Virtual Memory

EEL 3713C: Digital Computer Architecture

Quincy Flint

[Ionospheric Radio Lab in NEB]

Outline

1. Memory Problems
   - Not enough memory
   - Holes in address space
   - Programs overwriting
2. What is Virtual Memory?
   - Layer of indirection
   - How does indirection solve above
   - Page tables and translation
3. How do we implement VM?
   - Create and store page tables
   - Fast address translation
4. Virtual Memory and Caches
   - Prevent cache performance degradation when using VM

TLB Example

TLB Example

Computer Specs:
32-bit ISA, 256 MB of RAM, 4 kB pages, 2-entry TLB

32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

Virtual Address [32 bit]

TLB [2-entries big]

Tag	Physical Page #

Physical Address [28 bits]

Main Memory

PPN
DISK
0x000A
0x0005
0x0001
0x0002
…
0x00F5

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28-bit Physical Address

12-bit Page Offset [Index]

Virtual Address [32 bit]

TLB [2-entries big]

Tag	Physical Page #
0x0 0001	0x000A

1 entry already filled

Physical Address [28 bits]

Main Memory

PPN
DISK
0x000A
0x0005
0x0001
0x0002
…
0x00F5

TLB Example

Computer Specs:
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32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

VA: 0x00003 103

Virtual Address [32 bit]

TLB [2-entries big]

Tag	Physical Page #
0x0 0001	0x000A

Physical Address [28 bits]

Main Memory

PPN
DISK
0x000A
0x0005
0x0001
0x0002
…
0x00F5

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Tag	Physical Page #
0x0 0001	0x000A

Physical Address [28 bits]

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DISK
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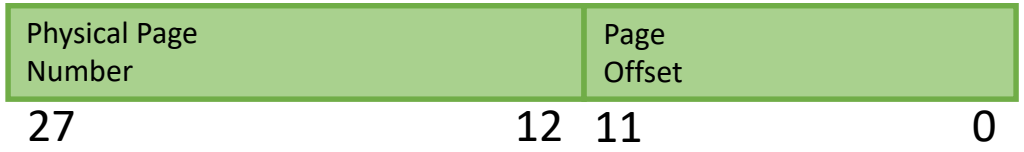
Physical Address [28 bits]



Main Memory

PPN
DISK
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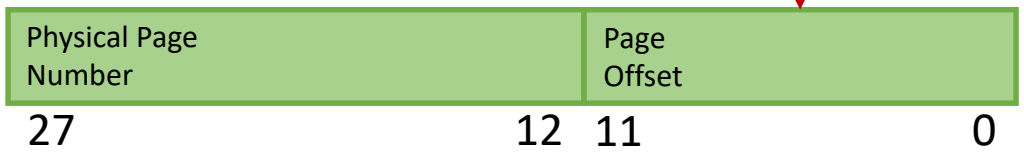

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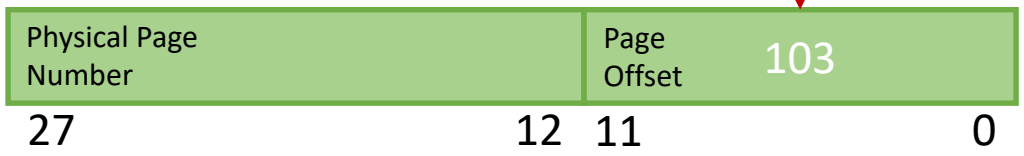

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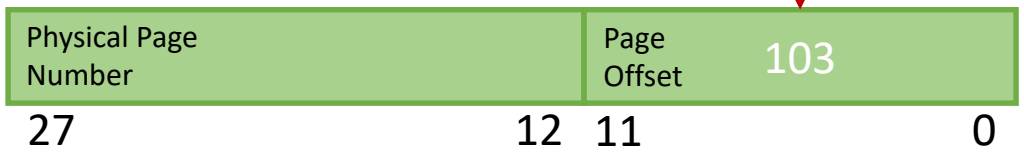

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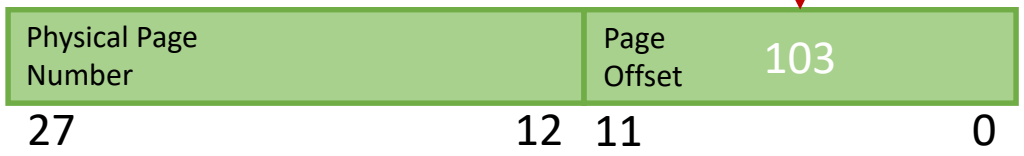

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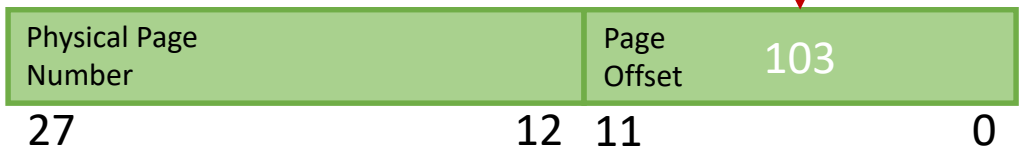

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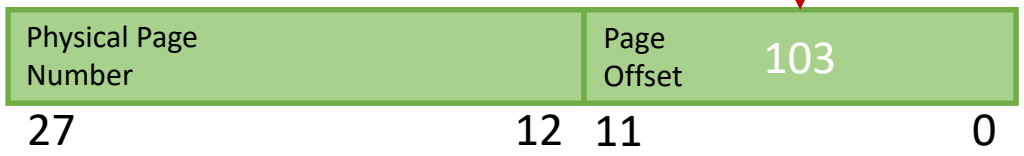

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Compulsory Miss!

