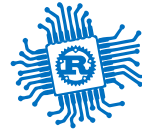




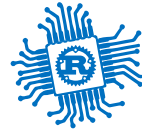
Memory Protection

Lecture 8



Memory Protection

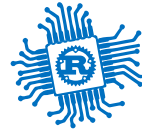
- Memory Protection Unit
 - Privilege Modes
 - Regions
- Memory Management Unit
 - Pages
 - Frames
 - TLB



Memory Protection

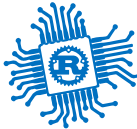
ARM: MPU, RISC-V: PMP





MPU for RP2040

Protected Memory System Architecture v7 (PMSAv7)

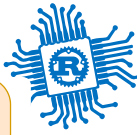


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Joseph Yiu, *The Definitive Guide to ARM® Cortex®-M0 and Cortex-M0+ Processors, 2nd Edition*

- Chapter 12 - *Memory Protection Unit*



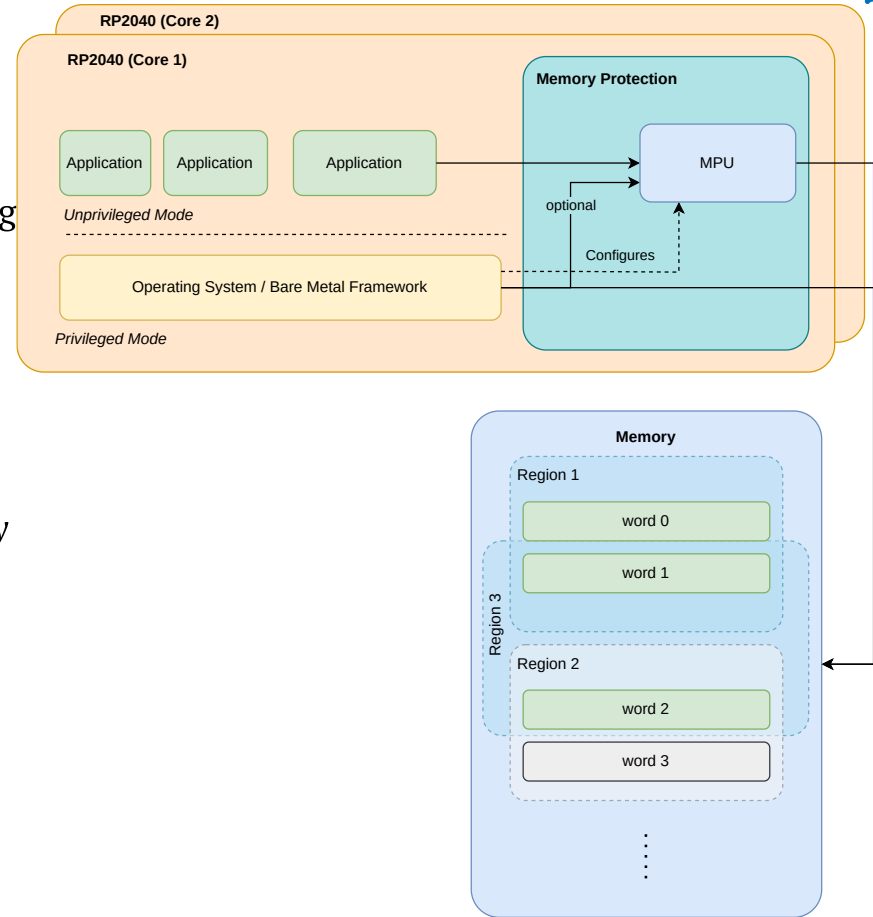
MPU for RP2040

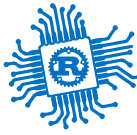
Cortex-M0+ works in three modes

- **handler** mode - *no restrictions* - used while executing ISRs and Exception Handlers
- **thread** mode
 - **privileged** *no restrictions* - usually used for the operating system
 - **unprivileged** mode - *allows only ALU and memory access through Memory Protection* - used for applications

MPU allows 8 regions

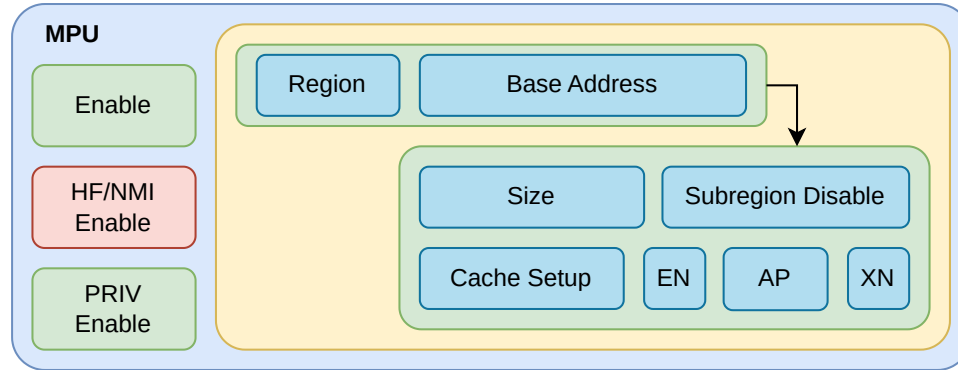
- each region has up to 8 subregions
- permissions R W X





