Main Memory

ICS332

Operating Systems

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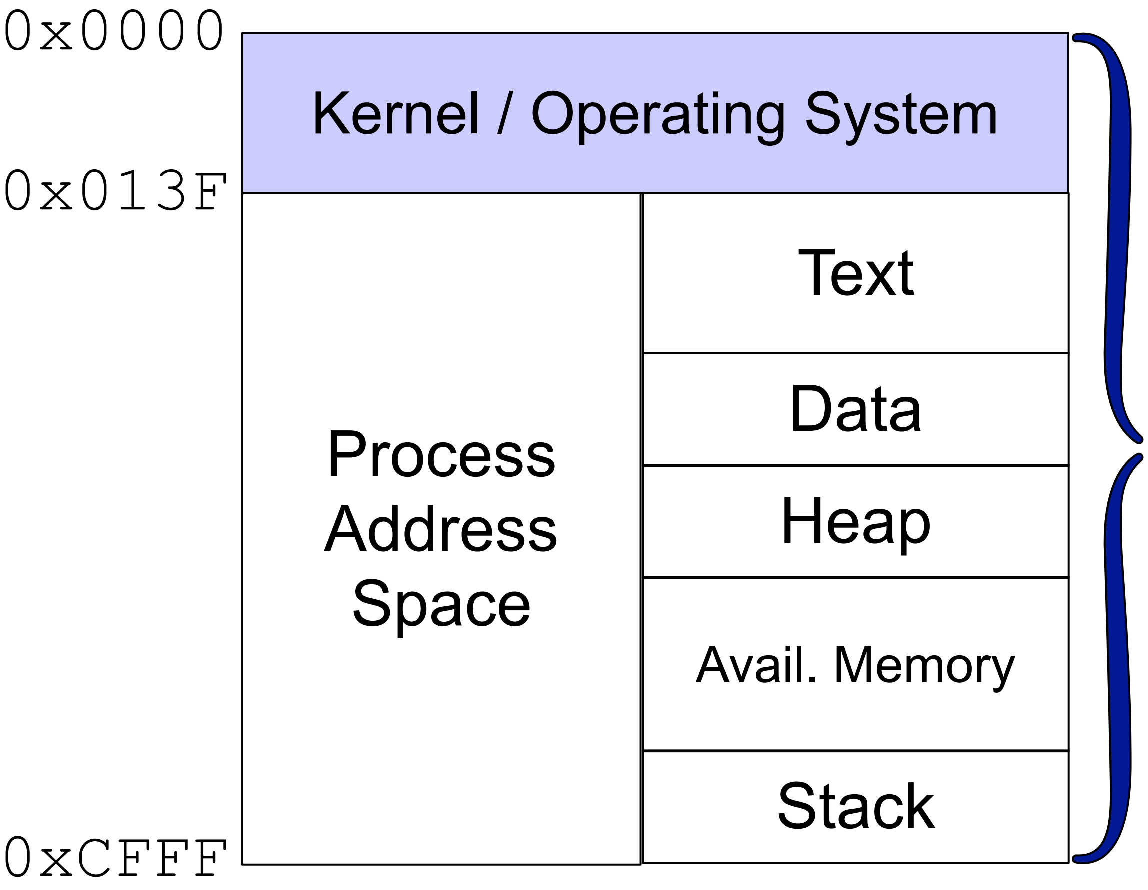
Main Memory: Basics

- Main Memory = Memory Unit (in Von Neumann model)
  - (Large) contiguous array of bytes/words, each with its own address
  - Stream of addresses coming in on the memory bus
  - Each incoming address is stored in the memory-address register of the memory unit
  - Which causes the memory unit to put the content at that address on the memory bus
  - And that content is then read in by the CPU
- Called the “Main” memory by contrast with registers, caches, which are all managed 100% by the hardware
- Processes share the main memory, therefore the OS must manage the main memory
- The CPU only works with registers, but it can issue addresses of locations (bytes) in main memory
  - Via load/store instructions (in MIPS assembly: LOAD and STORE; in x86 assembly: mov .., [..] and mov [..], ..)