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12-bit Page Offset [Index]

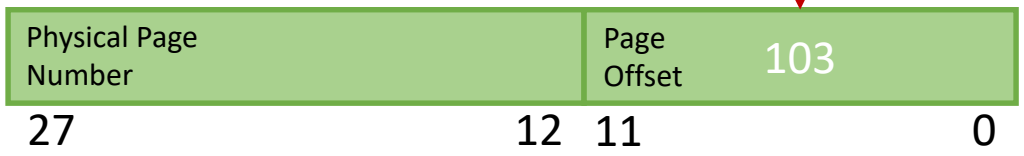
VA: 0x00003 103

Virtual Address [32 bit]

TLB [2-entries big]

Tag	Physical Page #
0x0 0003	
0x0 0001	0x000A

Physical Address [28 bits]



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0x000A
0x0005
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Virtual Address [32 bit]

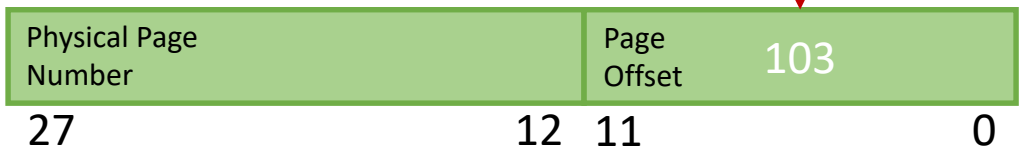
TLB [2-entries big]

Tag	Physical Page #
0x0 0003	
0x0 0001	0x000A

Main Memory

PPN
DISK
0x000A
0x0005
0x0001
0x0002
…
0x00F5

Physical Address [28 bits]



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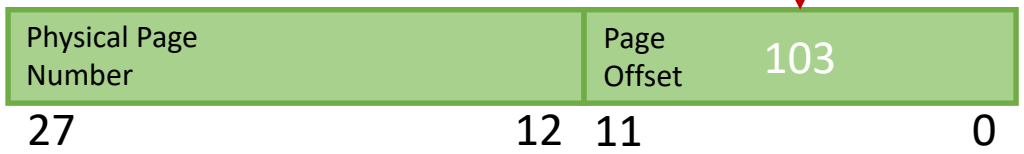

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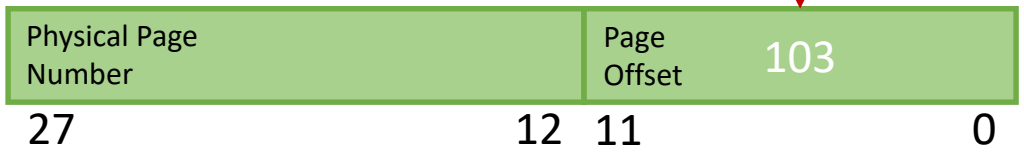

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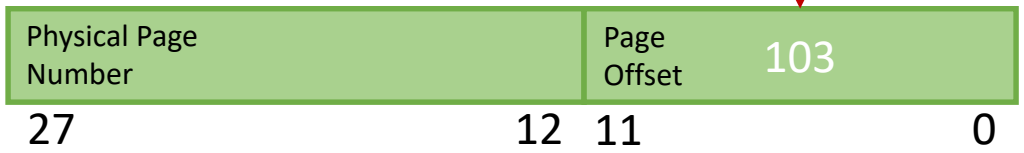

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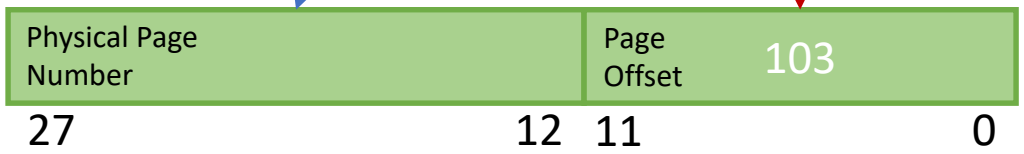

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Main Memory

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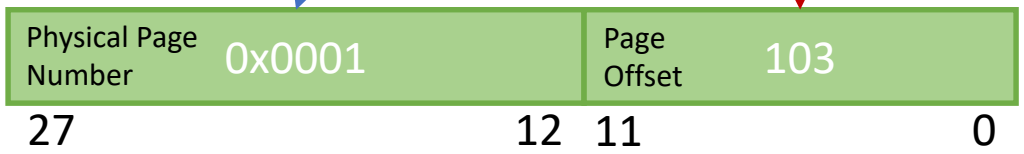

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PPN
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…
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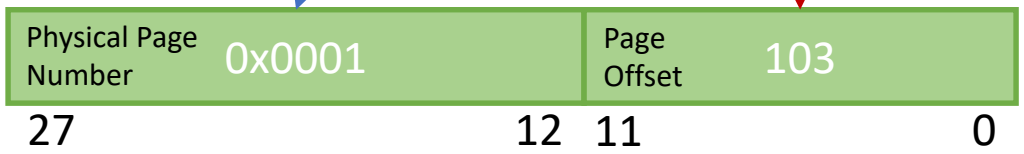
Physical Address [28 bits]



PA: 0x001 103 **Compulsory Miss!**

TLB Example

Computer Specs:
32-bit ISA, 256 MB of RAM, 4 kB pages, 2-entry TLB

32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

VA: 0x00004 555

Virtual Address [32 bit]

TLB [2-entries big]

Tag	Physical Page #
0x0 0003	0x0001
0x0 0001	0x000A

Physical Address [28 bits]

Main Memory

PPN
DISK
0x000A
0x0005
0x0001
0x0002
…
0x00F5

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VA: 0x00004 555

Virtual Address [32 bit]

TLB [2-entries big]