Memory Protection Unit

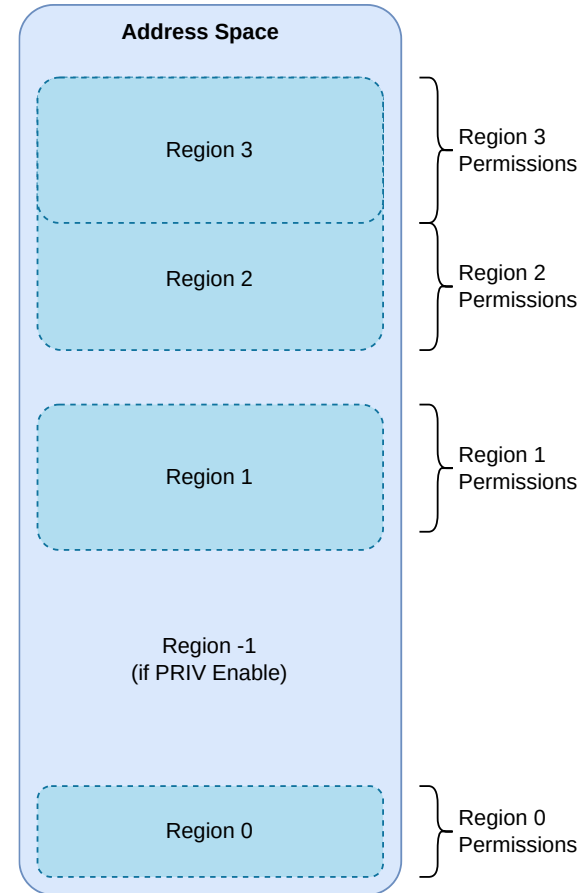
Cortex-M MPU (PMSAv7-m)



- allows the definition of *memory regions*
- regions can overlap, *highest region number takes priority*
- regions have access permissions (similar to rwx)

$$region_size = 2^{size}, size \geq 8$$

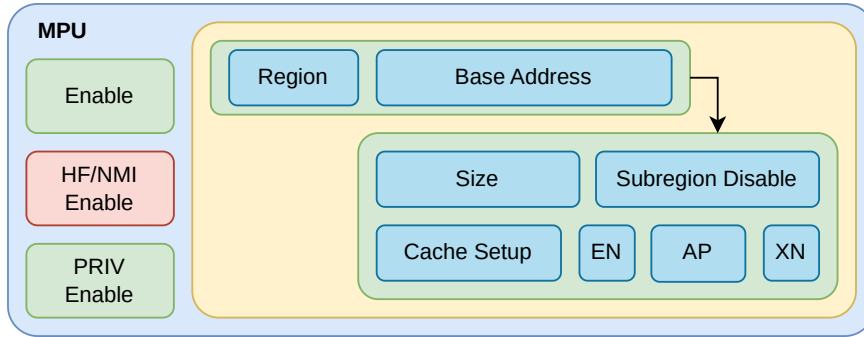
$$base_address = region_size \times N$$





Memory Protection Unit

Access Protection

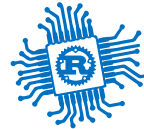


AP Access Protection

XN eXecute Never

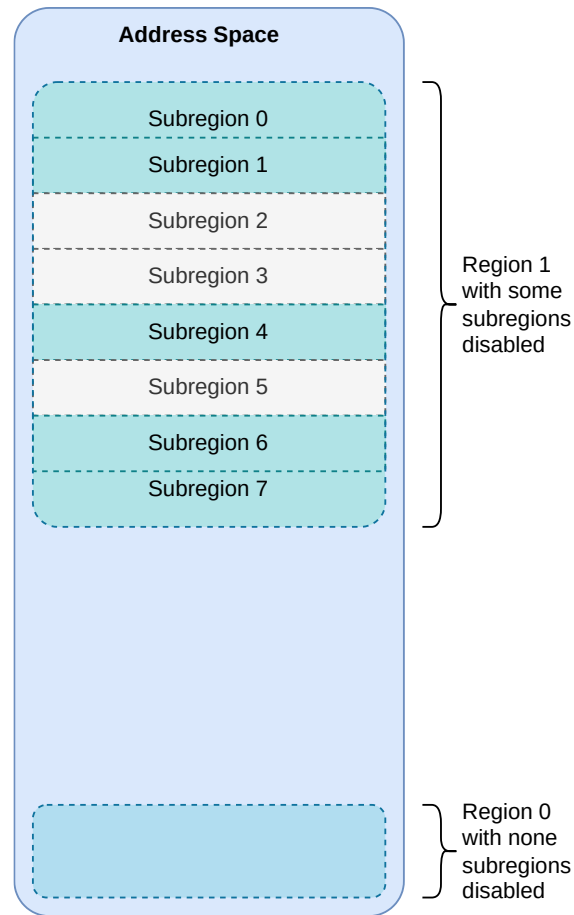
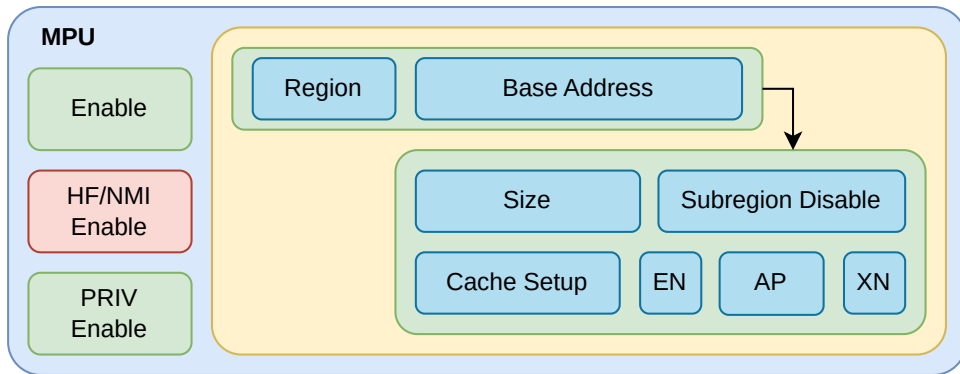
- faults if MCU has to read the next instruction from an *XN* region

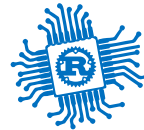
AP	Privileged Mode	Unprivileged Mode
000	No Access	No Access
001	Read/Write	No Access
010	Read/Write	Read only
011	Read/Write	Read/Write
100	Do not use	Do not use
101	Read only	No Access
110	Read only	Read only
111	Read/Write	Read only



