ALMA MATER STUDIORUM
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APAI Lab02: PULP Embedded Programming

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Objective of the Class

Intro: PULP platform and the PULP-SDK

Tasks: some basics of C programming on PULP:

- Hello world
- vector sum,
- Matrix-vector multiplication
- Measuring execution performance

Programming Language: C

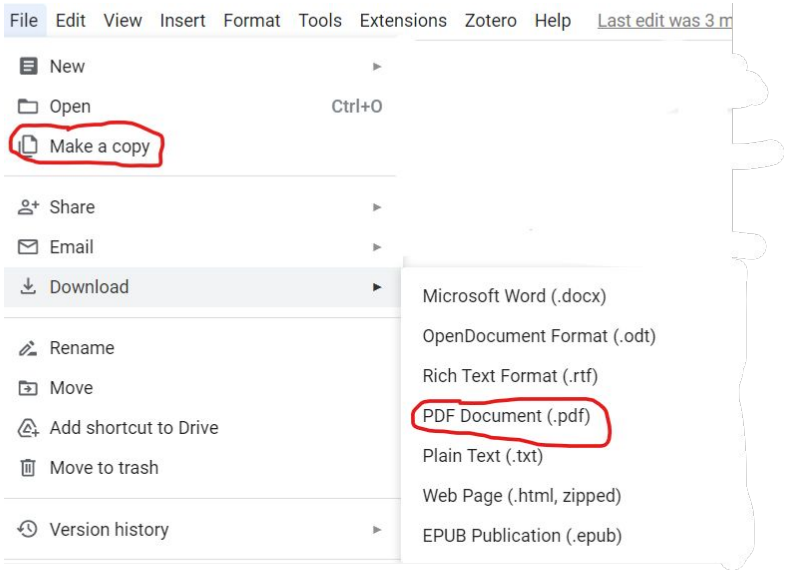
Lab duration: 3h

<u>The class is meant to be interactive: coding together and on your own!</u>

How to deliver the Assignment

You will deliver ONLY the GDOC assignment, no code

- Copy the google doc to your drive, so that you can edit. (File -> make a copy)
- Fill the tasks on this google doc.
- Export to pdf format.
- Rename the file to: LAB<number_of_the_lesson>_APAI_<your_name>.pdf
- Use Virtuale platform to load ONLY your .pdf file



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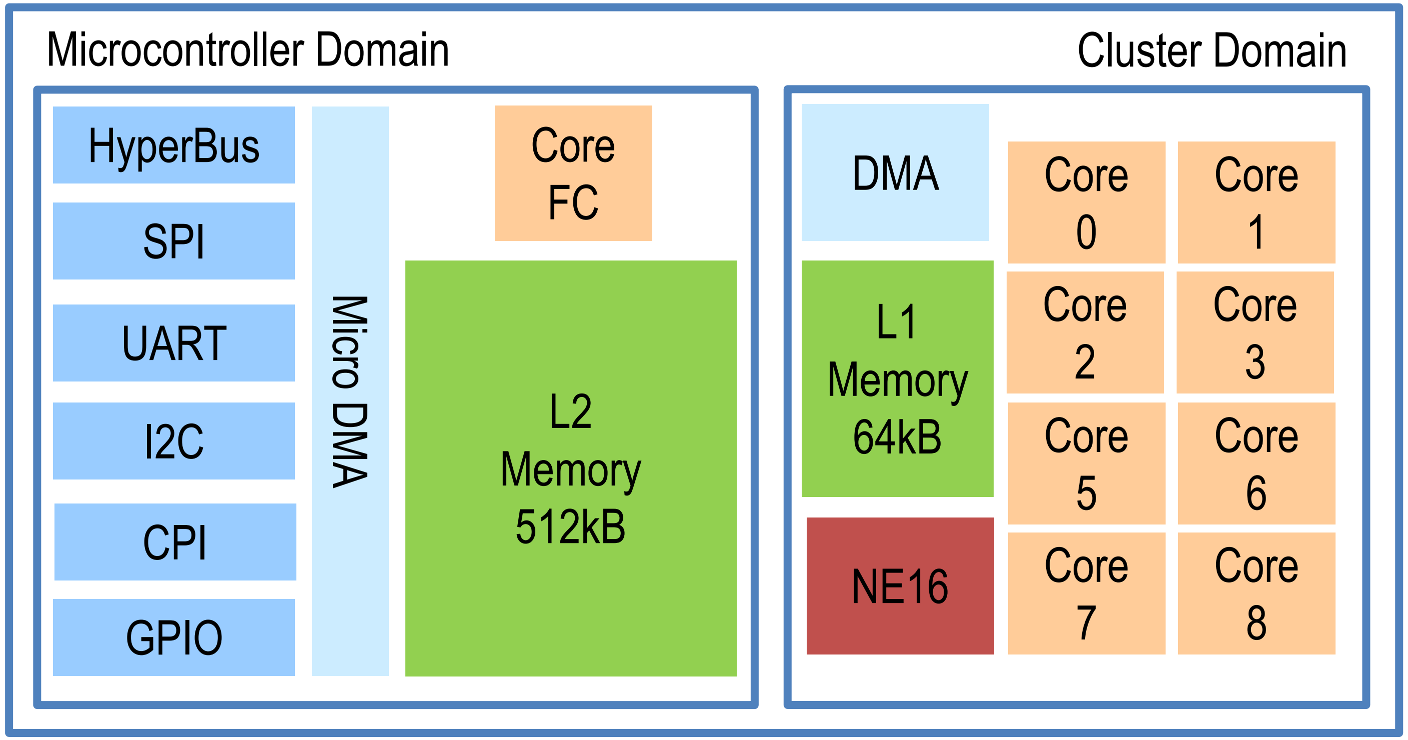
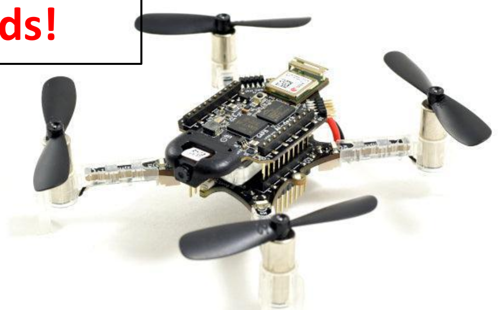
INTRO

Get confident with the PULP Platform



- **Cores**: 1 + 8
- **On-chip Memories**
  - A level 2 Memory, shared among all cores
  - A level 1 Memory, shared by the 8-cores cluster
- **cluster-DMA:** A multi-channel 1D/2D DMA, controlling the transactions between the L2 and L1 memories
- **micro-DMA**: A smart, lightweight and completely autonomous DMA () capable of handling complex I/O scheme
  - **Bus+Peripherals:** HyperBus, I2S, CPI, timers, SPI, GPIOs, etc…

NB: this is the architecture you find on our nano-drones and GAP boards!