Tag	Physical Page #
0x0 0003	0x0001
0x0 0001	0x000A

Physical Address [28 bits]

Main Memory

PPN
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TLB [2-entries big]

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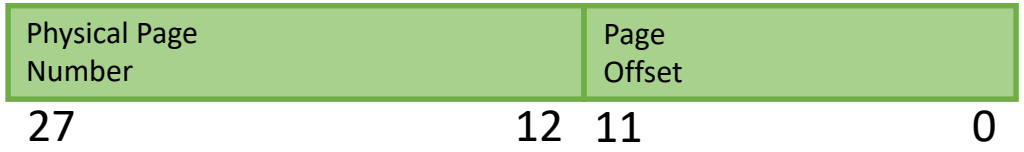
0x0 0003	0x0001
0x0 0001	0x000A

Physical Address [28 bits]



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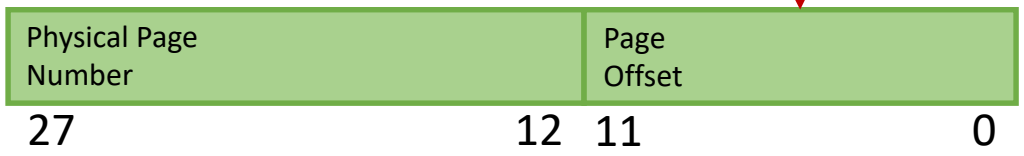

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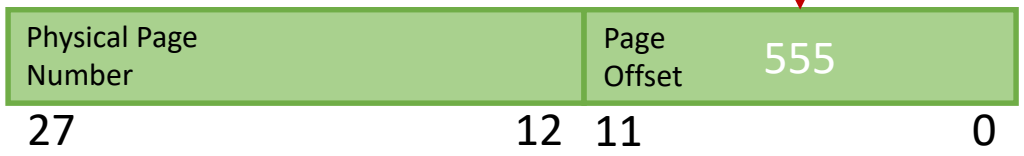

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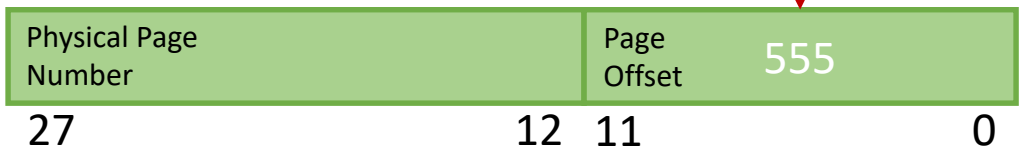

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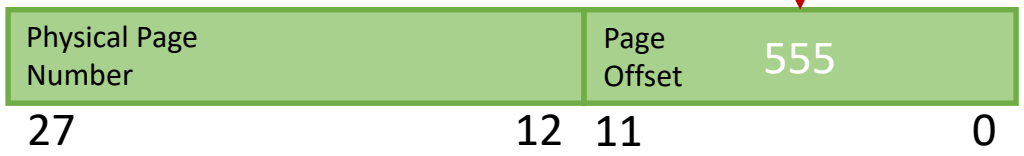

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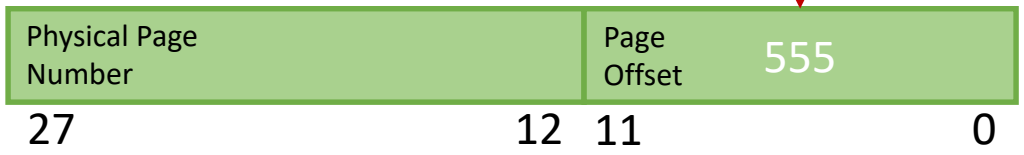

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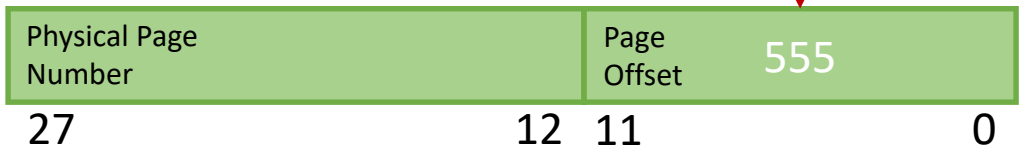

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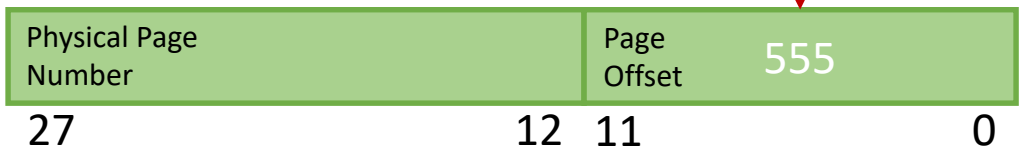
0x0 0003	0x0001

Physical Address [28 bits]



Main Memory

PPN
DISK
0x000A
0x0005
0x0001
0x0002
…
0x00F5

Capacity Miss!

TLB Example

Computer Specs:
32-bit ISA, 256 MB of RAM, 4 kB pages, 2-entry TLB

32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

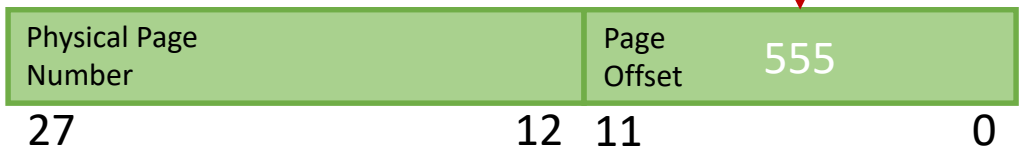
VA: 0x00004 555

Virtual Address [32 bit]

TLB [2-entries big]

Tag	Physical Page #
0x0 0003	0x0001

Physical Address [28 bits]



Main Memory

PPN
DISK
0x000A
0x0005
0x0001
0x0002
…
0x00F5

Capacity Miss!