Subregions

- each region is divided in 8 subregion
- each bit in **Subregion Disable** disables a subregion
- a disabled subregion triggers a fault if accessed





Subregions' Usage

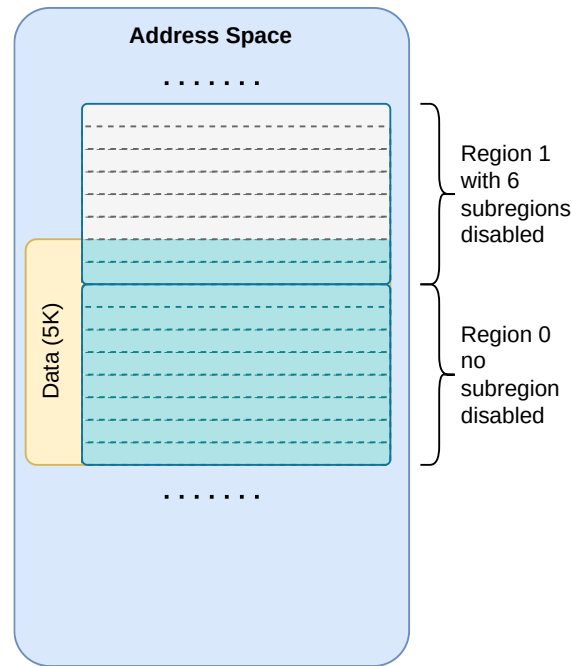
improve granularity

$$region_size = 2^{size}, size \geq 8$$

$$base_address = region_size \times N$$

$$subregion_size = \frac{region_size}{8}$$

- a 5K region is not allowed (5K is not a power of 2)
- use two 4K regions back to back
- disable 6 of the subregions (subregion is 512B)



Memory Layout

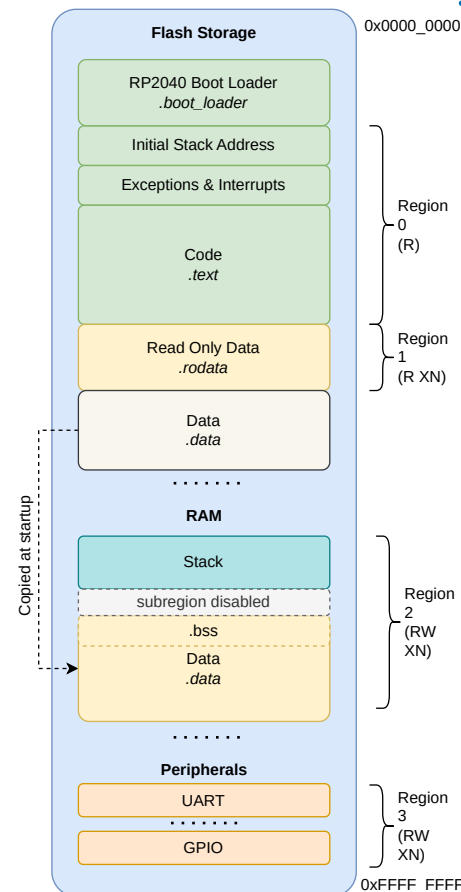
protection

Flash

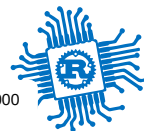
- **Code** - *read and execute*
- **.rodata** - constants - *read only*
- **.data** - *in flash* - initialized global variables
 - is copied to RAM at startup by the `init` function
 - *should not be accessed after startup*

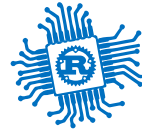
RAM

- **stack** - *read and write*
 - *usually protected by unaccessible memory before and after*
- **.data** - *in RAM* - global variables - *read and write*
- **.bss** - global variables (not initialized or initialized to `0`) - *read and write*



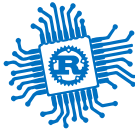
* drawing is not at scale, code and data are significantly greater than the interrupt vector





MPU for RP2350

Protected Memory System Architecture v8 (PMSAv8)

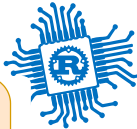


Bibliography

for this section

Joseph Yiu, *The Definitive Guide to ARM® Cortex®-M23 and Cortex-M33 Processors*

- Chapter 6 - *Memory System*
 - Subchapter 6.4 - *Access Permission Management*
- Chapter 12 - *Memory Protection Unit (MPU)*