GitHub HW Project: https://github.com/pulp-platform/pulp
HW Documentation:
https://raw.githubusercontent.com/pulp-platform/pulp/master/doc/datasheet.pdf

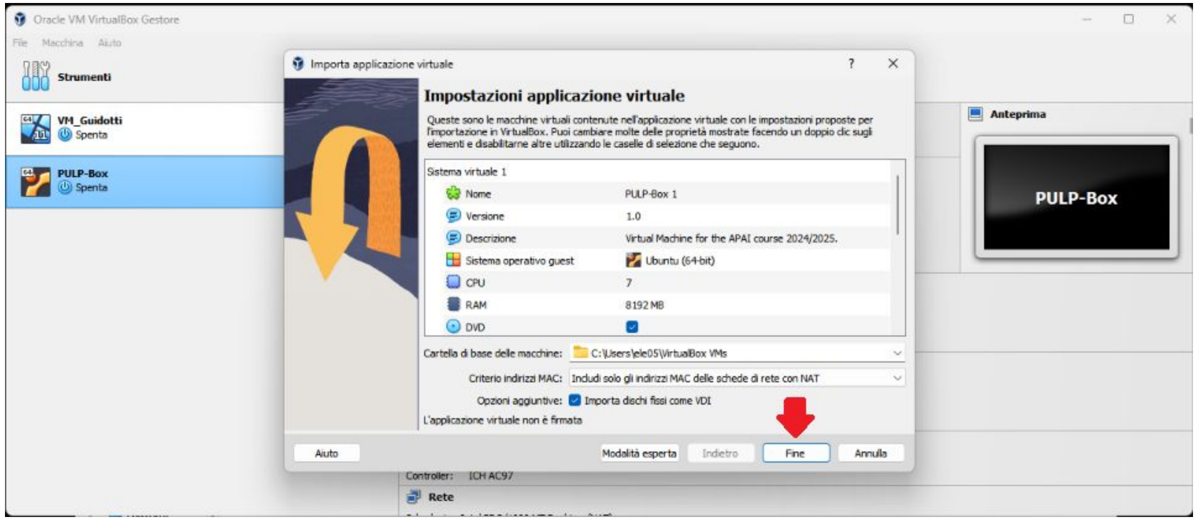
We will work in groups of 2 people

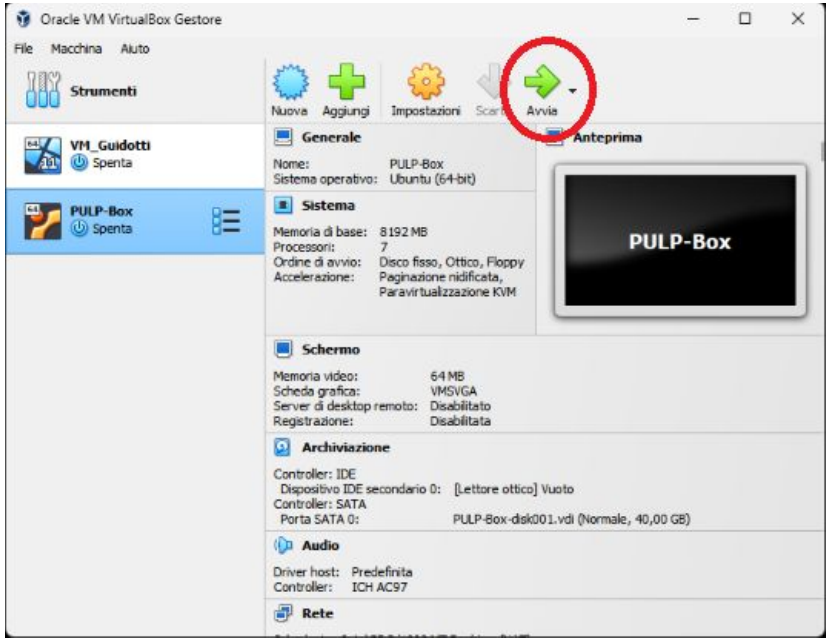
Lab PCs are limited! Find a colleague to work with!

Remember to send the assignment with both names in the file name!!

Opening the VM and VSCode

1. On the lab's PCs, open the file explorer and go to This PC, C:/VM_Nadalini/
2. Double click on PULP-box.ova
3. VirtualBox opens, just click on "Fine"
4. Wait for the VM to be imported
5. Open the VM with "Avvia"





Password is 'pulp'

Opening the VM and VSCode

1. Open a terminal (right click – open a new terminal)

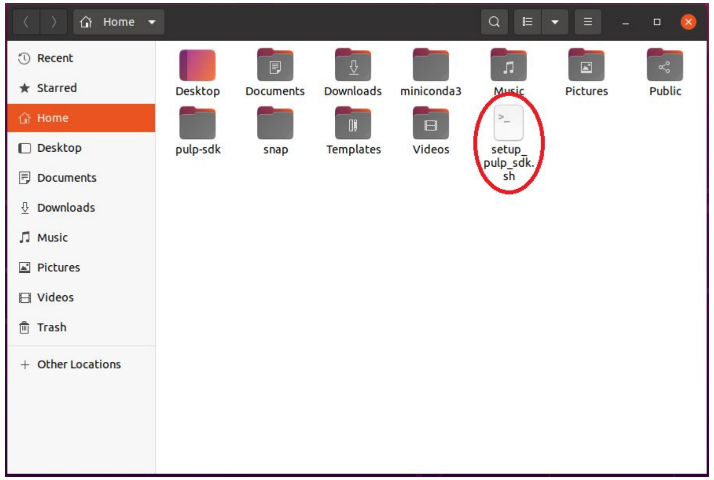
2. Open a text editor (For example “VSCode”):

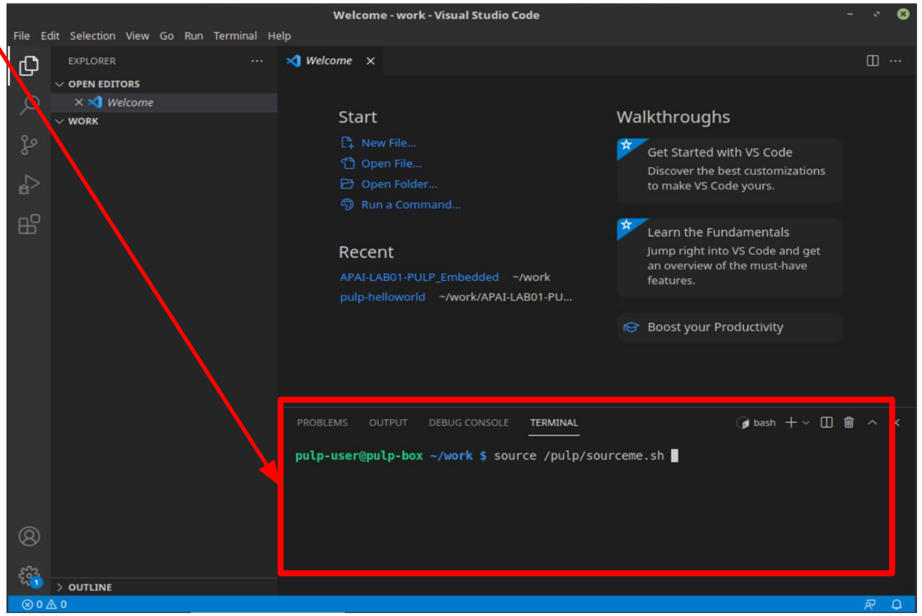
```
$ code .
```

   Now you can use the integrated terminal (open with CTRL+J) to run your applications!

IMPORTANT: every time you open a new terminal to work on PULP, launch

```
$ source setup_pulp_sdk.sh
```





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Getting Started: *Helloworld*

IMPORTANT: activate the pulp-sdk module file <u>every</u> time a new shell is open.

```
$ source setup_pulp_sdk.sh
```

HOW TO RUN THE CODE:

```
$ git clone https://github.com/EEESlab/APAI24-LAB02-PULP-Embedded-Programming
$ cd APAI24-LAB02-PULP-Embedded-Programming
$ cd pulp-helloworld/
$ make clean all run
```

test.c

- Can you see the **Helloworld from PULP!** ?

```
int main()
{
    printf("Helloworld from PULP!\n");
}
```

Behind the box: Build Automation with Makefiles

Clean previous build processes
(folder *BUILD/*)

Compile the program and produce the ***binary code***

Run ***binary code*** *on the target platform*

```
$ make clean all run
```

Build automation is the process of automating the main steps required to create a software, including *compiling*, *assembling*, *linking* and (possibly) *testing*

Make is one of the most widespread utilities

 configuration files are called **Makefiles**

A *Makefile* contains rules in the form:

```
target: prerequisites
<TAB> command
```