Contiguous Memory Allocation

- Let us assume what we have always assumed so far: each process is allocated a contiguous zone of physical memory



In this example memory is fully utilized by the kernel and one process:

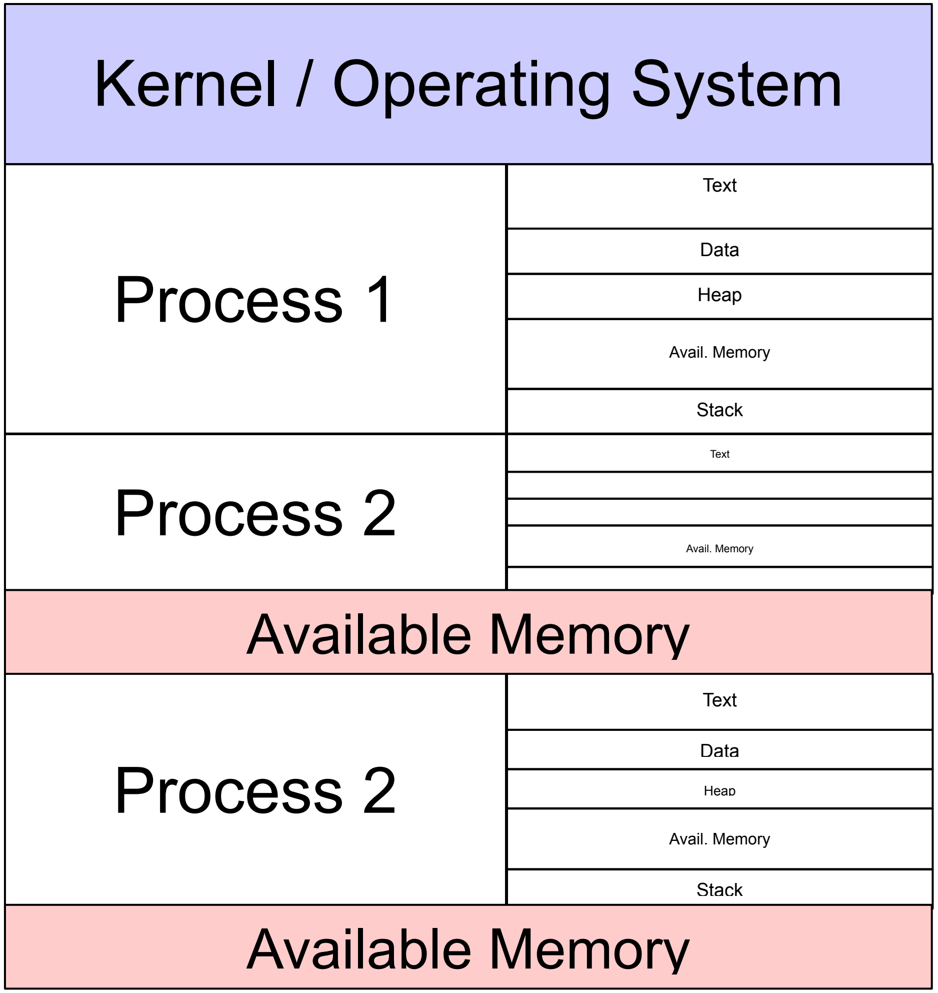
Total RAM size

= 0xCFFF + 1

= 53248d

= 52 KiB

Contiguous Memory Allocation + Multiprogramming



Kernel / Operating System

Process 1
Text
Data
Heap
Avail. Memory
Stack

Process 2
Text
Avail. Memory

Available Memory

Process 2
Text
Data
Heap
Avail. Memory
Stack

Available Memory

This is the typical picture shown with multiple processes in memory, each with its own contiguous address space, and perhaps some left over available memory