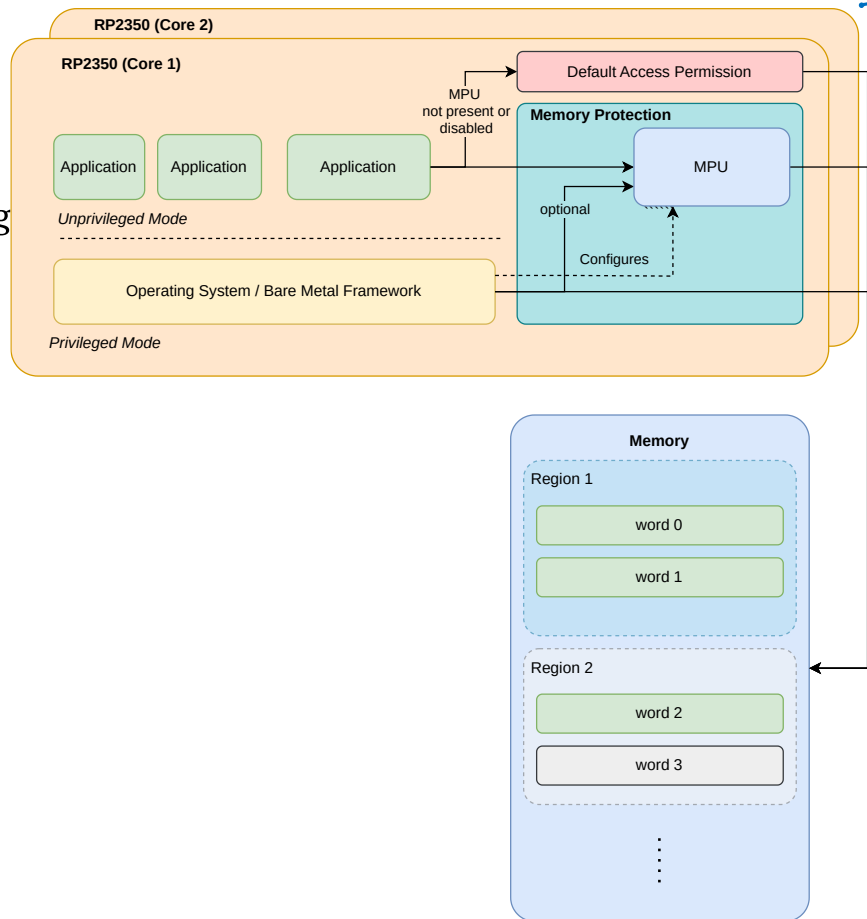
MPU for RP2350

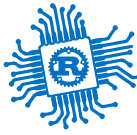
Cortex-M33 works in three modes

- **handler** mode - *no restrictions* - used while executing ISRs and Exception Handlers
- **thread** mode
 - **privileged** *no restrictions* - usually used for the operating system
 - **unprivileged** mode - *used for applications*, allows only ALU and memory access through:
 - Default Access Permission - *restricts unprivileged access to the Cortex-M Peripherals*
 - Memory Protection

MPU allows 8 regions

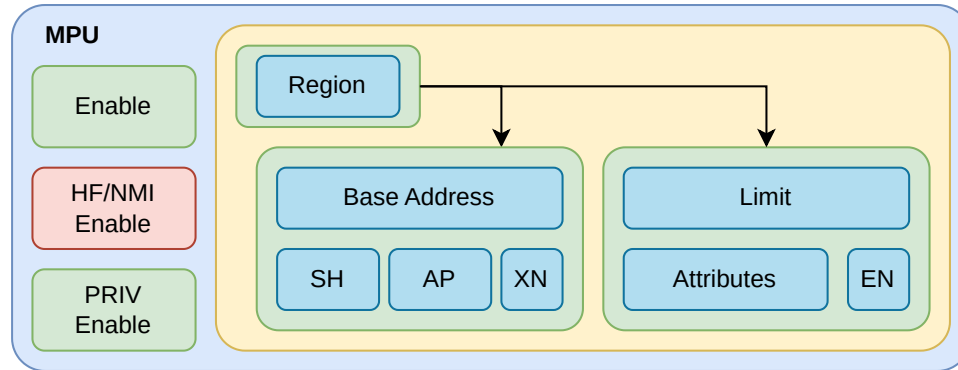
- permissions R W X





Memory Protection Unit

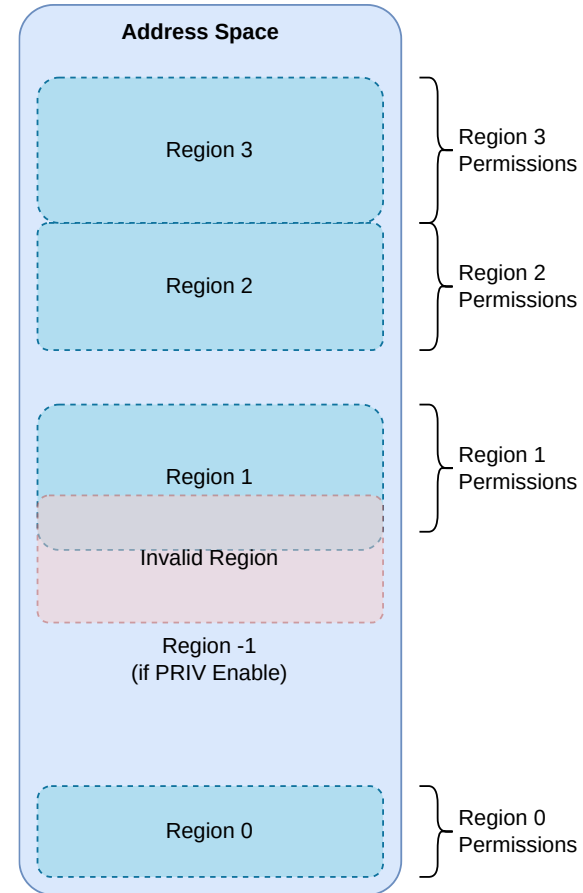
Cortex-M MPU (PMSAv8)

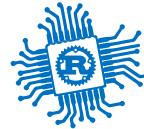


- allows the definition of *memory regions*
- regions cannot overlap
- regions have access permissions (similar to rwx)

$$region_size = 32 \times N$$

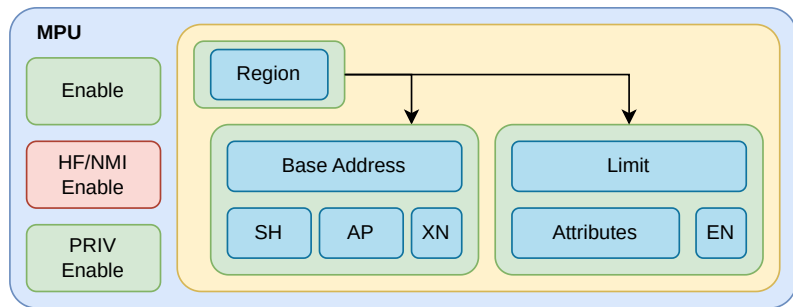
$$base_address = 32 \times N$$





Memory Protection Unit

Access Protection



AP Access Protection

XN eXecute Never

- faults if MCU has to read the next instruction from an *XN* region

SH Shared between cores and peripherals

Attributes *used for cache*

AP	Privileged Mode	Unprivileged Mode
----	-----------------	-------------------

00	Read/Write	No Access
----	------------	-----------

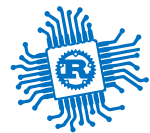
01	Read/Write	Read/Write
----	------------	------------

10	Read only	No Access
----	-----------	-----------

11	Read only	Read only
----	-----------	-----------

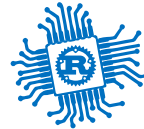
Better granularity -> there is no need for *No Access* in privileged mode.