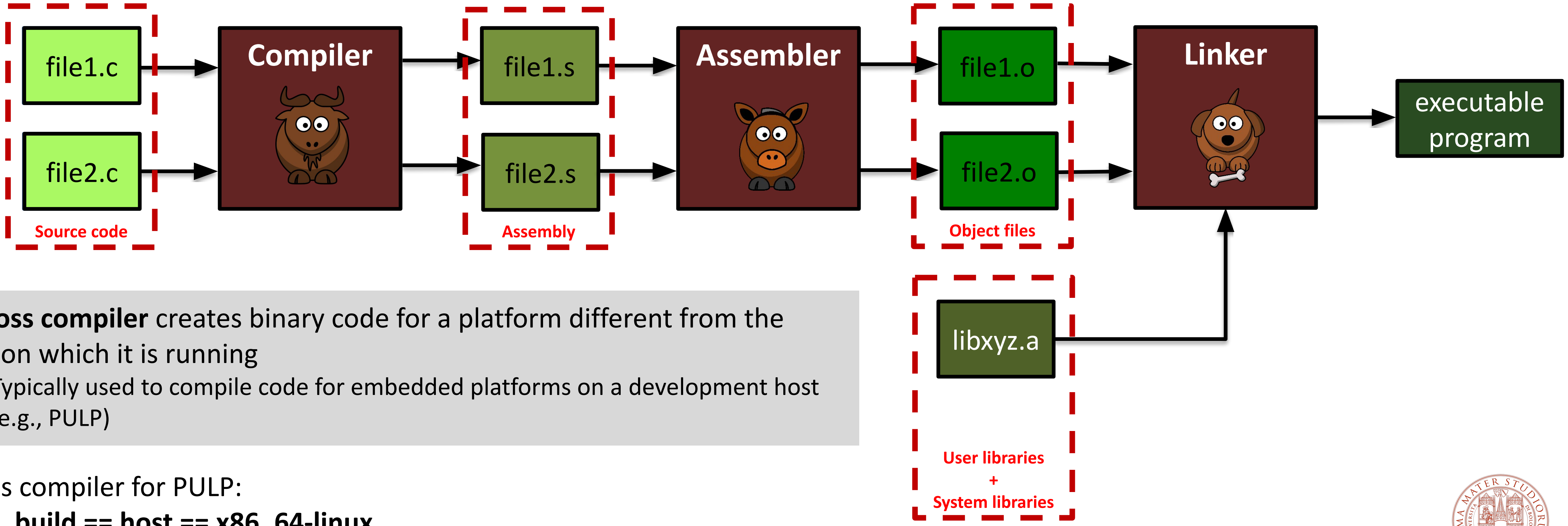
Makefile

```
APP = test

# This is a comment
APP_SRCS    += test.c
APP_CFLAGS  += -O3 -g
APP_LDFLAGS +=

include $(RULES_DIR)/pmsis_rules.mk
```

Compilation toolchain

A compilation toolchain includes several tools to achieve its final goal

- The **COMPILER** translates high-level source code (e.g., C) to a lower-level representation (e.g., assembly)
- The **ASSEMBLER is** program that translates assembly language to machine language
- The **LINKER** combines multiple object files into a single executable



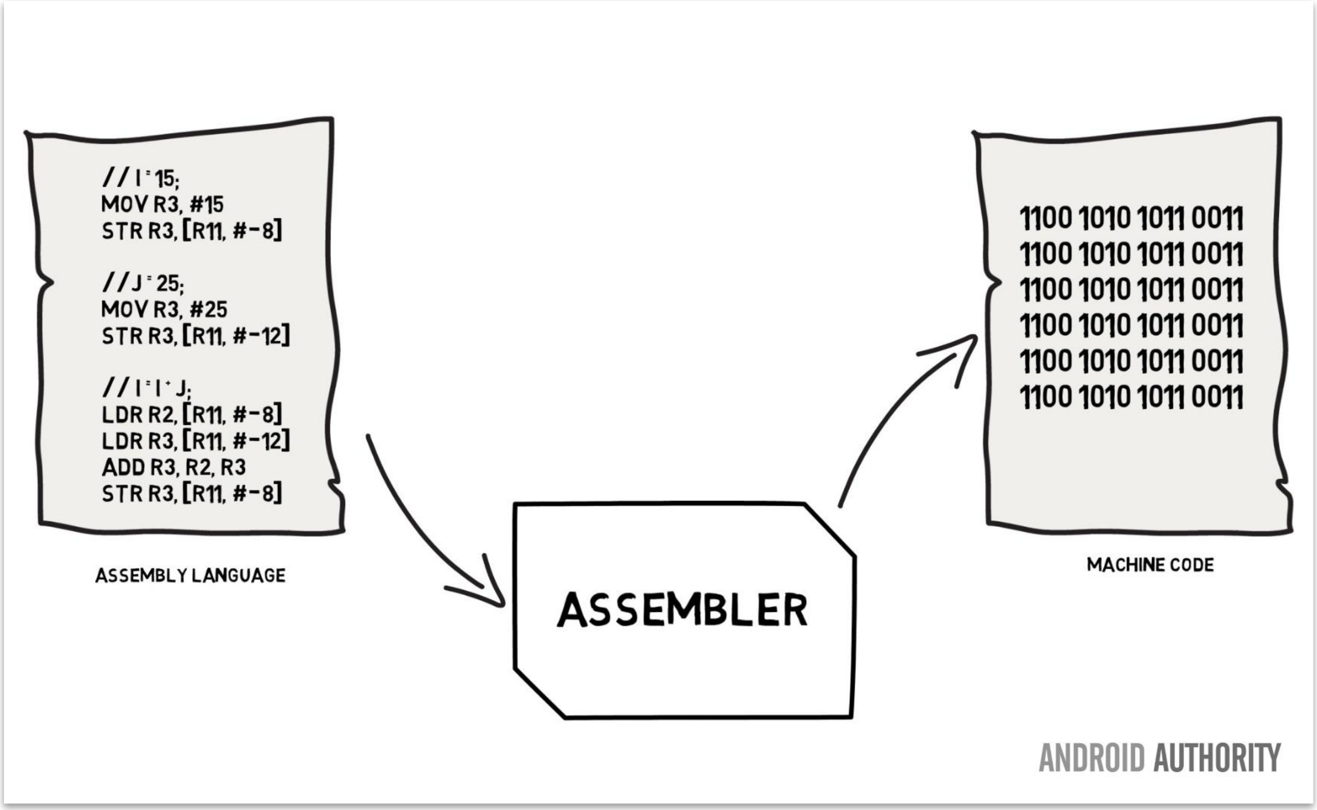
A **cross compiler** creates binary code for a platform different from the one on which it is running

- Typically used to compile code for embedded platforms on a development host (e.g., PULP)

Cross compiler for PULP:

build == host == x86_64-linux

target = riscv-none



Assembly vs. machine code

Machine code bytes	Assembly language statements
	`foo:`
`B8 22 11 00 FF`	`movl $0xFF001122, %eax`
`01 CA`	`addl %ecx, %edx`
`31 F6`	`xorl %esi, %esi`
`53`	`pushl %ebx`
`8B 5C 24 04`	`movl 4(%esp), %ebx`
`8D 34 48`	`leal (%eax,%ecx,2), %esi`
`39 C3`	`cmpl %eax, %ebx`
`72 EB`	`jnae foo`
`C3`	`retl`