Address Binding

- One important question is that of address binding: when are physical addresses determined for bytes of data/instruction?
- In your high-level code you write something like:

C source code

```
int a; // global
. . .
if (a != 0) {
  a++;
}
. . .
```

- When is the address of where the value of **`a`** is located determined??
- When is the address of the instruction to which to jump in case the value of **`a`** is zero determined??
- Let’s look at the compiled version of this program…

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Compiled Assembly Code

```
   . . .
   cmp [label_a], 0
   jz Nope
   inc word [label_a]
Nope:
   . . .
```

- When is the address of where the value of **a** is located determined??
- When is the address of the instruction to which to jump in case the value of **a** is zero determined??
- The assembler transforms the assembly code into a binary executable
- Let's look at the compiled version of this program…

Address Binding - Absolute Addressing?

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}
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```

Compiled Assembly Code

```
    . . .
    cmp [label_a], 0
    jz Nope
    inc word [label_a]
Nope:
    . . .
```

- One approach is to use absolute addressing so that the binary executable contains physical addresses:

```
    Address   Content
        ...   ...
0x5623FAB2    AFFB 0x6677FFBB    // cmp [label_a], 0
0x5623FAB4    DC32 0x5623FAB8    // jz Nope
0x5623FAB6    E013 0x6677FFBB    // a++
0x5623FAB8    ...
        ...   ...
0x6677FFBB    0                  // "int a" is here
        ...   ...
```

Problems of Absolute Addressing

- Absolute addressing is simple, but is has not been used in decades
- Anybody sees what a problem is with it?

Problems of Absolute Addressing

- Absolute addressing is simple, but is has not been used in decades
- Anybody sees what a problem is with it?
- **With absolute addressing a program must be loaded exactly at the same place into memory each time we run it**
  - Otherwise the addresses will be wrong!

- Therefore we may not be able to run a program because another program is running and encroaches on the address range!
- **Corollary**: We cannot run multiple instances of a single program!
- One solution would be to recompile a program each time you need to run it
  - Because only when you're about to run a program can you know where it should fit in memory
  - But this has problems: while you're recompiling your program, somebody else starts another program, so you can never be sure your program can run

- **Bottom-line:** absolute addressing is not a good idea and hasn't been used for a loooong time on general-purpose computers

Address Binding - Relative Addressing?

- We can solve the problem of absolute addressing with a very simple idea called relative addressing
- Let’s assume the address space starts at some BASE address, and compute all addresses as an offset from the BASE:

```
   Address   Content
0x56230000   F43D 0x5623000             // set BASE = 0x56230000
       ...   …
0x5623FAB2   AFFB BASE + 1054FFBB       // cmp [label_a], 0
0x5623FAB4   DC32 BASE + FAB8           // jz Nope
0x5623FAB6   E013 BASE + 1054FFBB       // a++
0x5623FAB8   ...
       ...   ...
0x6677FFBB   0                          // “int a” is here
       ...   ...
```

- The code is now completely **relocatable**: Only the BASE needs to be determined before running it
- The same program can be run anywhere in memory, at whatever BASE address
- Multiple instances can run, each with a different BASE address, provided they don’t overlap

RAM Virtualization

- All addresses in the process address space are expressed as an offset relative to the base value
- A program can be anywhere in RAM and doesn’t care where:
  - Instead of saying “the 4th byte in my address space is at address x”, it says “the 4th byte in my address space is at address BASE + 4”
- And just like that we have memory virtualization!
- OSTEP shows C programs that highlight this
  - OSTEP 2.2
- Let’s do another simple example here…

Memory-Virtualization Uncovered

Memory-Allocating Program

```
#include <stdlib.h>
#include <stdio.h>
#include <unistd.h>
int main(int argc, char **argv) {
  if (argc != 2) {
    fprintf(stderr,"Usage: %s <int value>\n", argv[0]); exit(1);
  }
  int value;
  if (sscanf(argv[1], "%d", &value) != 1) {
    fprintf(stderr,"Invalid command-line argument\n");
    exit(1);
  }
  int *address = (int*)malloc(sizeof(int));
  *address = value;
  printf("I wrote value %d at address %p\n", value, address);
  sleep(10);
  printf("At address %p I see value %d\n", address, *address);
  exit(0);
}
```