There is no need to overlap regions to obtain the required protected memory space.



Memory Management

MMU



Bibliography

for this section

1. **Andrew Tanenbaum**, *Modern Operating Systems (4th edition)*

- Chapter 3 - *Memory Management*
 - Subchapter 3.3 - *Virtual Memory*

2. **Philipp Oppermann**, *Writing an OS in Rust*

- *Introduction to Paging*
- *Paging Implementation*



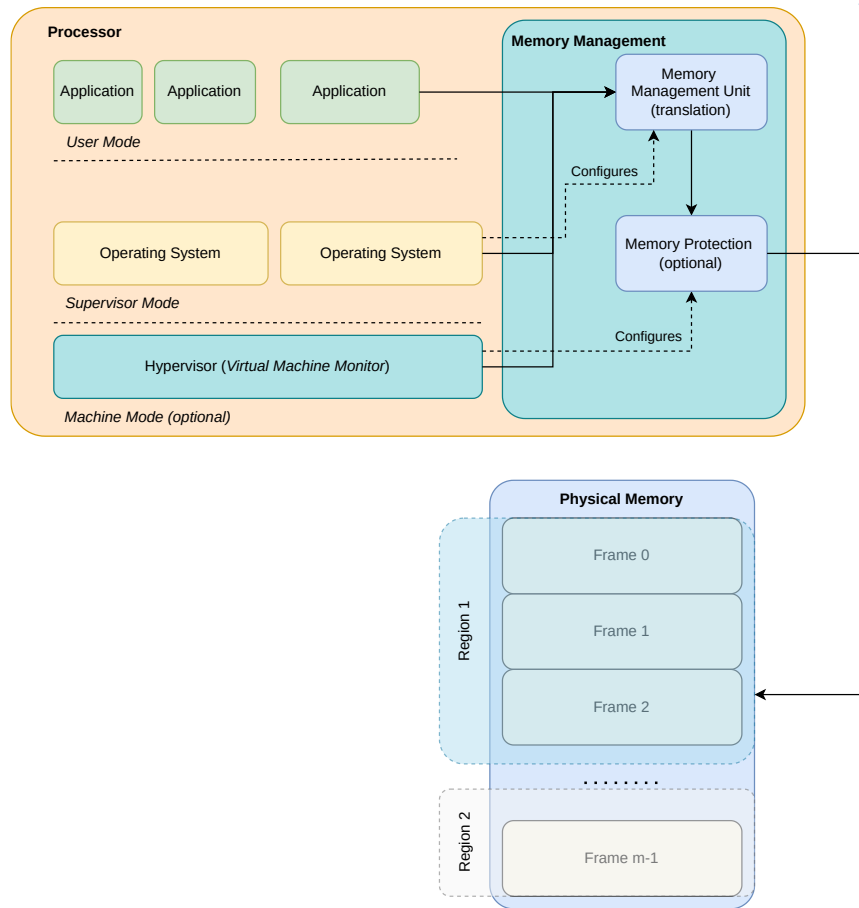
Memory Management

memory access defined page by page

- uses *logical addresses*
- **translates** to *physical addresses*

The processor works in at least two modes:

- **supervisor mode**
 - restricts access to some registers
 - accesses virtual addresses through Memory Protection (*if machine mode exists*)
- **user mode**
 - allows only ALU and memory load and store
 - accesses memory access through the Memory Management Unit (*MMU*)





