

# CSC 374/407: Computer Systems II

## Lecture 6

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# Reading

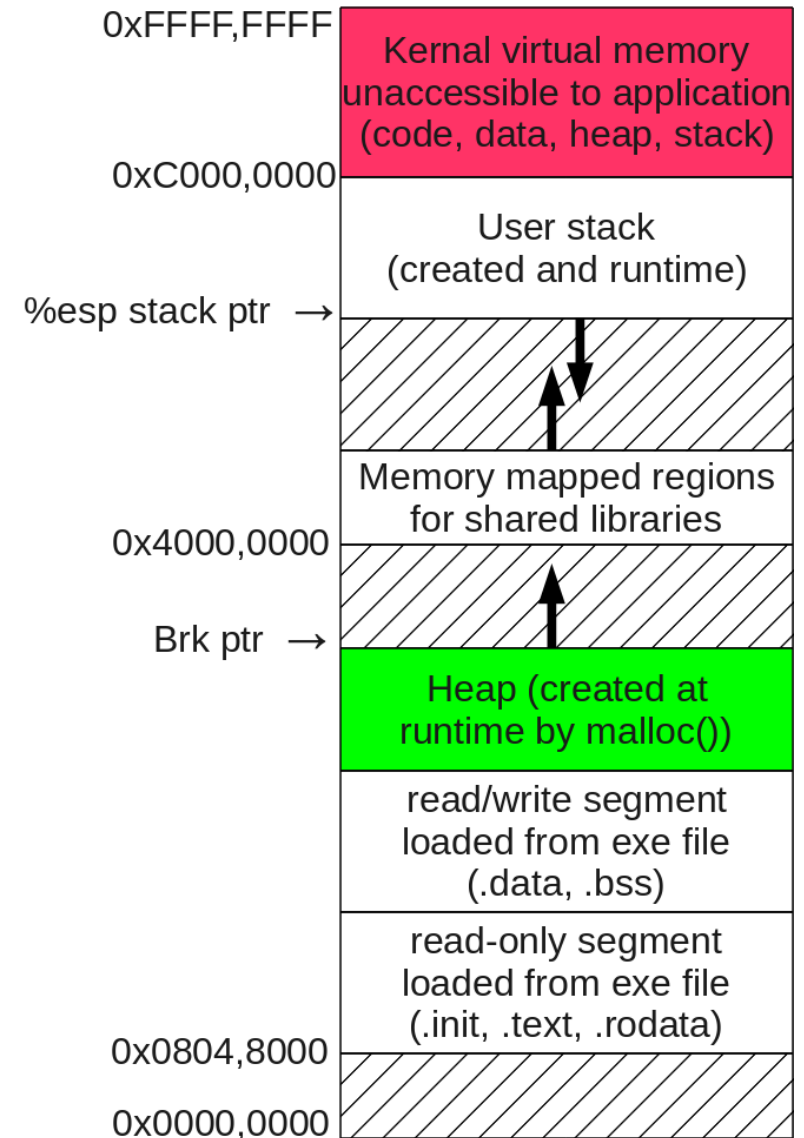
- ♦ Bryant & O'Hallaron “*Computer Systems, 2<sup>nd</sup> Ed.*”
  - ♦ Chapter 9.1-9.8: Virtual Memory
  - ♦ Chapter 9.9: Dynamic Memory Allocation
- ♦ Hoover “*System Programming*”
  - ♦ Chap 4: Pointers and Structures
    - ♦ Especially: 4.2.3: Dynamic Memory Allocation

# Topics

- ◆ The heap
  - ◆ Heap Motivation
  - ◆ Heap Programming at C level (glibc)
    - ◆ malloc(), free(), calloc() and realloc()
    - ◆ How **not** to abuse the heap
  - ◆ Heap Programming at OS level (Linux)
    - ◆ getrlimit(), setrlimit(), brk(), sbrk()
- ◆ C-Strings
  - ◆ Buffer overflow attacks
  - ◆ Preventing buffer overflow attacks
- ◆ Linux virtual memory and paging