Instruction stream

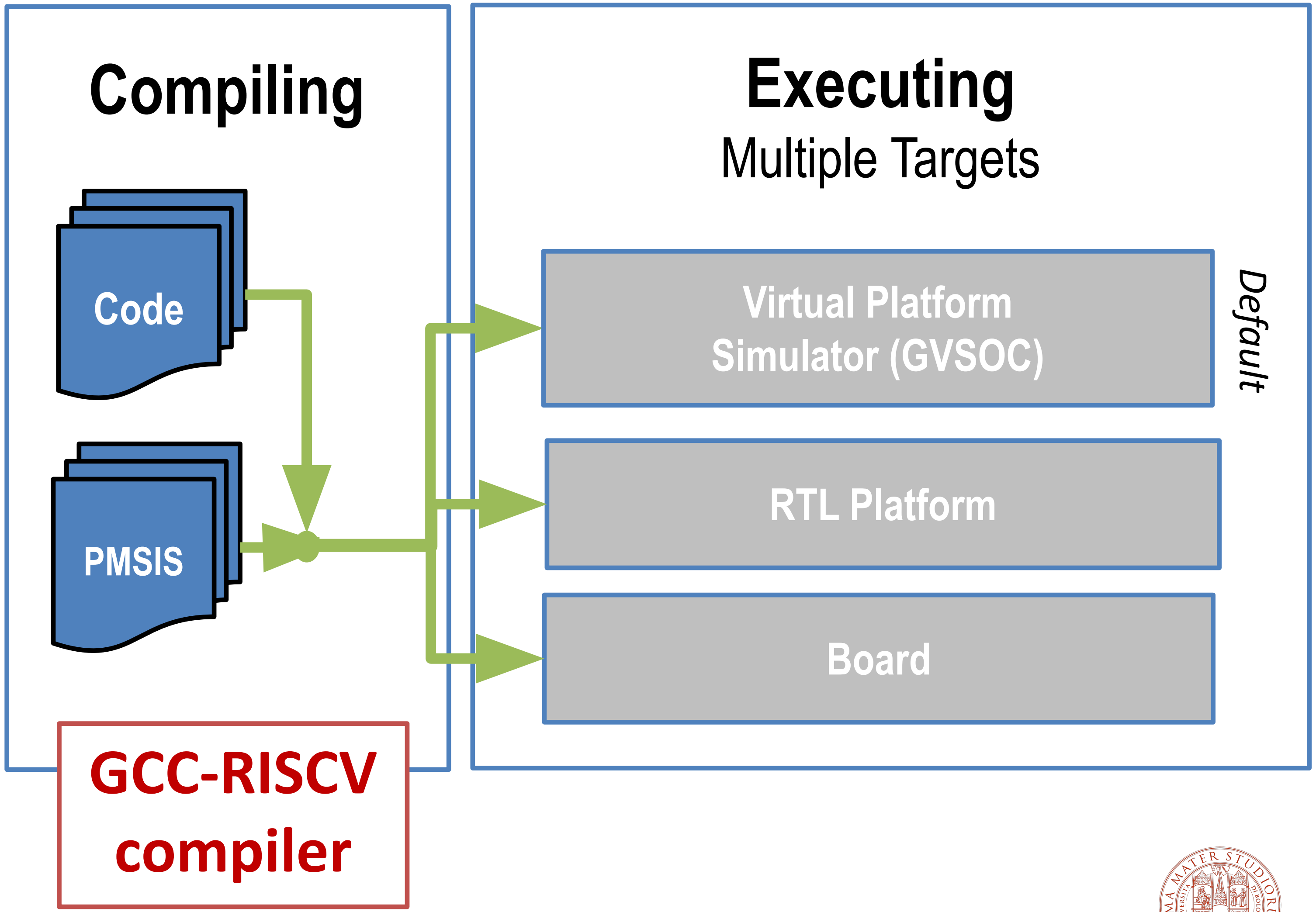
```
B8 22 11 00 FF 01 CA 31 F6 53 8B 5C 24
04 8D 34 48 39 C3 72 EB C3
```

PULP Software Environment Workflow

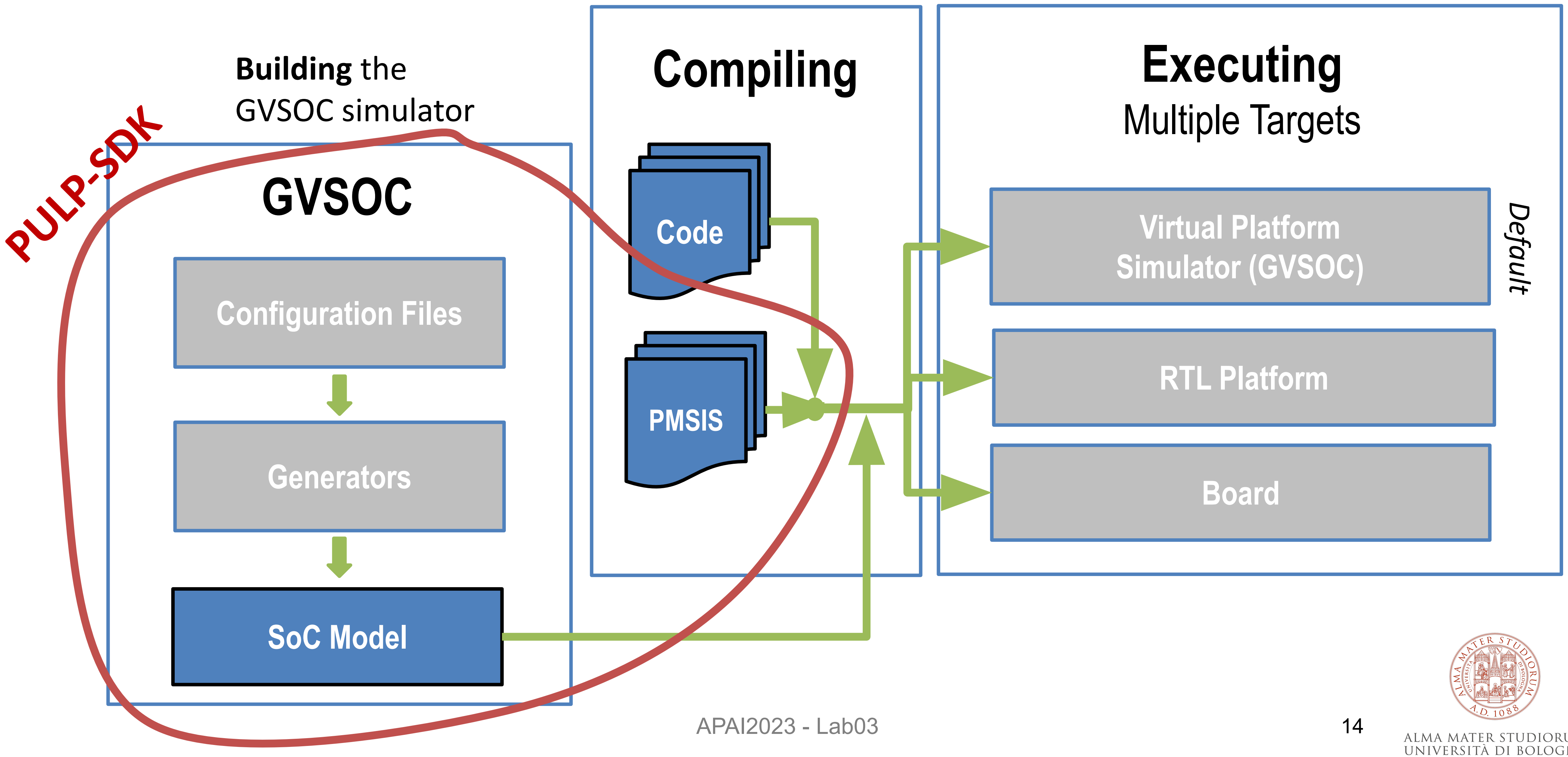
Application code: *main* function, application libraries, e.g. CNN inference function code…

Runtime SW: Peripheral *Drivers,* RTOS, Board support packages (BSP)

- *PMSIS layer*



PULP Software Environment Workflow



PULP SDK (software development kit)

The PULP-SDK (https://github.com/pulp-platform/pulp-sdk) includes a **PULP platform simulator (GVSOC)** and the SW libraries.