Compile and run on Linux

```
gcc -o memory_virtualization memory_virtualization.c -fsanitize=address
```

Let’s run two instances in two terminals on Linux

Take Away

- Both programs print the same address, therefore **it cannot be a physical address!**
- Instead, the address issued by programs and handled by the CPU are logical addresses or virtual addresses (both terms are used)

- What was that **`-fsanitize=address`** thing???
  - This command-line option to gcc enables the use of AddressSanitizer
  - AddressSanitizer is an open-source tool developed by Google
    - It is supported by most compilers on Linux and MacOS
  - It detects memory errors for C/C++
    - buffer overflow, stack overflow, use after free, stack overflow
  - It turns out that to do its work AddressSanitizer disables address space layout randomization (ASLR)
  - Let’s remove that option and see what happens....

Memory Virtualization

- Thanks to virtualization: Each program instance has the illusion that it's alone in RAM and that its address space starts at address 0
- This gives us Memory Protection
  - A program doesn't need to know anything about other programs
  - It never has to think "ooh... I shouldn't write there in RAM because that address is used by another program"
  - This is good, because when you write the code you don't know what other programs will be running anyway!

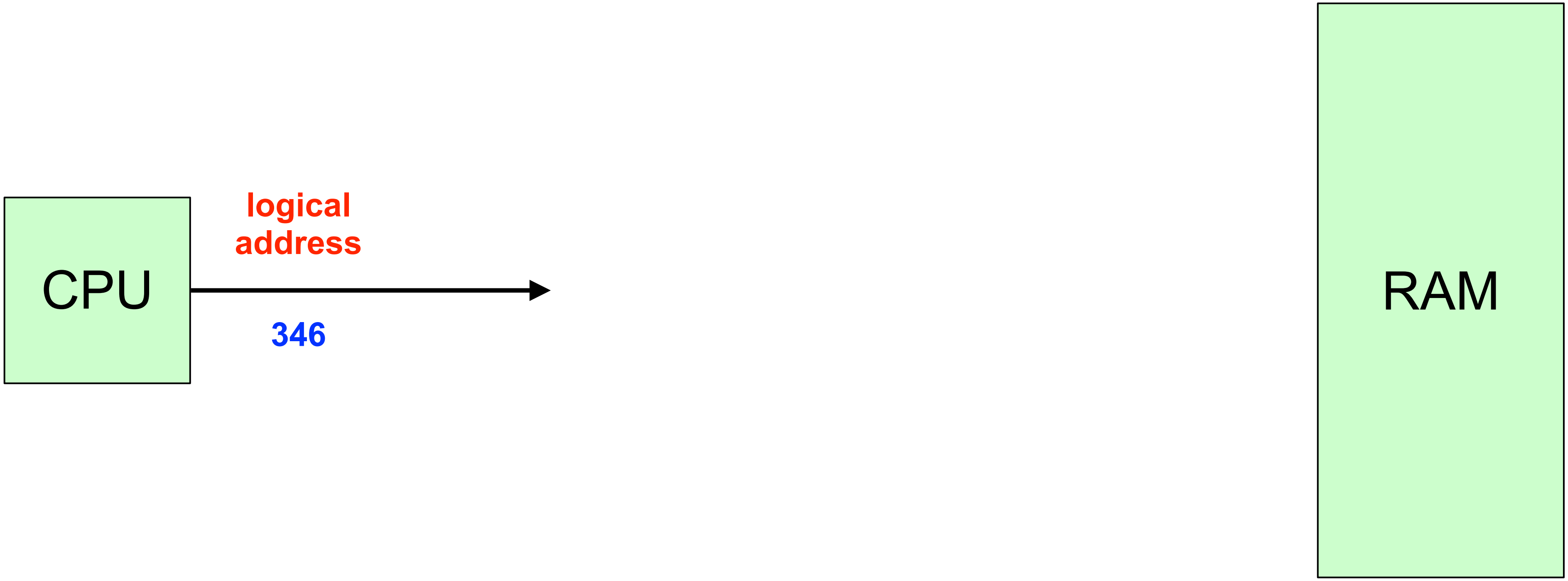
- **Bottom Line:** A program references a logical address space, which corresponds to a physical address space in the memory