TLB Example

Computer Specs:
32-bit ISA, 256 MB of RAM, 4 kB pages, 2-entry TLB

32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

VA: 0x00004 555

Virtual Address [32 bit]

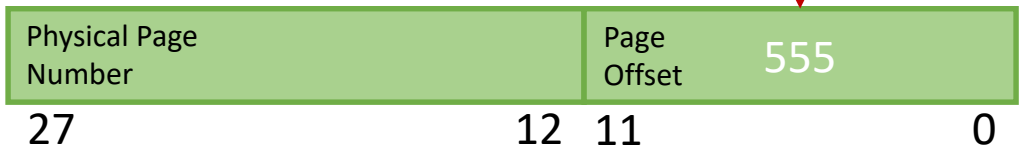
TLB [2-entries big]

Tag	Physical Page #
0x0 0003	0x0001

Main Memory

PPN
DISK
0x000A
0x0005
0x0001
0x0002
…
0x00F5

Physical Address [28 bits]



Capacity Miss!

TLB Example

Computer Specs:
32-bit ISA, 256 MB of RAM, 4 kB pages, 2-entry TLB

32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

VA: 0x00004 555

Virtual Address [32 bit]

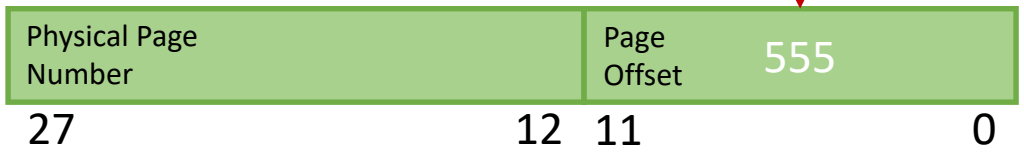
TLB [2-entries big]

Tag	Physical Page #
0x0 0003	0x0001

Main Memory

PPN
DISK
0x000A
0x0005
0x0001
0x0002
…
0x00F5

Physical Address [28 bits]



Capacity Miss!

TLB Example

Computer Specs:
32-bit ISA, 256 MB of RAM, 4 kB pages, 2-entry TLB

32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

VA: 0x00004 555

Virtual Address [32 bit]

Virtual Page Number	Page Offset
0x00004	555

31 12 11 0

TLB [2-entries big]

Tag	Physical Page #
0x0 0003	0x0001

Main Memory

PPN
DISK
0x000A
0x0005
0x0001
0x0002
…
0x00F5

Physical Address [28 bits]

Physical Page Number	Page Offset
	555

27 12 11 0

Capacity Miss!

TLB Example

Computer Specs:
32-bit ISA, 256 MB of RAM, 4 kB pages, 2-entry TLB

32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

VA: 0x00004 555

Virtual Address [32 bit]

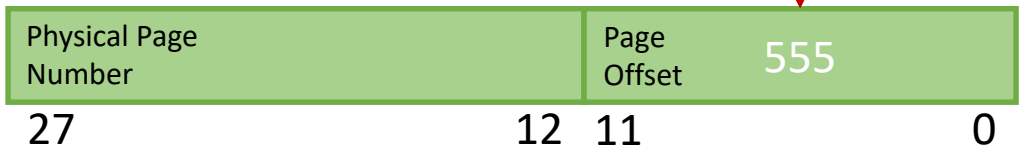
TLB [2-entries big]

Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Main Memory

PPN
DISK
0x000A
0x0005
0x0001
0x0002
…
0x00F5

Physical Address [28 bits]



Capacity Miss!

TLB Example

Computer Specs:
32-bit ISA, 256 MB of RAM, 4 kB pages, 2-entry TLB

32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

VA: 0x00004 555

Virtual Address [32 bit]

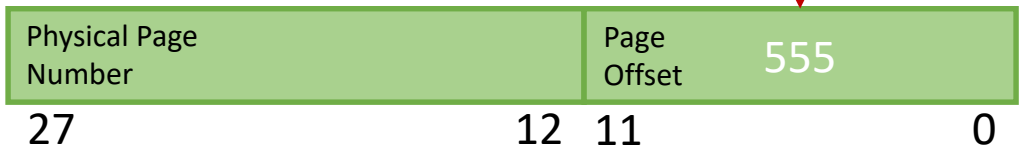
TLB [2-entries big]

Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Main Memory

PPN
DISK
0x000A
0x0005
0x0001
0x0002
…
0x00F5

Physical Address [28 bits]



Capacity Miss!

TLB Example

Computer Specs:
32-bit ISA, 256 MB of RAM, 4 kB pages, 2-entry TLB

32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

VA: 0x00004 555

Virtual Address [32 bit]

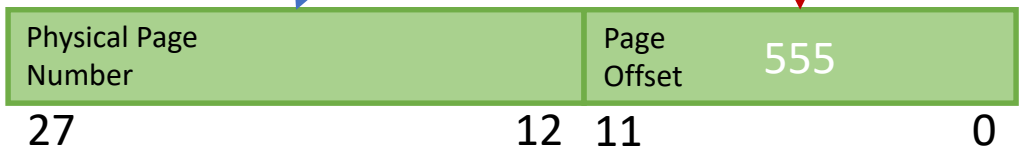
TLB [2-entries big]

Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Main Memory

PPN
DISK
0x000A
0x0005
0x0001
0x0002
…
0x00F5

Physical Address [28 bits]



Capacity Miss!