Check the */pulp/pulp-sdk* folder:

- `rtos/` runtime code and software stack
- `tools/` configuration files, python generators, pulp runner and the gvsoc components
- `tests/` sample code to test the platform's features
- `applications/` full-application codes

```
$ cd /pulp/pulp-sdk
```

```
pulp-user@pulp-box /pulp/pulp-sdk $ ll
total 60
drwxrwxr-x  9 pulp-user pulp-user  4096 Feb  3  2021 ./
drwxrwxr-x  6 pulp-user pulp-user  4096 Feb  3  2021 ../
drwxrwxr-x  6 pulp-user pulp-user  4096 Feb  3  2021 build/
drwxrwxr-x  2 pulp-user pulp-user  4096 Feb  3  2021 configs/
drwxrwxr-x  8 pulp-user pulp-user  4096 Feb  3  2021 .git/
-rw-rw-r--  1 pulp-user pulp-user    80 Feb  3  2021 .gitignore
drwxrwxr-x  4 pulp-user pulp-user  4096 Feb  3  2021 install/
-rw-rw-r--  1 pulp-user pulp-user 11357 Feb  3  2021 LICENSE
-rw-rw-r--  1 pulp-user pulp-user   877 Feb  3  2021 Makefile
-rw-rw-r--  1 pulp-user pulp-user  2455 Feb  3  2021 README.md
drwxrwxr-x  4 pulp-user pulp-user  4096 Feb  3  2021 rtos/
drwxrwxr-x  2 pulp-user pulp-user  4096 Feb  3  2021 rules/
drwxrwxr-x 10 pulp-user pulp-user  4096 Feb  3  2021 tools/
pulp-user@pulp-box /pulp/pulp-sdk $
```

You could get the latest update from the open-source community and rebuild the GVSOC simulator

```
$ git pull origin main
$ source configs/pulp-open.sh
$ make build
```

Do NOT do it

GVSoC – Features

Virtual platform features:

- *C++* for fast native simulation
- *Python* for instantiation + configuration
- Complete set of traces to see what happen

Timing model:

- Fully-event based, instances can generate events at specific time
- Includes timing models for interconnects, DMACs, memories…
- Performance counters for information from the execution

Simulation performance:

- Around 1MIPS simulation speed
- Functionally aligned and calibrated with HW
- Timing accuracy is within 10-20% of target HW

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TASK1

TASK 1: vector sum example

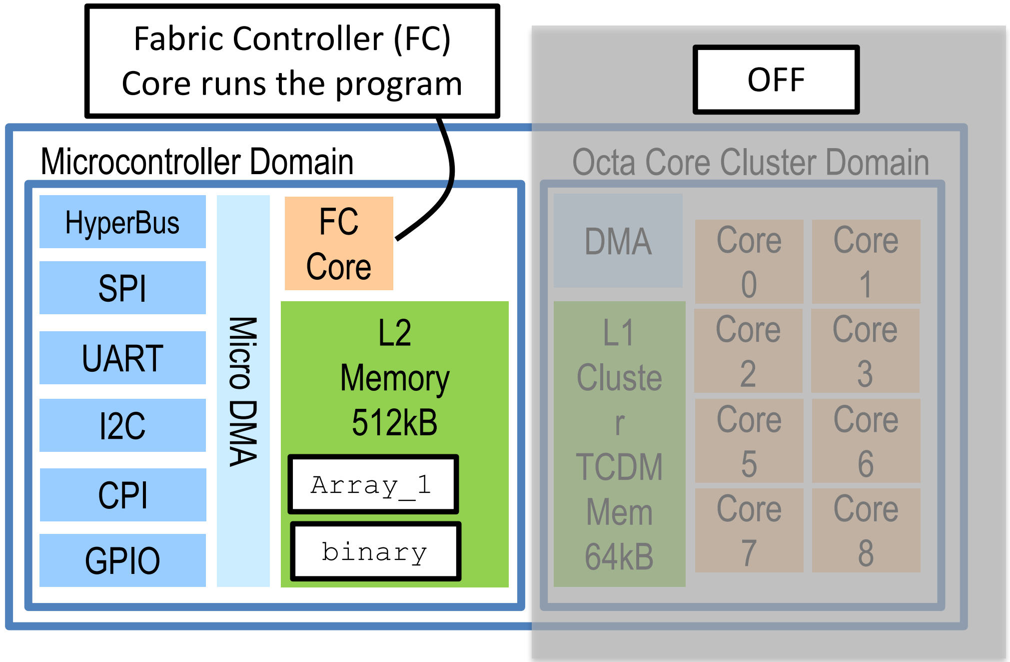
Preparation

1. Clone repository for the lab, if you didn't already do it

```
git clone
https://github.com/EEESlab/APAI24-LAB02-PULP-Embedded-Programming
```

2. Go into folder for task1

```
cd APAI24-LAB02-PULP_Embedded_Programming/
cd vector_sum/
make clean all run
```



Tasks

Read your assignment!

The `vector_sum()` function returns the element-wise add of the values in `array_1[N]`.

Note: the `main` include the function testbench : $S = \sum_{i=1}^{N} i = \frac{N \cdot (N-1)}{2}$

Good practice for test!

I. Array initialization (*a[i] = i*)
II. Function Call
III. Check Result

Task 1.2

Take now a look to the code.
What happen if you change:
(*line 13*) `#define N 350`
□ **How would you solve it?**

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SOLUTION: Casting Variables

(line 13) `#define N 350`

Output: Result is **not** correct. Got 37105 instead of 61425

If printing the `array_1` values after initialization:

```
1 2 3 4 5 6 7 8 9 10 11 12 13 14 [….] 247 248 249 250 251 252 253 254 255 0 1 2 3 4 5 6 7 8 […] 88 89 90 91 92 93 94
```

- `unsigned char` datatype can represent numbers from 0 to 255!! If >255, assigned values get truncated (value % 256)!
- **Solution:** cast array_1 to `int` or `short int` (and the function's arguments!)

(optional) Passing parameters via `Makefile`

(OPTIONAL) After applying the fix
We can pass parameters via Makefile: comment line 13, change the *Makefile* and launch:

```
$ make clean all run N=350
```

Makefile

```
APP = test
N?=50

APP_SRCS    += test.c
APP_CFLAGS  += -O3 -g
APP_CFLAGS  += -DN=$(N)
APP_LDFLAGS +=
include $(RULES_DIR)/pmsis_rules.mk
```

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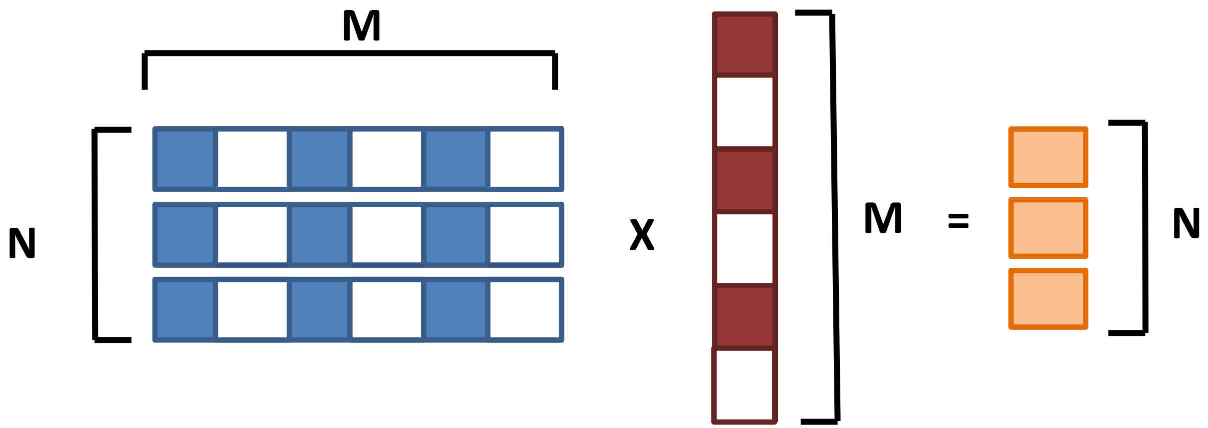
Intro: TASK2