Paging

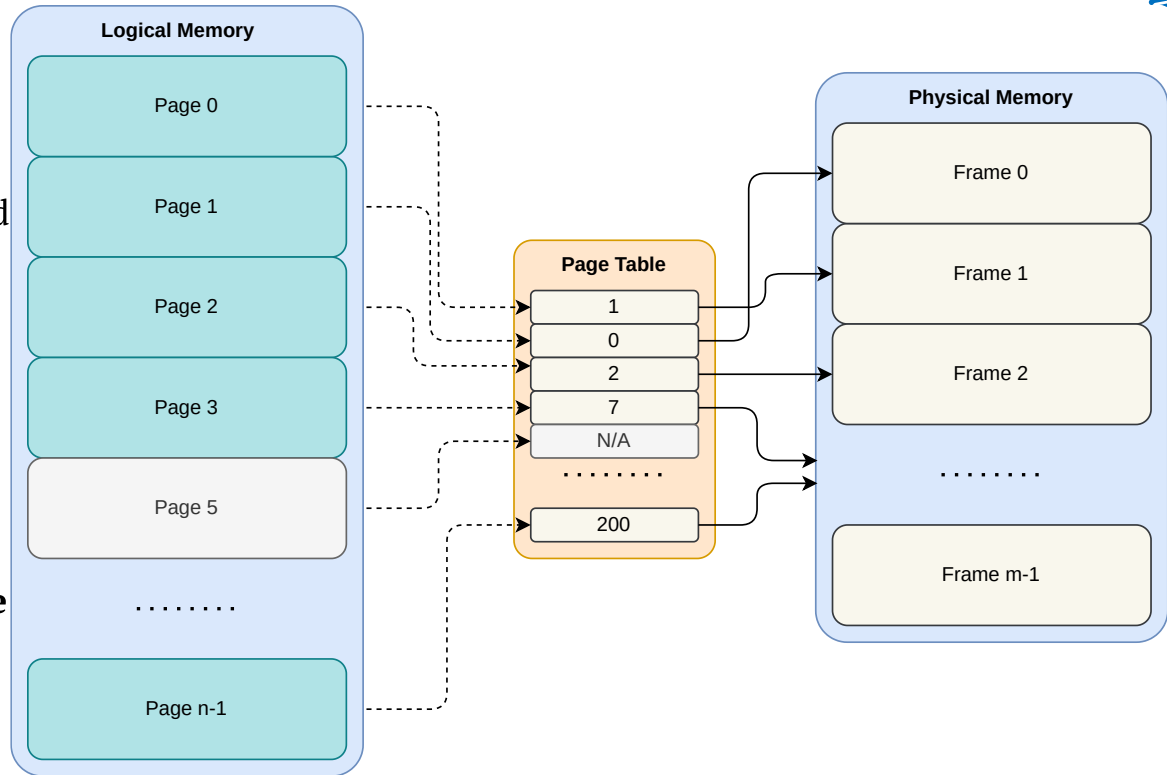
the memory *unit* is the page

- Physical Memory (*RAM*) is divided in **frames**
- Logical Memory is divided in **pages**
- $page = frame = 4 \text{ KB}$ (usually)

logical addresses are translated to *physical addresses* using a **page table**

the **page table** is located in the **physical memory**

- each memory access requires at least 2 memory accesses





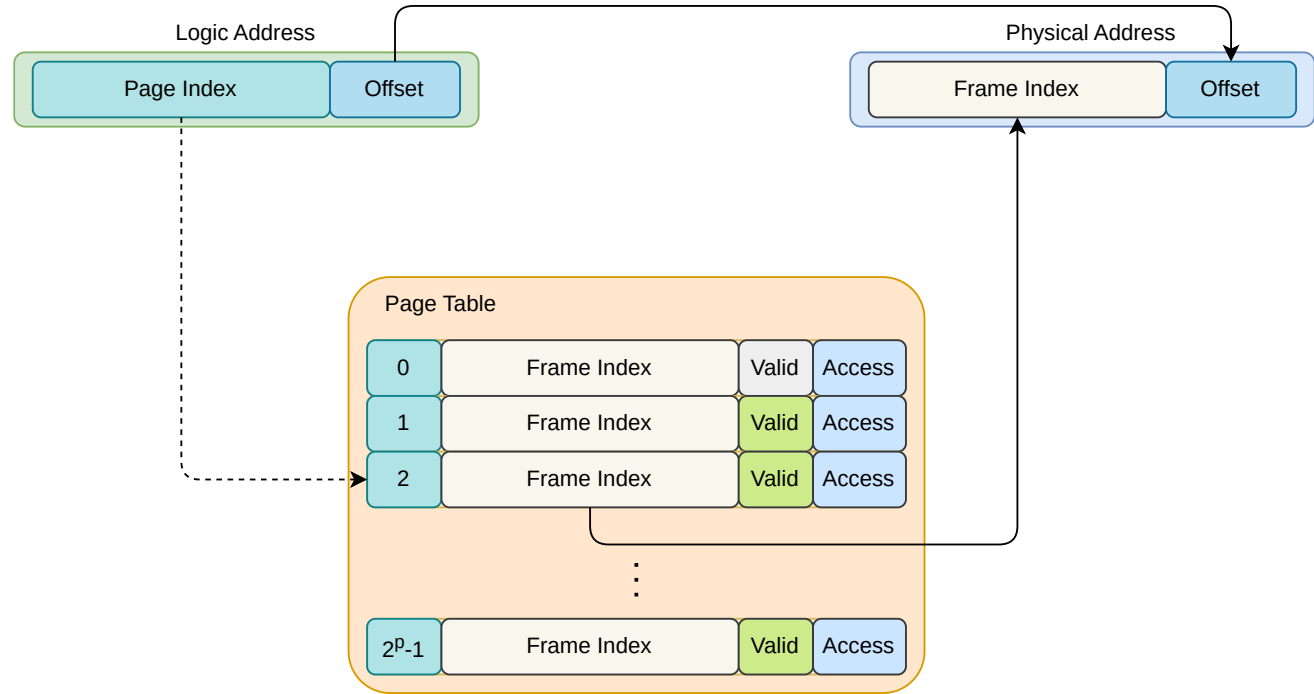
Address Translation

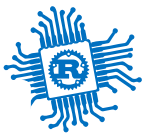
page to frame

the logic address is divided in two parts:

- *page index*
- *offset* within the page

the MMU translates every logic address into a physical address using a *page table*





