Laboratory

DEMO

Arduino Real-Time Extension

- **Additional possible usage:**
  - **Fast prototyping**: an ERIKA application is automatically generated from the sketch; it can be used for extending the development by directly working with the RTOS.

Conclusion

- *ARTE* is an extension for the Arduino framework to support Real-Time Multitasking;
  - Simple programming interface with minimal impact on the Arduino programming model;
  - Relies on an OSEK/VDX RTOS (ERIKA Enterprise);

Thank you!

Alessandro Biondi
alessandro.biondi@sssup.it

Pasquale Buonocunto
p.buonocunto@sssup.it