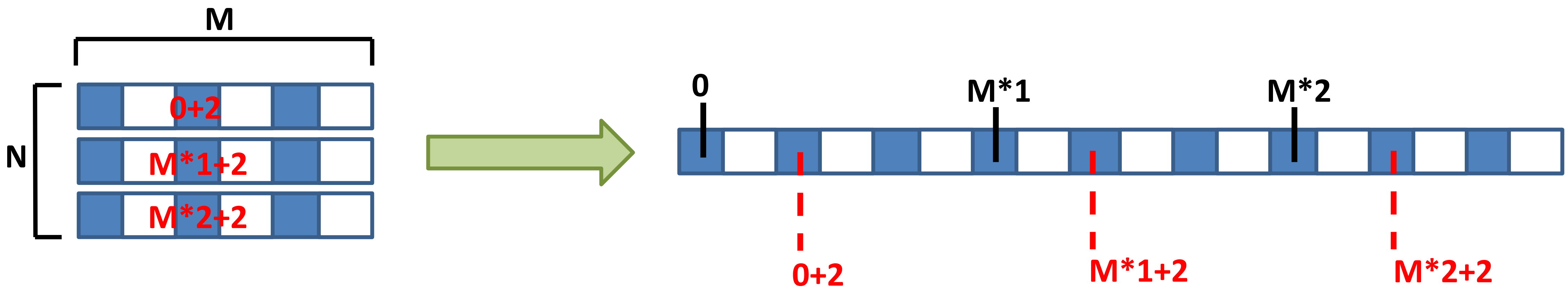
TASK2: Matrix-Vector Product




```
$ cd matrix_vector/
$ make clean all run
```

Example II: Matrix-Vector Product

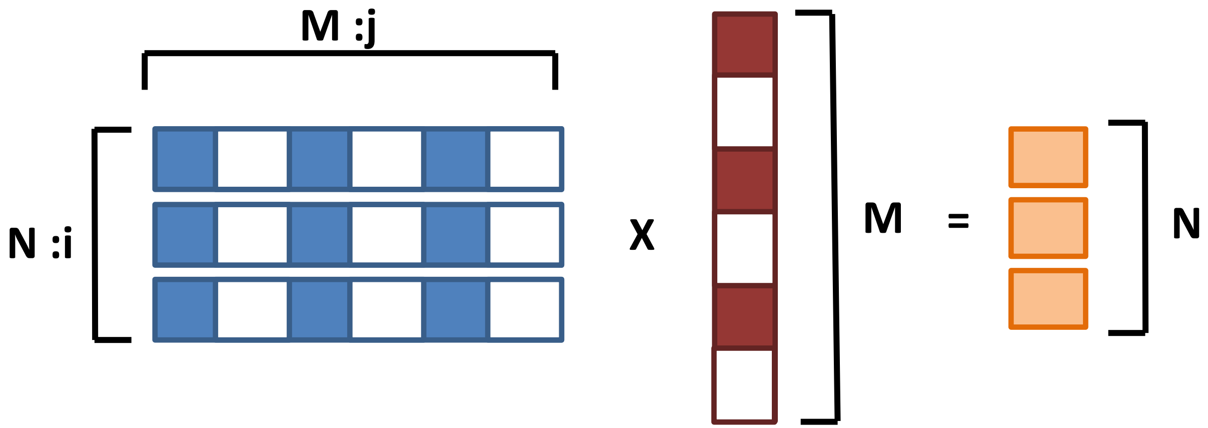
A multi-dimensional array, including a matrix, is efficiently represented as a memory-contiguous array (**NOT** Mat[M][N]).



In general: **Mat[i][j]** -> **M[i*M+j]**

```
$ cd matrix_vector/
$ make clean all run
```

Example II: Matrix-Vector Product




```
// generic matrix-vector multiplication
int gemv(int N, int M, float * mat, float *vec, float * output_vec){

    for (int i=0; i<N; i++){
      for (int j=0; j<M; j++){
        vec_o[i] += mat_i[i*size_M+j] * vec_i[j];
      }
    }

}
```

Assembly Code

A disassembler is a computer program that translates machine language into assembly language → the inverse operation to that of an assembler.

Disassembly, the output of a disassembler, is often formatted for human-readability rather than suitability for input to an assembler, making it principally a reverse-engineering tool. *[Wikipedia]*

To obtain the assembly code use the command:

```
$ make dis > dis.txt
```

Check the RI5CY User manual:

https://riscv.org/wp-content/uploads/2017/05/riscv-spec-v2.2.pdf
https://www.pulp-platform.org/docs/ri5cy_user_manual.pdf

Assembly Code

```
1c008706 <gemv>:
1c008706:   02a05d63        blez   a0,1c008740 <gemv+0x3a>
1c00870a:   00259f13        slli   t5,a1,0x2
1c00870e:   8fb6            mv     t6,a3
1c008710:   01e68e33        add    t3,a3,t5
1c008714:   4e81            li     t4,0
1c008716:   a005            j      1c008736 <gemv+0x30>
1c008718:   0048230b        p.lw   t1,4(a6!)
1c00871c:   0046a88b        p.lw   a7,4(a3!)
1c008720:   431c            lw     a5,0(a4)
1c008722:   431307b3        p.mac  a5,t1,a7
1c008726:   c31c            sw     a5,0(a4)
1c008728:   ffc698e3        bne    a3,t3,1c008718 <gemv+0x12>
1c00872c:   0e85            addi   t4,t4,1
1c00872e:   967a            add    a2,a2,t5
1c008730:   0711            addi   a4,a4,4
1c008732:   01d50763        beq    a0,t4,1c008740 <gemv+0x3a>
1c008736:   86fe            mv     a3,t6
1c008738:   8832            mv     a6,a2
1c00873a:   fcb04fe3        bgtz   a1,1c008718 <gemv+0x12>
1c00873e:   b7fd            j      1c00872c <gemv+0x26>
```

1c008738: 8832 mv a6,a2

PC | opcode | Instruction

Program counter

```
// generic matrix-vector multiplication
void gemv(int size_N, int size_M,
      float * mat_I, float *vec_i, float * vec_o)
{
    for (int i=0; i<size_N; i++){
      for (int j=0; j<size_M; j++){
        // multiply accumulate operation
        vec_o[i] += mat_i[i*size_M+j] * vec_i[j];
      }
    }
}
```

Inner loop

In the **Makefile**:

1. Change from -01 to -03. What has changed in the assembly?
2. Remove –mnohwloop. What has changed in the assembly?

<u>NB</u>. After changing the compiler flags, compile the code again and generate and disassembly using `make dis`

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Assembly Code: O3 optimization

```
APP = matrix-vector

APP_SRCS += test.c
APP_CFLAGS += -O3 -g -mnohwloops
APP_LDFLAGS +=

include $(RULES_DIR)/pmsis_rules.mk
```

```
1c008706 <gemv>:
1c008706:   02a05c63        blez   a0,1c00873e <gemv+0x38>
1c00870a:   02b05a63        blez   a1,1c00873e <gemv+0x38>
1c00870e:   00259e93        slli   t4,a1,0x2
1c008712:   050a            slli   a0,a0,0x2
1c008714:   00a70e33        add    t3,a4,a0
1c008718:   01d68333        add    t1,a3,t4
1c00871c:   0047258b        p.lw   a1,4(a4!) # 10004 <__l1_heap_size+0x20>
1c008720:   87b6            mv     a5,a3
1c008722:   8532            mv     a0,a2
1c008724:   0045288b        p.lw   a7,4(a0!)
1c008728:   0047a80b        p.lw   a6,4(a5!)
1c00872c:   430885b3        p.mac  a1,a7,a6
1c008730:   feb72e23        sw     a1,-4(a4)
1c008734:   fef318e3        bne    t1,a5,1c008724 <gemv+0x1e>
1c008738:   9676            add    a2,a2,t4
1c00873a:   feee11e3        bne    t3,a4,1c00871c <gemv+0x16>
1c00873e:   8082            ret
```

The -03 optimized code get rid of a *lw* instruction because the accumulator is kept in the register file!