TLB Example

Computer Specs:
32-bit ISA, 256 MB of RAM, 4 kB pages, 2-entry TLB

32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

VA: 0x00004 555

Virtual Address [32 bit]

Virtual Page Number	Page Offset
0x00004	555

31 12 11 0

TLB [2-entries big]

Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Main Memory

PPN
DISK
0x000A
0x0005
0x0001
0x0002
…
0x00F5

Physical Address [28 bits]

Physical Page Number	Page Offset
0x0002	555

27 12 11 0

Capacity Miss!

TLB Example

Computer Specs:
32-bit ISA, 256 MB of RAM, 4 kB pages, 2-entry TLB

32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

VA: 0x00004 555

Virtual Address [32 bit]

Virtual Page Number	Page Offset
0x00004	555

31 12 11 0

TLB [2-entries big]

Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Main Memory

PPN
DISK
0x000A
0x0005
0x0001
0x0002
…
0x00F5

Physical Address [28 bits]

Physical Page Number	Page Offset
0x0002	555

27 12 11 0

PA: 0x0002 555

Capacity Miss!

TLB Example

Computer Specs:
32-bit ISA, 256 MB of RAM, 4 kB pages, 2-entry TLB

32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

VA: 0x00003 099

Virtual Address [32 bit]

TLB [2-entries big]

Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Physical Address [28 bits]

Main Memory

PPN
DISK
0x000A
0x0005
0x0001
0x0002
…
0x00F5

TLB Example

VA: 0x00003 099

Computer Specs:
32-bit ISA, 256 MB of RAM, 4 kB pages, 2-entry TLB

32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

Virtual Address [32 bit]

TLB [2-entries big]

Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Physical Address [28 bits]

Main Memory

PPN
DISK
0x000A
0x0005
0x0001
0x0002
…
0x00F5

TLB Example

Computer Specs:
32-bit ISA, 256 MB of RAM, 4 kB pages, 2-entry TLB

32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

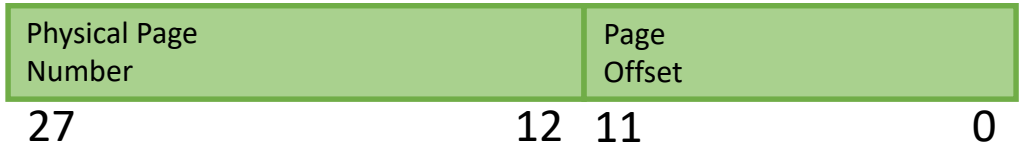
VA: 0x00003 099

Virtual Address [32 bit]

TLB [2-entries big]

Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Physical Address [28 bits]



Main Memory

PPN
DISK
0x000A
0x0005
0x0001
0x0002
…
0x00F5

TLB Example

Computer Specs:
32-bit ISA, 256 MB of RAM, 4 kB pages, 2-entry TLB

32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

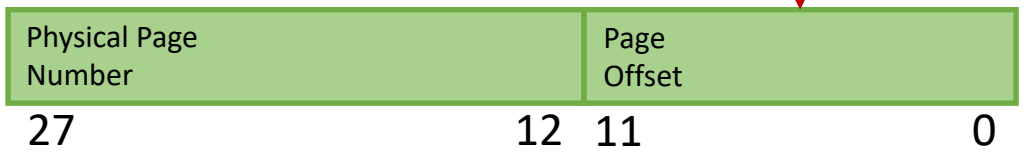
VA: 0x00003 099

Virtual Address [32 bit]

TLB [2-entries big]

Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Physical Address [28 bits]



Main Memory

PPN
DISK
0x000A
0x0005
0x0001
0x0002
…
0x00F5

TLB Example

Computer Specs:
32-bit ISA, 256 MB of RAM, 4 kB pages, 2-entry TLB

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28-bit Physical Address

12-bit Page Offset [Index]

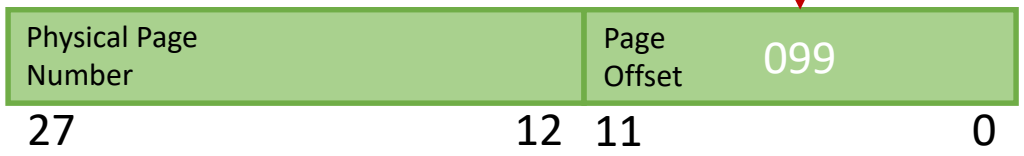
VA: 0x00003 099

Virtual Address [32 bit]

TLB [2-entries big]

Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Physical Address [28 bits]



Main Memory

PPN
DISK
0x000A
0x0005
0x0001
0x0002
…
0x00F5

TLB Example

Computer Specs:
32-bit ISA, 256 MB of RAM, 4 kB pages, 2-entry TLB

32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

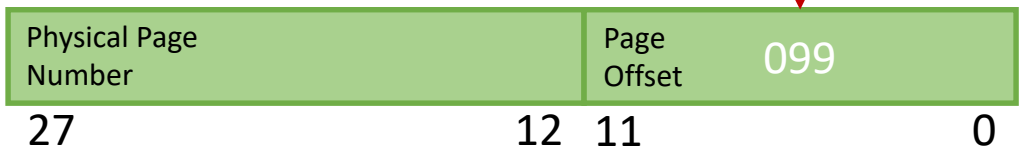
VA: 0x00003 099

Virtual Address [32 bit]

TLB [2-entries big]

Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Physical Address [28 bits]