- "Something" needs to tell the CPU how to translate from virtual to physical addresses, i.e., some address translation mechanism

Virtualizing Address Spaces

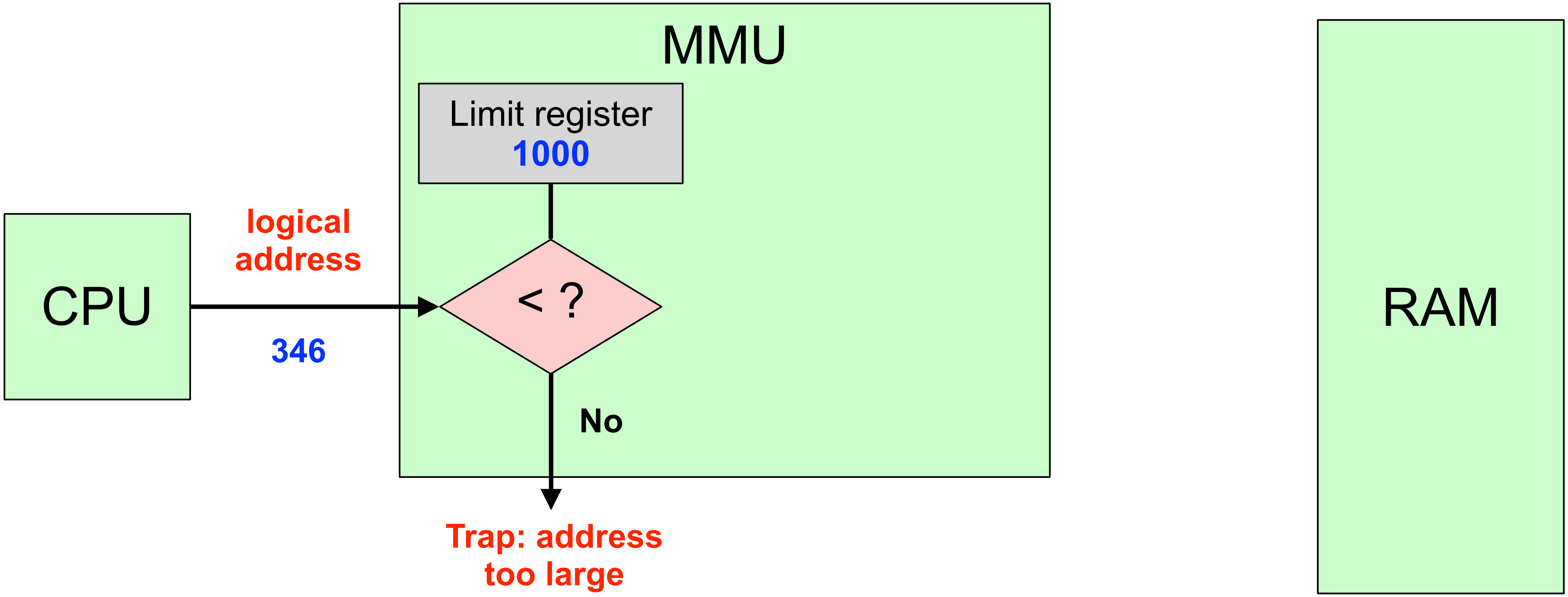
- Some component needs to translate virtual addresses into physical addresses: add an offset to the BASE
- **Address translation happens very frequently** (each load, store, jump)
- Therefore: The BASE Address is accessed very frequently
  - The memory translation component should store it in a register or something as fast as a register
- And: Offsets are added to the BASE address very frequently
  - Wasting even one CPU cycle to do the addition would be very expensive
- Furthermore: It would be nice if only valid logical addresses were translated
  - For memory protection: we don't want processes to step on each other's toes
- So we use a base register and a limit register that stores the base address and the largest possible logical address
- **And we implement the above as a super fast hardware component: the Memory Management Unit (MMU)**