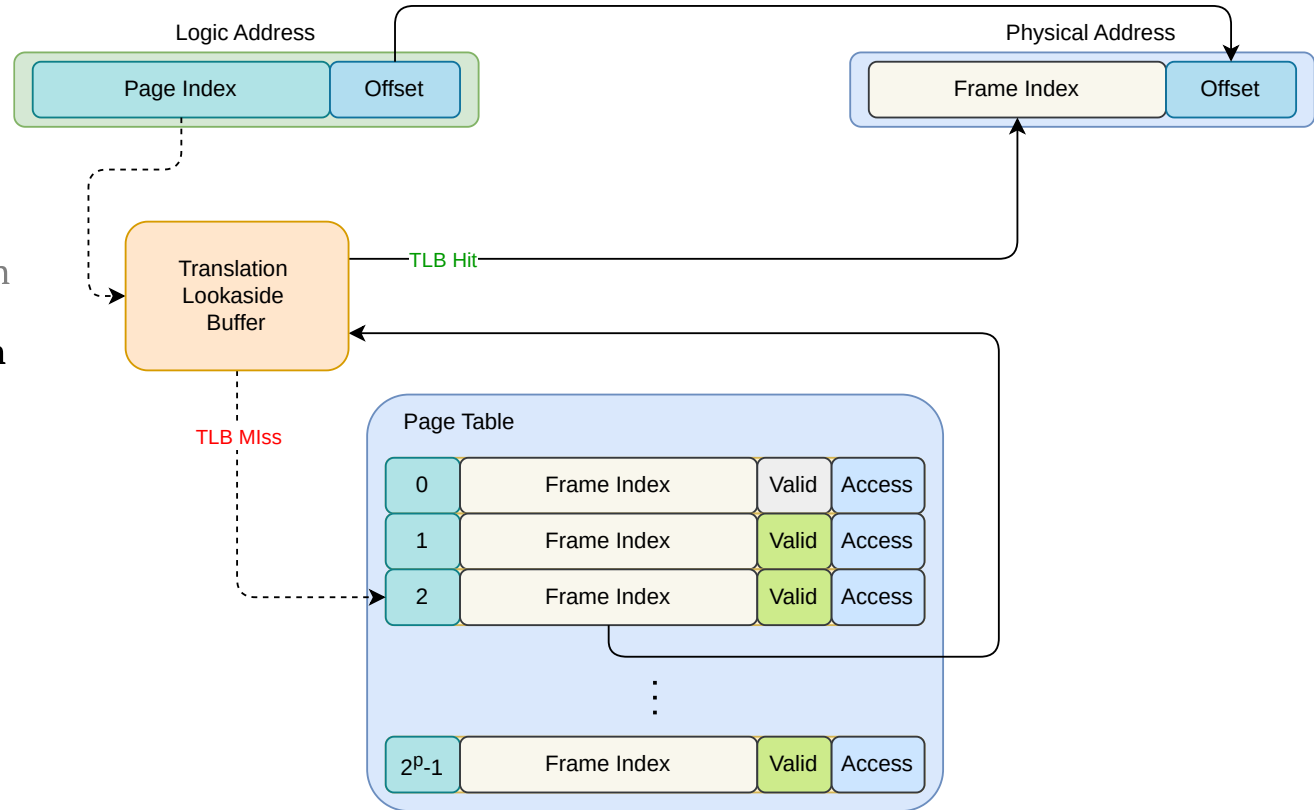
Translation Lookaside Buffer (TLB)

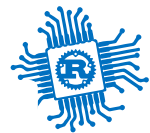
caching address translation

the **page table** is stored in **RAM**

each memory access **requires 2 accesses**

1. read the page table entry to translate the address
2. the requested access





Page Directory

caching address translation

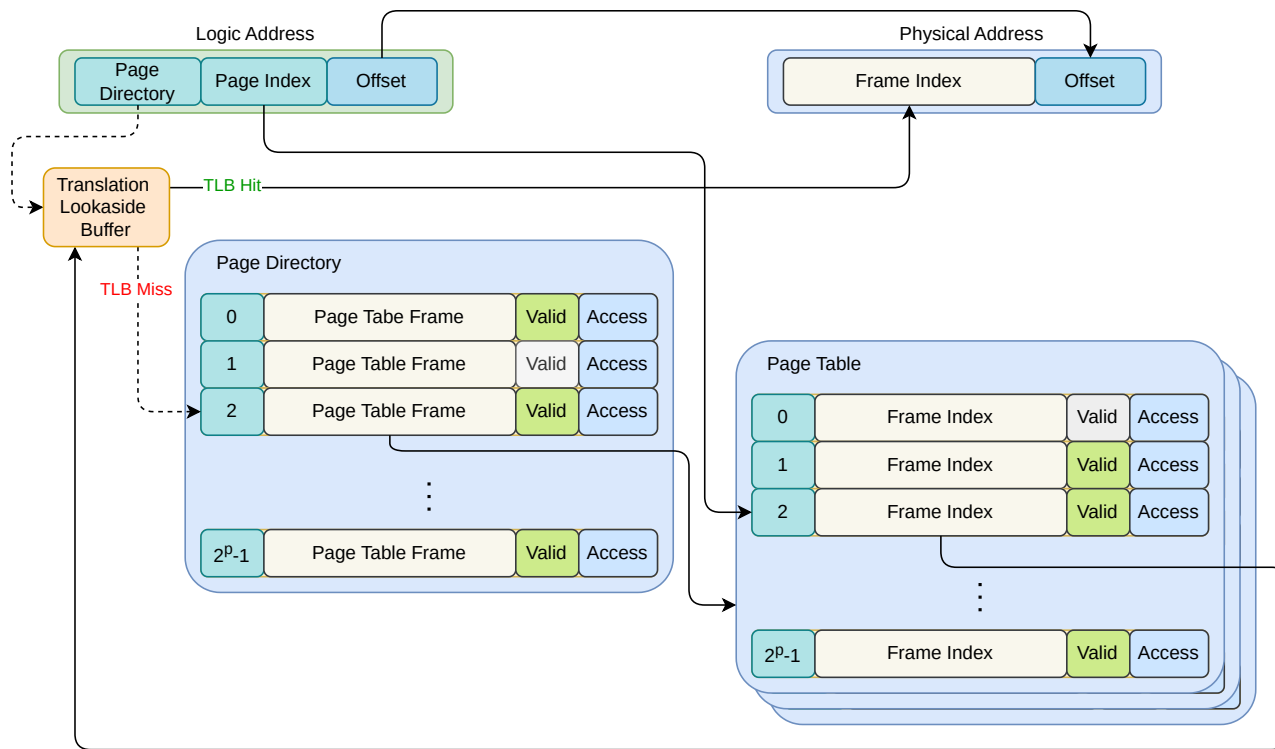
$$size_{table} = \frac{size_{ram}}{size_{page}}$$