Main Memory

PPN
DISK
0x000A
0x0005
0x0001
0x0002
…
0x00F5

TLB Example

Computer Specs:
32-bit ISA, 256 MB of RAM, 4 kB pages, 2-entry TLB

32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

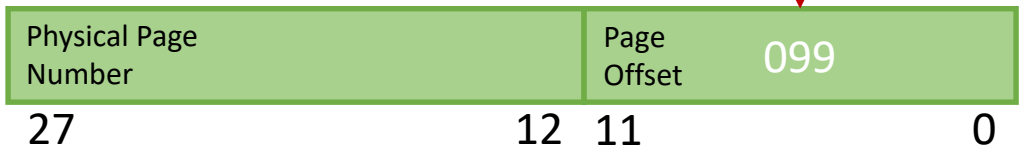
VA: 0x00003 099

Virtual Address [32 bit]

TLB [2-entries big]

Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Physical Address [28 bits]



Main Memory

PPN
DISK
0x000A
0x0005
0x0001
0x0002
…
0x00F5

TLB Example

Computer Specs:
32-bit ISA, 256 MB of RAM, 4 kB pages, 2-entry TLB

32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

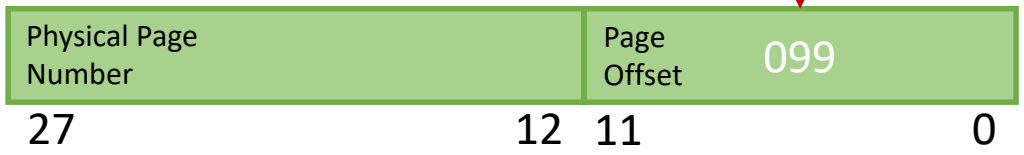
VA: 0x00003 099

Virtual Address [32 bit]

TLB [2-entries big]

Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Physical Address [28 bits]



Main Memory

PPN
DISK
0x000A
0x0005
0x0001
0x0002
…
0x00F5

TLB Example

Computer Specs:
32-bit ISA, 256 MB of RAM, 4 kB pages, 2-entry TLB

32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

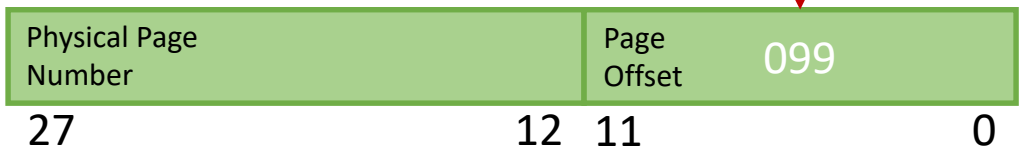
VA: 0x00003 099

Virtual Address [32 bit]

TLB [2-entries big]

Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Physical Address [28 bits]



Main Memory

PPN
DISK
0x000A
0x0005
0x0001
0x0002
…
0x00F5

TLB Hit!

TLB Example

Computer Specs:
32-bit ISA, 256 MB of RAM, 4 kB pages, 2-entry TLB

32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

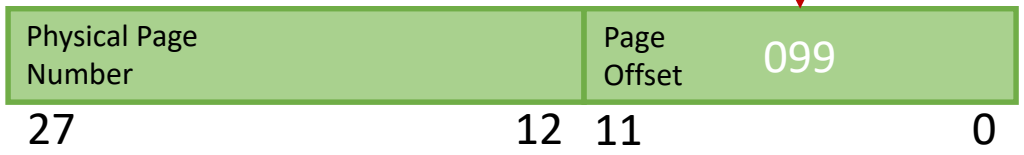
VA: 0x00003 099

Virtual Address [32 bit]

TLB [2-entries big]

Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Physical Address [28 bits]



Main Memory

PPN
DISK
0x000A
0x0005
0x0001
0x0002
…
0x00F5

TLB Hit!

TLB Example

Computer Specs:
32-bit ISA, 256 MB of RAM, 4 kB pages, 2-entry TLB

32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

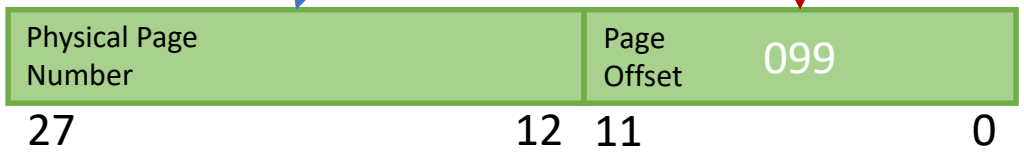
VA: 0x00003 099

Virtual Address [32 bit]

TLB [2-entries big]

Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Physical Address [28 bits]



Main Memory

PPN
DISK
0x000A
0x0005
0x0001
0x0002
…
0x00F5

TLB Hit!

TLB Example

Computer Specs:
32-bit ISA, 256 MB of RAM, 4 kB pages, 2-entry TLB

32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

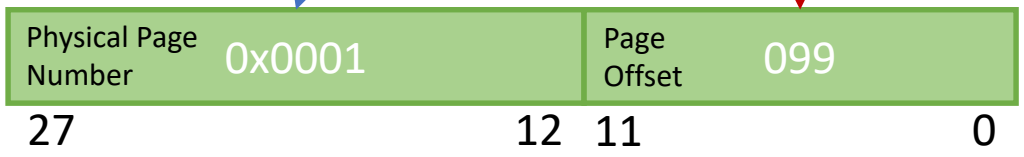
VA: 0x00003 099

Virtual Address [32 bit]

TLB [2-entries big]

Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Physical Address [28 bits]



Main Memory

PPN
DISK
0x000A
0x0005
0x0001
0x0002
…
0x00F5

TLB Hit!