Memory Management Unit



- Historically: A specialized circuit between the CPU and the memory
- Nowadays: Integrated with the CPU

Memory Management Unit



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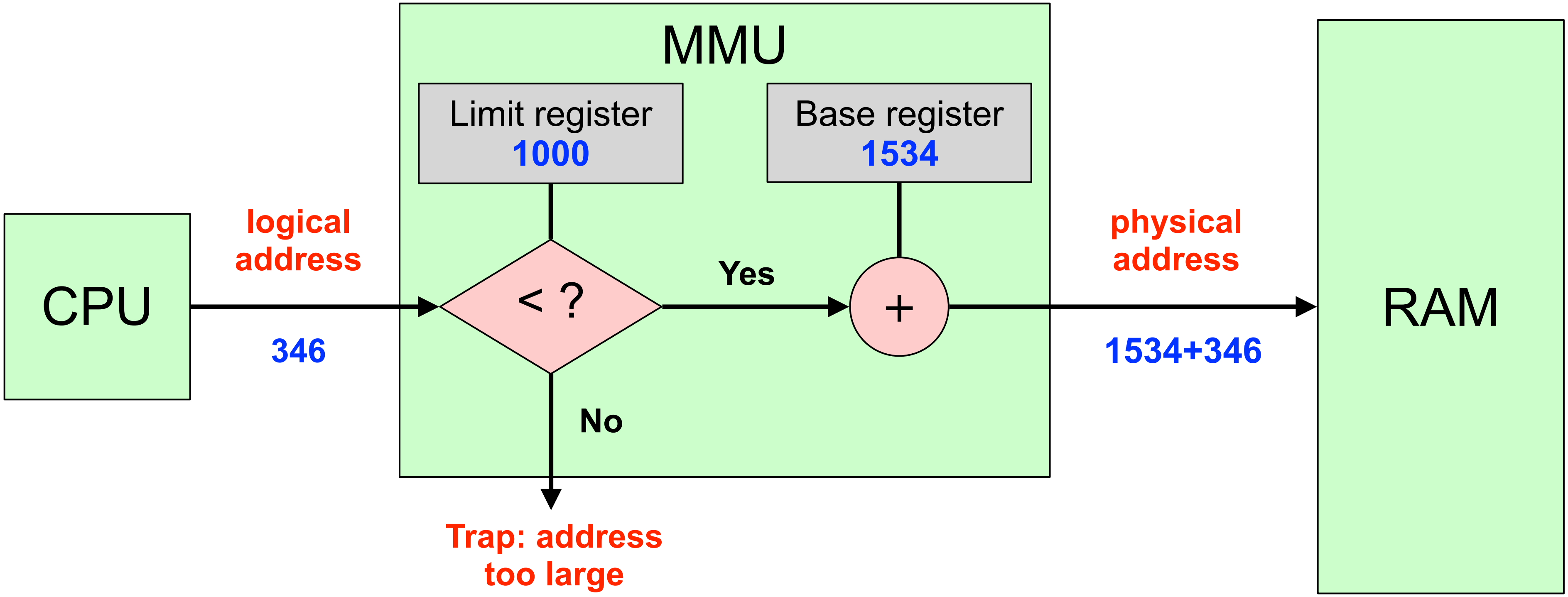
Memory Management Unit



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Summary So Far

- Your program generates only logical addresses >=0
- Each such address is checked to see if it's beyond the limit, and if it is, a trap is generated and the program aborts
- If not, then the address is translated (just added it to the base to compute the physical address)
- That translated physical address is then sent to the memory bus, and the RAM will do its job based on that address (read or write some bytes)