Inner loop

```
// generic matrix-vector multiplication
void gemv(int size_N, int size_M,
float * mat_I, float *vec_i, float * vec_o)
{
    for (int i=0; i<size_N; i++){
        for (int j=0; j<size_M; j++){
            // multitply accumulate operation
            vec_o[i] += mat_i[i*size_M+j] * vec_i[j];
        }
    }
}
```

Assembly Code: HW loops

APP = matrix-vector

APP_SRCS += test.c

APP_CFLAGS += **-O3** -g ~~-mnohwloops~~

APP_LDFLAGS +=

include $(RULES_DIR)/pmsis_rules.mk

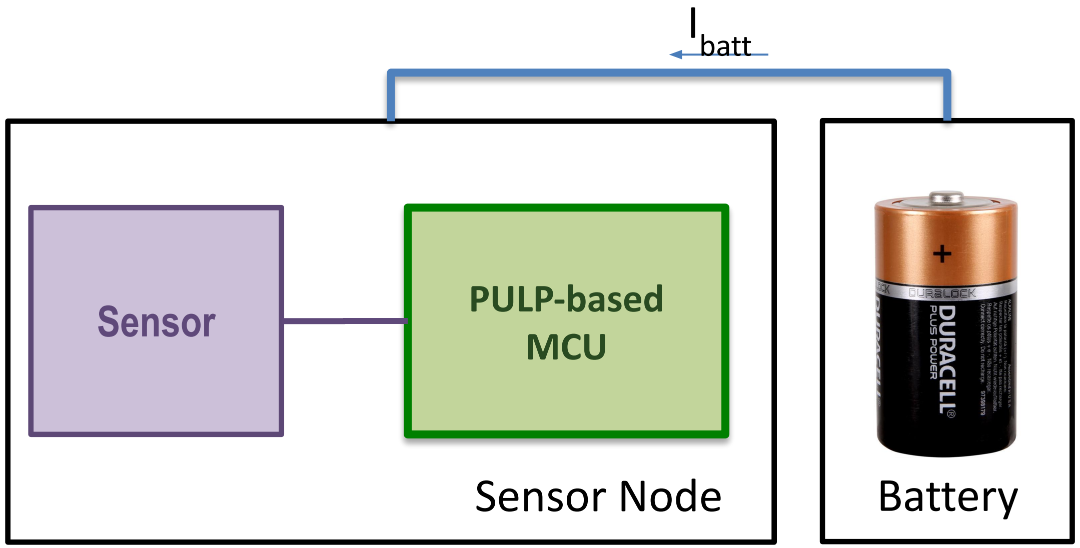
```
1c008706 <gemv>:
1c008706:   04a05463   blez    a0,1c00874e <gemv+0x48
1c00870a:   04b05263   blez    a1,1c00874e <gemv+0x48
1c00870e:   00251e13   slli    t3,a0,0x2
1c008712:   1e71       addi    t3,t3,-4
1c008714:   00259e93   slli    t4,a1,0x2
1c008718:   002e5e13   srli    t3,t3,0x2
1c00871c:   01d68f33   add     t5,a3,t4
1c008720:   0e05       addi    t3,t3,1
1c008722:   015e407b   lp.setup   x0,t3,1c00874c <gemv+0x46>
1c008726:   40df07b3   sub     a5,t5,a3
1c00872a:   17f1       addi    a5,a5,-4
1c00872c:   0047258b   p.lw    a1,4(a4!) # 10004 <__l1_heap_size+0x20>
1c008730:   8389       srli    a5,a5,0x2
1c008732:   8836       mv      a6,a3
1c008734:   8532       mv      a0,a2
1c008736:   0785       addi    a5,a5,1
1c008738:   0087c0fb   lp.setup   x1,a5,1c008748 <gemv+0x42>
1c00873c:   0045230b   p.lw    t1,4(a0!)
1c008740:   0048288b   p.lw    a7,4(a6!)
1c008744:   431305b3   p.mac   a1,t1,a7
1c008748:   feb72e23   sw      a1,-4(a4)
1c00874c:   9676       add     a2,a2,t4
1c00874e:   8082       ret
```

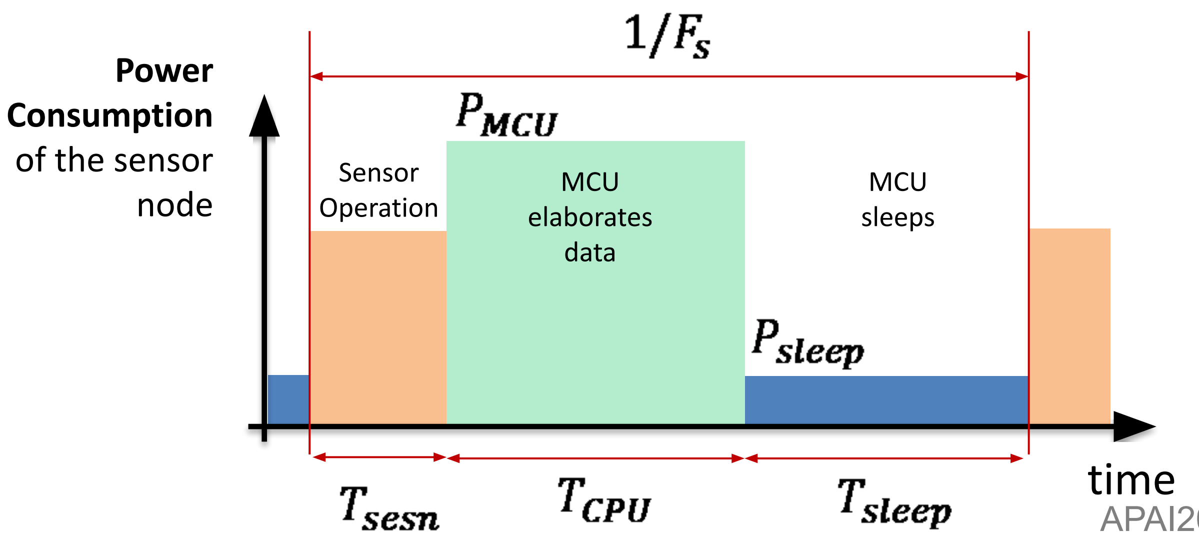
Hardware Loops Instructions have been placed!

Inner loop

```
// generic matrix-vector multiplication
void gemv(int size_N, int size_M,
float * mat_I, float *vec_i, float * vec_o)
{
    for (int i=0; i<size_N; i++){
      for (int j=0; j<size_M; j++){
        // multiply accumulate operation
        vec_o[i] += mat_i[i*size_M+j] * vec_i[j];
      }
    }
}
```

Assessing the MCU performance





Goal

- Extending the battery lifetime
  - Minimize the sensor node energy consumption
- Real time processing of sensor data

$$\min E_s + E_{MCU}$$
$$\text{s.t. } T_{CPU} < 1/F_s$$

Assuming:

- a fixed sample rate F_s a negligible sensor energy cost $E_s \ll E_{MCU}$(e.g., $T_{sesn} \ll 1/F_s$)
- a constant power envelope of the MCU for active (P_{MCU}) and sleep ($P_{sleep} \ll P_{MCU}$) modes

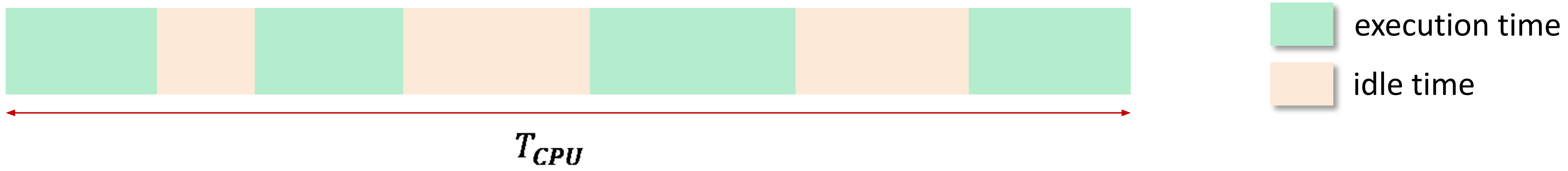
$$\min T_{CPU}\, P_{MCU} + T_{sleep} P_{sleep}$$
$$T_{CPU} + T_{sleep} = 1/F_s$$