TLB Example

Computer Specs:
32-bit ISA, 256 MB of RAM, 4 kB pages, 2-entry TLB

32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

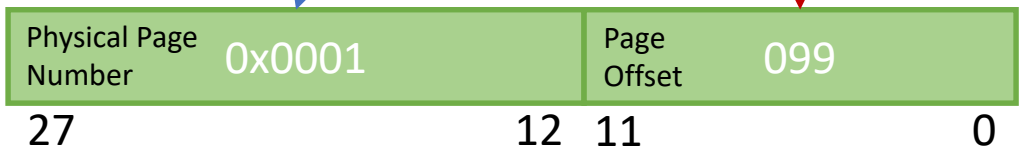
VA: 0x00003 099

Virtual Address [32 bit]

TLB [2-entries big]

Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Physical Address [28 bits]



PA: 0x0001 099

TLB Hit!

Main Memory

PPN
DISK
0x000A
0x0005
0x0001
0x0002
…
0x00F5

TLB Example

Computer Specs:
32-bit ISA, 256 MB of RAM, 4 kB pages, 2-entry TLB

32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

VA: 0x00000 123

Virtual Address [32 bit]

TLB [2-entries big]

Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Physical Address [28 bits]

Main Memory

PPN
DISK
0x000A
0x0005
0x0001
0x0002
…
0x00F5

TLB Example

Computer Specs:
32-bit ISA, 256 MB of RAM, 4 kB pages, 2-entry TLB

32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

VA: 0x00000 123

Virtual Address [32 bit]

TLB [2-entries big]

Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Q: What is the **PA** associated with this **VA**?

Main Memory

PPN
DISK
0x000A
0x0005
0x0001
0x0002
…
0x00F5

Physical Address [28 bits]

TLB Example

Computer Specs:
32-bit ISA, 256 MB of RAM, 4 kB pages, 2-entry TLB

32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

VA: 0x00000 123

Virtual Address [32 bit]

TLB [2-entries big]

Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Physical Address [28 bits]

Main Memory

PPN
DISK
0x000A
0x0005
0x0001
0x0002
…
0x00F5

TLB Example

Computer Specs:
32-bit ISA, 256 MB of RAM, 4 kB pages, 2-entry TLB

32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

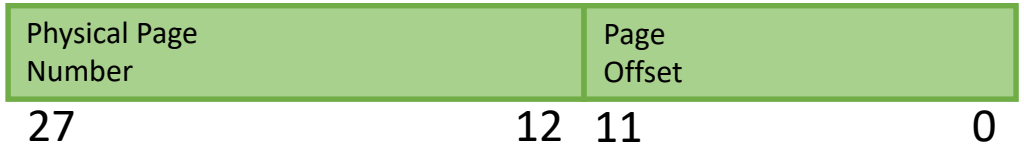
VA: 0x00000 123

Virtual Address [32 bit]

TLB [2-entries big]

Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Physical Address [28 bits]



Main Memory

PPN
DISK
0x000A
0x0005
0x0001
0x0002
…
0x00F5

TLB Example

Computer Specs:
32-bit ISA, 256 MB of RAM, 4 kB pages, 2-entry TLB

32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

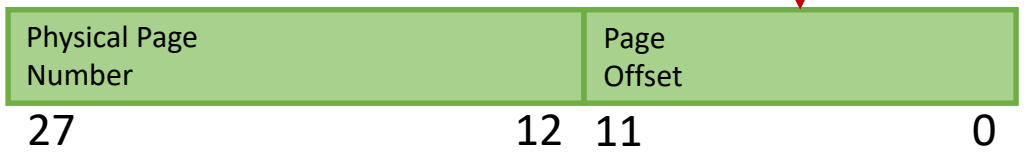
VA: 0x00000 123

Virtual Address [32 bit]

TLB [2-entries big]

Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Physical Address [28 bits]



Main Memory

PPN
DISK
0x000A
0x0005
0x0001
0x0002
…
0x00F5

TLB Example

Computer Specs:
32-bit ISA, 256 MB of RAM, 4 kB pages, 2-entry TLB

32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

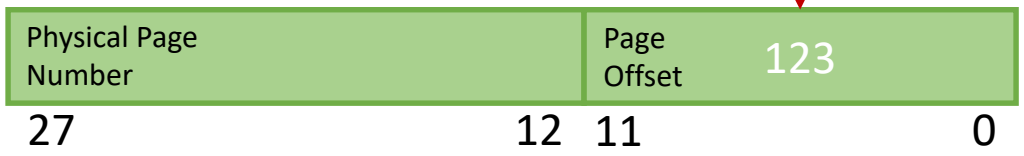
VA: 0x00000 123

Virtual Address [32 bit]

TLB [2-entries big]

Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Physical Address [28 bits]



Main Memory

PPN
DISK
0x000A
0x0005
0x0001
0x0002
…
0x00F5

TLB Example

Computer Specs:
32-bit ISA, 256 MB of RAM, 4 kB pages, 2-entry TLB

32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

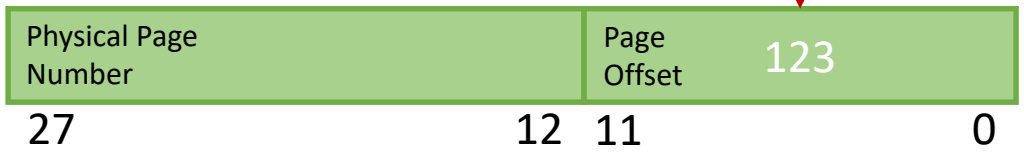
VA: 0x00000 123

Virtual Address [32 bit]

TLB [2-entries big]

Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Physical Address [28 bits]



Main Memory

PPN
DISK
0x000A
0x0005
0x0001
0x0002
…
0x00F5

TLB Example

Computer Specs:
32-bit ISA, 256 MB of RAM, 4 kB pages, 2-entry TLB

32-bit Virtual Address
28-bit Physical Address

12-bit Page Offset [Index]