- **Bottom line:**
  - Your CPU only "sees" logical addresses
  - Your RAM only "sees" physical addresses

Segmentation

- Recall the structure of the address space
  - The figure doesn’t show the ”data” part
- An address space is full of empty space
  - In which the heap/stack will grow
- Therefore having a single contiguous “segment” is wasteful

- Segmentation: Avoid waste by breaking up the address space into pieces
  - Each piece has its own base/limit register

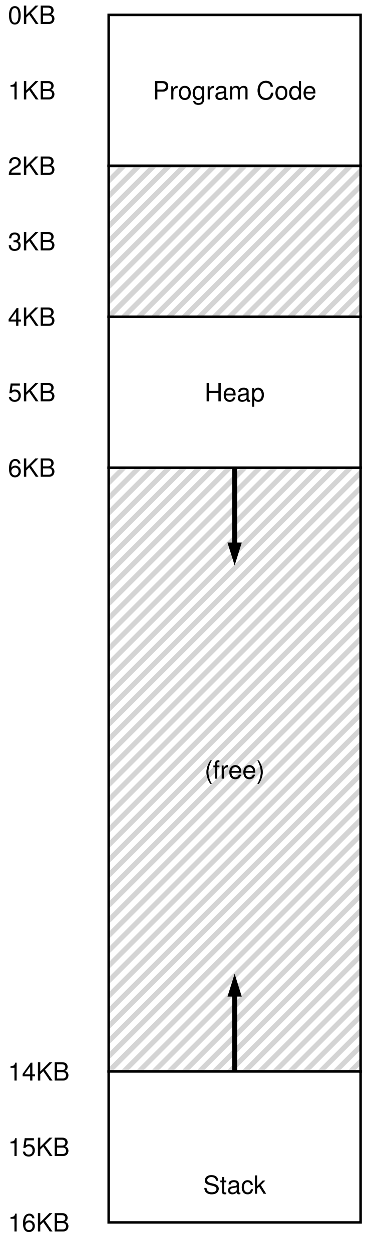
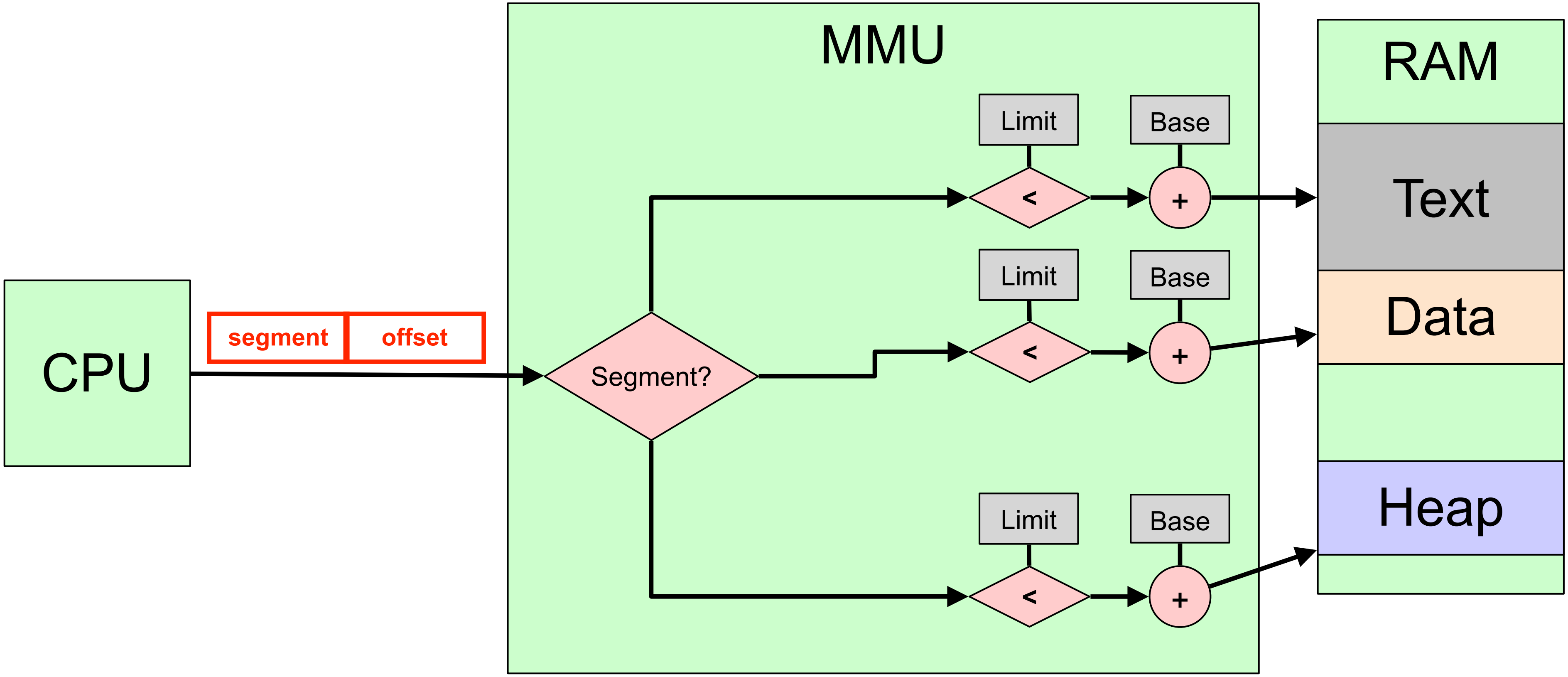