Aim: minimize the processing time T_{CPU}

What can we optimize? -> the execution time

The processing time T_{CPU} composes of:

- the **execution time**, where the CPU
- the **idle time**, where the CPU waits for events or IRQ (the core may be clock gated to save power)



Given a CPU clock frequency, the <u>performance of a task (e.g. a C function) can be measured by</u> accounting:

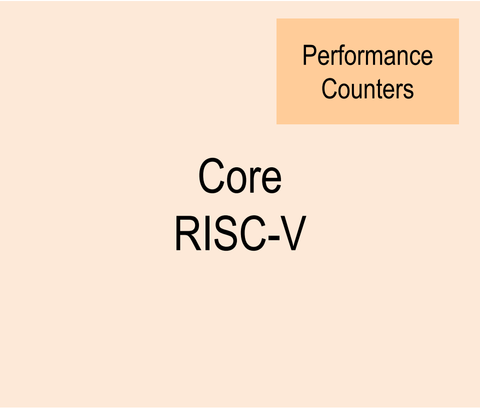
- the number of **elapsed clock cycles** (N_{clk})
- the **number of instructions** (N_{instr}) executed within the task depends on the code optimization!
- **CPI (Clock Cycles Per Instruction)**: different instructions may take a different number of **clock cycles** (depending on the CPU microarchitecture)

$$\boxed{T_{CPU} = N_{clk} \times T_{clk} = CPI_{avg} \times N_{instr} \times T_{clk}}$$

$$CPI_{avg} = \frac{N_{clk}}{N_{instr}}$$

$\boxed{N_{clk} \text{ and } N_{instr} \text{ greatly affects CPU performance!}}$

Performance Counters: Measuring the CPU Time



Each RI5CY cores of the PULP platform provide a **performance counter**. These 32-bit counters can be configured to count the:

- Total number of cycles (also includes the cycles where the core is sleeping)
- Number of cycles the core was active (not sleeping)
- Number of instructions executed
- Number of load data hazards
- Number of jump register data hazards
- Number of cycles waiting for instruction fetches, i.e. number of instructions wasted due to non-ideal caching
- Number of data memory loads executed. Misaligned accesses are counted twice
- Number of data memory stores executed. Misaligned accesses are counted twice
- Number of unconditional jumps (j, jal, jr, jalr)
- Number of both taken and not taken branches
- Number of taken branches
- Number of compressed instructions executed

The performance counters of the cluster cores can also account:

- Number of memory loads to EXT executed. Misaligned accesses are counted twice. Every non-L1 access is considered external
- Number of memory stores to EXT executed. Misaligned accesses are counted twice. Every non-L1 access is considered external
- Number of cycles used for memory loads to EXT. Every non-L1 access is considered external
- Number of cycles used for memory stores to EXT. Every non-L1 access is considered external
- Number of cycles wasted due to L1/log-interconnect contention

Important: while on the PULP Virtual Platform multiple perf counters can be enabled concurrently, only one counter is available on a real HW device!

Using the performance Counters on PULP

Using the PMSIS library APIs:

Configure which performance counters to enable!

```c
// enable the perf counters of interest
pi_perf_conf(     1 << PI_PERF_CYCLES  |
        1 << PI_PERF_INSTR );

// reset the performance counters
pi_perf_reset();
// start the performance counters
pi_perf_start();

// task to profile
foo();

// stop the performance counters
pi_perf_stop();

// collect and print statistics
uint32_t instr_cnt = pi_perf_read(PI_PERF_INSTR);
uint32_t cycles_cnt = pi_perf_read(PI_PERF_CYCLES);
```

```c
typedef enum {
  PI_PERF_CYCLES        = 17, /*!< Total number of cycles (also includes the
    cycles where the core is sleeping). Be careful that this event is using a
    timer shared within the cluster, so resetting, starting or stopping it on
    one core will impact other cores of the same cluster. */
  PI_PERF_ACTIVE_CYCLES = 0,  /*!< Counts the number of cycles the core was
    active (not sleeping). */
  PI_PERF_INSTR         = 1,  /*!< Counts the number of instructions executed.
  */
  PI_PERF_LD_STALL      = 2,  /*!< Number of load data hazards. */
  PI_PERF_JR_STALL      = 3,  /*!< Number of jump register data hazards. */
  PI_PERF_IMISS         = 4,  /*!< Cycles waiting for instruction fetches, i.e.
    number of instructions wasted due to non-ideal caching. */
  PI_PERF_LD            = 5,  /*!< Number of data memory loads executed.
    Misaligned accesses are counted twice. */
  PI_PERF_ST            = 6,  /*!< Number of data memory stores executed.
    Misaligned accesses are counted twice. */
  PI_PERF_JUMP          = 7,  /*!< Number of unconditional jumps (j, jal, jr,
    jalr). */
  PI_PERF_BRANCH        = 8,  /*!< Number of branches. Counts both taken and
    not taken branches. */
  PI_PERF_BTAKEN        = 9, /*!< Number of taken branches. */
  PI_PERF_RVC           = 10, /*!< Number of compressed instructions
    executed. */
  PI_PERF_LD_EXT        = 12, /*!< Number of memory loads to EXT executed.
    Misaligned accesses are counted twice. Every non-TCDM access is considered
    external (cluster only). */
  PI_PERF_ST_EXT        = 13, /*!< Number of memory stores to EXT executed.
    Misaligned accesses are counted twice. Every non-TCDM access is considered
    external (cluster only). */
  PI_PERF_LD_EXT_CYC    = 14, /*!< Cycles used for memory loads to EXT.
  Every non-TCDM access is considered external (cluster only). */
  PI_PERF_ST_EXT_CYC    = 15, /*!< Cycles used for memory stores to EXT.
  Every non-TCDM access is considered external (cluster only). */
  PI_PERF_TCDM_CONT     = 16, /*!< Cycles wasted due to TCDM/log-interconnect
  contention (cluster only). */
} pi_perf_event_e;
```

/rtos/pmsis/pmsis_api/include/pmsis/chips/default.h

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TASK2

Profile the *gemv*

Make a new project by copying the *matrix-vector gemv* example into a new folder

```
$ cd matrix_vector/
make clean all run
```

For any of the previous compiler optimization, **measure the performance** using the PMSIS performance counters and report:

- number of clock cycles.
- number of instructions.
- Number of Multiply-Add operations
- the CPI.
- compute the number of clock cycles and instructions per *elementary operation*.
  - Define 1 elementary operation == 1 Multiply-and-Accumulate

$$a \leftarrow a + (b \times c)$$

#MAC = N x M = 50 x 50 = 2500

	-01	-03	-03 HWLoops
Clock Cycles			
Instr.			
MAC			
CPI			
Intr/Cycles			
Instr / MAC			

SOLUTION: Profile the *gemv*

Make a new project by copying the *matrix-vector gemv* example into a new folder

```
$ cd matrix_vector/
make clean all run
```

Solution:

```
  pi_perf_conf(1<<PI_PERF_CYCLES | 1<<PI_PERF_INSTR);
  pi_perf_reset();

  pi_perf_start();
  // call the matrix-vector fucntion
  gemv(N, M, matrix, vector, output_vec);
  pi_perf_stop();

  uint32_t instr_cnt = pi_perf_read(PI_PERF_INSTR);
  uint32_t cycles_cnt = pi_perf_read(PI_PERF_CYCLES);
  printf("Num.Istr: %d Num.Cycles: %d \n", instr_cnt,
cycles_cnt);
```

#*MAC* = N x M = 50 x 50 = 2500

	-01	-03	-03 HWLoops
Clock Cycles			
Instr.			
MAC			
CPI			
Intr/Cycles			
Instr / MAC			

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