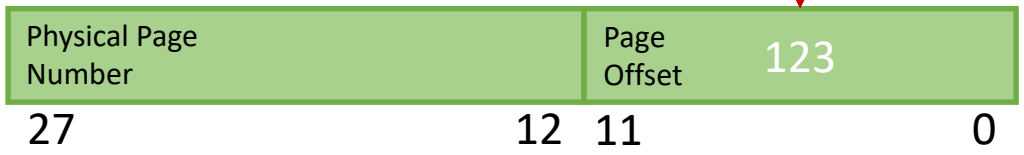
VA: 0x00000 123

Virtual Address [32 bit]

TLB [2-entries big]

Tag	Physical Page #
0x0 0003	0x0001
0x0 0004	0x0002

Physical Address [28 bits]



Main Memory

PPN
DISK
0x000A
0x0005
0x0001
0x0002
…
0x00F5

TLB Example

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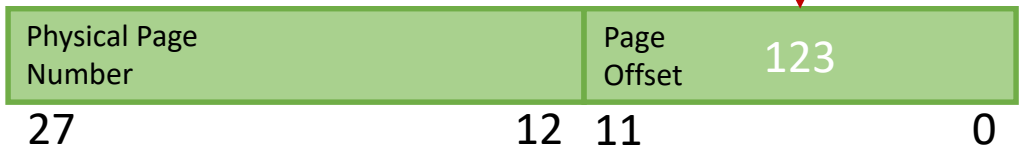

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TLB Miss!

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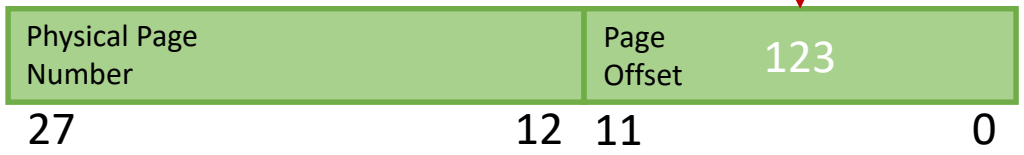

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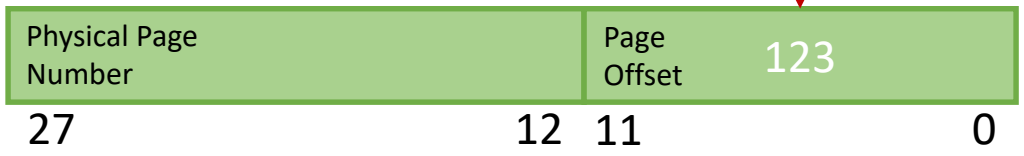

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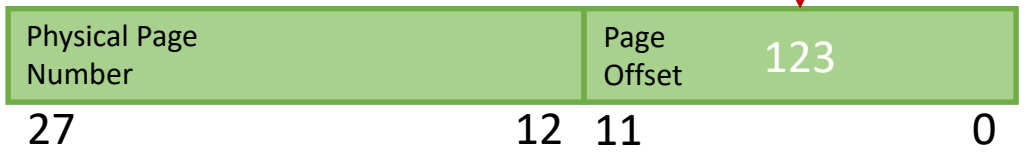

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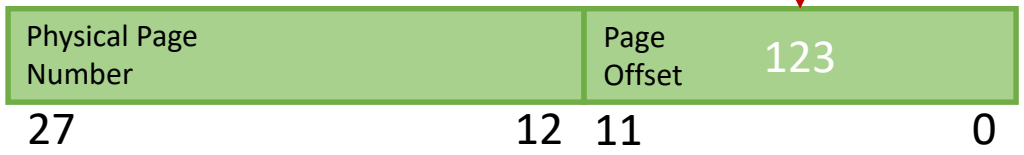

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DISK
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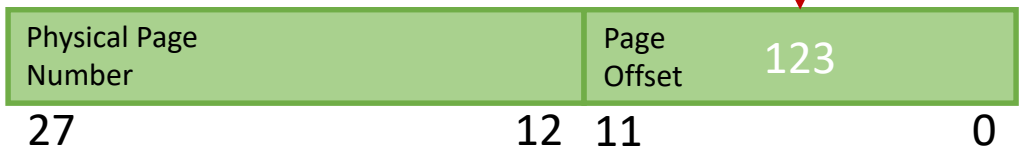

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Must bring into RAM from disk

Main Memory

PPN
DISK
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0x0005
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0x0002
…
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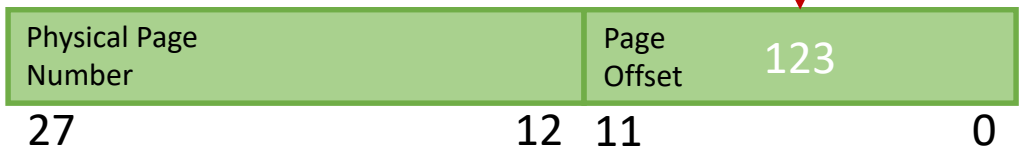
Physical Address [28 bits]



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Virtual Page Number	Page Offset
0x0 0000	123

31 12 11 0

TLB [2-entries big]

Tag	Physical Page #
0x0 0003	0x0001
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Must bring into RAM from disk

Page Fault!

Physical Address [28 bits]

Physical Page Number	Page Offset
	123

27 12 11 0

Main Memory

PPN
DISK
0x000A
0x0005
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TLB Miss!

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PA: Need more info

TLB Miss!

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PPN
DISK
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0x0001
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…
0x00F5

References

- David Black-Schaffer: Lecture Series on Virtual Memory
- Patterson, Hennessy: Computer Organization and Design: the Hardware/Software Interface
- Intel Hardware Data-Sheets
- Linux: Anatomy of a Program in Memory