Figure 16.1: **An Address Space (Again)**

Segmentation

- The logical address space is now a collection of segments
- The compiler/language interpreter handles the segments and the logical addresses are built appropriately
  - If you write in assembly language, you may have to deal with segments manually
- Typical segments used by a C compiler
  - text
  - data
  - heap
  - stacks
  - standard C library
- The first bits of the logical address are used to identify which segment is being referenced
- Let's see this on a picture

MMU Segmentation



- Implementing segmentation is easy
- Reserve bits (e.g., the left-most ones) in the logical address to reference a segment (the segment bits)
- Question: how do we know which segment is being referenced?

Segment Table

- A segment table with one entry per segment number is used to keep track of segments
- For each segment, its entry stores:
  - Base: Starting address of the segment
  - Limit: Length of the segment
- The segment table is stored in memory
  - (but cached on the CPU to avoid extra memory accesses… a common theme we'll come back to)
- A **Segment-Table Base Register** (STBR): Points to the segment table address
- A **Segment-Table Length Register** (STLR): Gives the length of the segment table
  - Makes it easy to detect an invalid segment offset
- These registers are saved/restored at each context switch

Segmentation for Protection

- Now that we have each “piece” of the address space in its own segment we can easily implement some protection mechanisms!
- The segment table can include bits that answer:
  - Is the segment readable?
  - Is the segment writable?
  - Is the segment executable?
  - Any combination of 3 bits: RWX
    - RX: Read and execute (e.g. text)
    - RW: Read and write (e.g. stack)
- This allows the CPU to detect errors/bugs such as “executing data as if it were code”, “overwriting code”, ...

Main Takeaways

- Programs should be rellocatable
- Memory address virtualization
- Segmentation
- The CPU sees logical addresses, and the MMU transforms them into physical addresses
    - Determines the segment
    - Look up the segment table to find the segment’s base and limit values
    - Check that the logical address is within the limit, and if not generate a trap
    - Add the base to the logical address
    - And voila, we have the physical address

Conclusion

- Now that we have virtualized addresses, we’ve solved all kinds of problems

- But there is still one question: what happens if our program does not fit in RAM?
- Onward to the next set of lecture notes…