- each table entry is 4B
- the address space is 4GB
(for 32 bits processors)

$$size_{table_32_bits} = \frac{2^{32}}{4 \times 2^{10}}$$

$$size_{table_32_bits} = 4MB$$

RAM was counted in MB
when paging started being
used



two levels, page directory and table, usually used for 32 bits systems

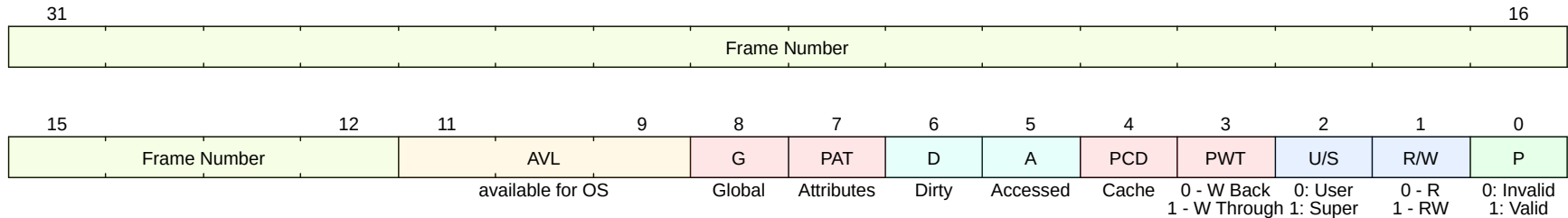


Page Table Entry

for x86 - 32 bits

this is one entry of the page table

- **P** - is the page's frame present in RAM?
- **R/W** - read only or read write access
- **U/S** - can the page be accessed in user mode?
- **D** and **A** - has this page been written since the OS has reset these bits?
- **AVL** - bits available for the OS to use, ignored by MMU



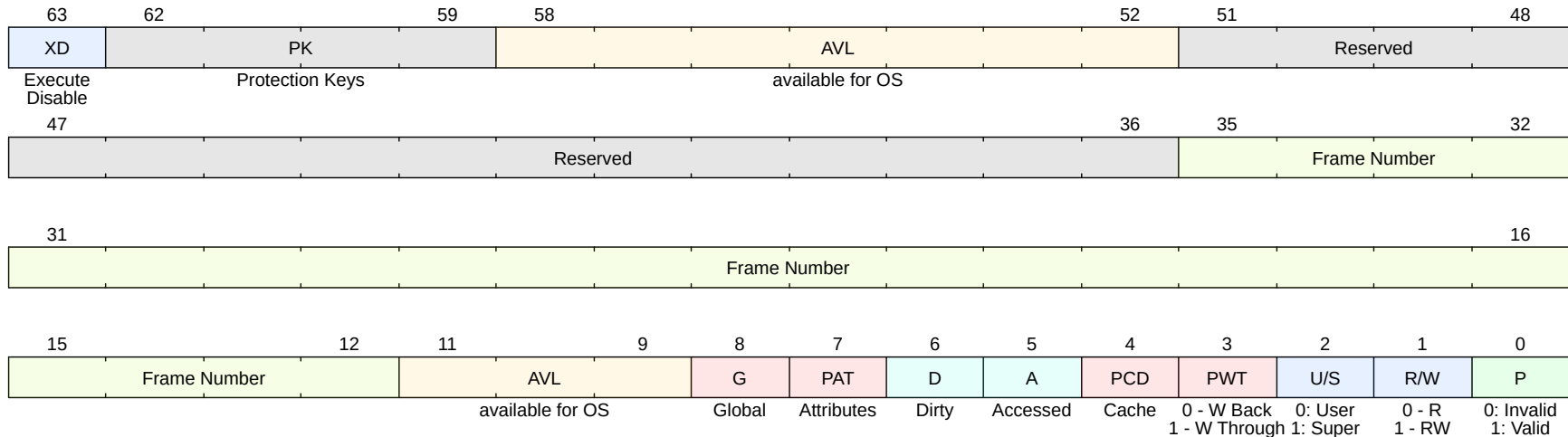


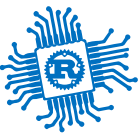
Page Table Entry

for x86 - 32 bits with PAE

this is one entry of the page table using Physical Address Extension (*PAE*)

- **XD** - eXecute Disable (aka *DEP*), if set triggers a fault if an instruction is read from the page
- **PK** - Protection Keys, allows user mode to set protection (64 bit only)

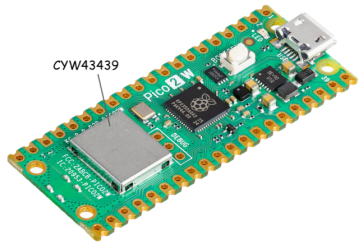




Microcontroller (MCU)

Integrated in embedded systems for certain tasks

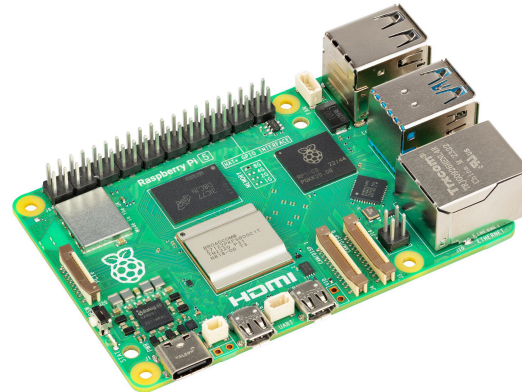
- low operating frequency (MHz)
- a lot of I/O ports
- controls hardware
- does not require an Operating System
- costs \$0.1 - \$25
- uses **Memory Protection Unit**

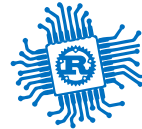


Microprocessor (CPU)

General purpose, for PC & workstations

- high operating frequency (GHz)
- limited number of I/O ports
- usually requires an Operating System
- costs \$75 - \$500
- uses **Memory Management Unit**





Conclusion

we talked about

- Memory Protection Unit
 - Privilege Modes
 - Regions
- Memory Management Unit
 - Pages
 - Frames
 - TLB