# Today's topic (in space)

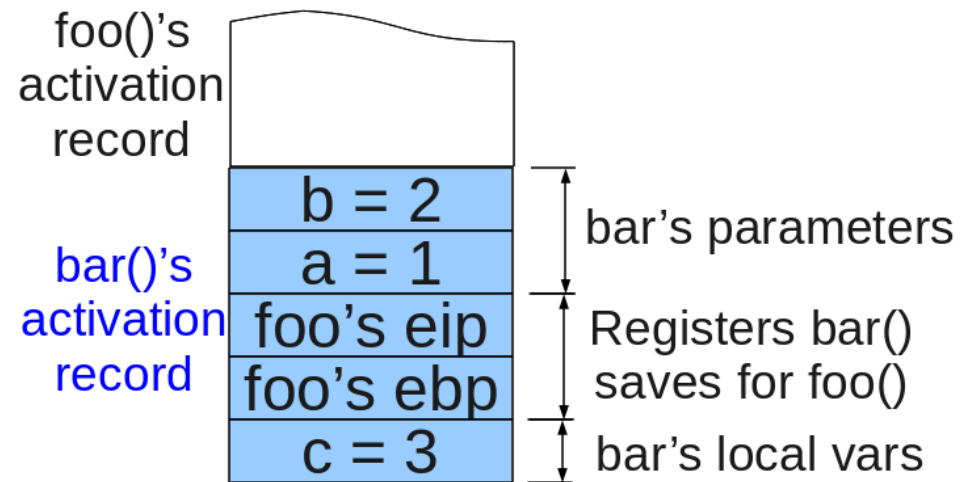
## ◆ Runtime heap



# We all know that local vars live on the stack

```
int bar (int a, int b)
{
    int c = a + b;
    return(c);
}
```

```
int foo ()
{
    int x = bar(1,2);
    . . .
}
```

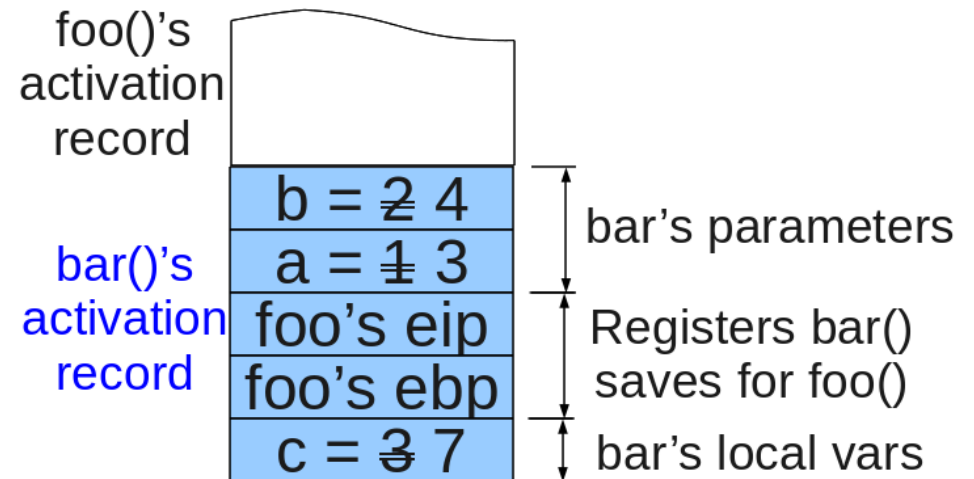


# And we all know that the stack gets overwritten by subsequent function calls

```
int bar (int a, int b)
{
    int c = a + b;
    return(c);
}
```

```
int foo ()
{
    int x = bar(1,2);

    x = bar(3,4);
    . . .
}
```



# Question?

But what if you  
want your object to  
*persist*?

# Answer!

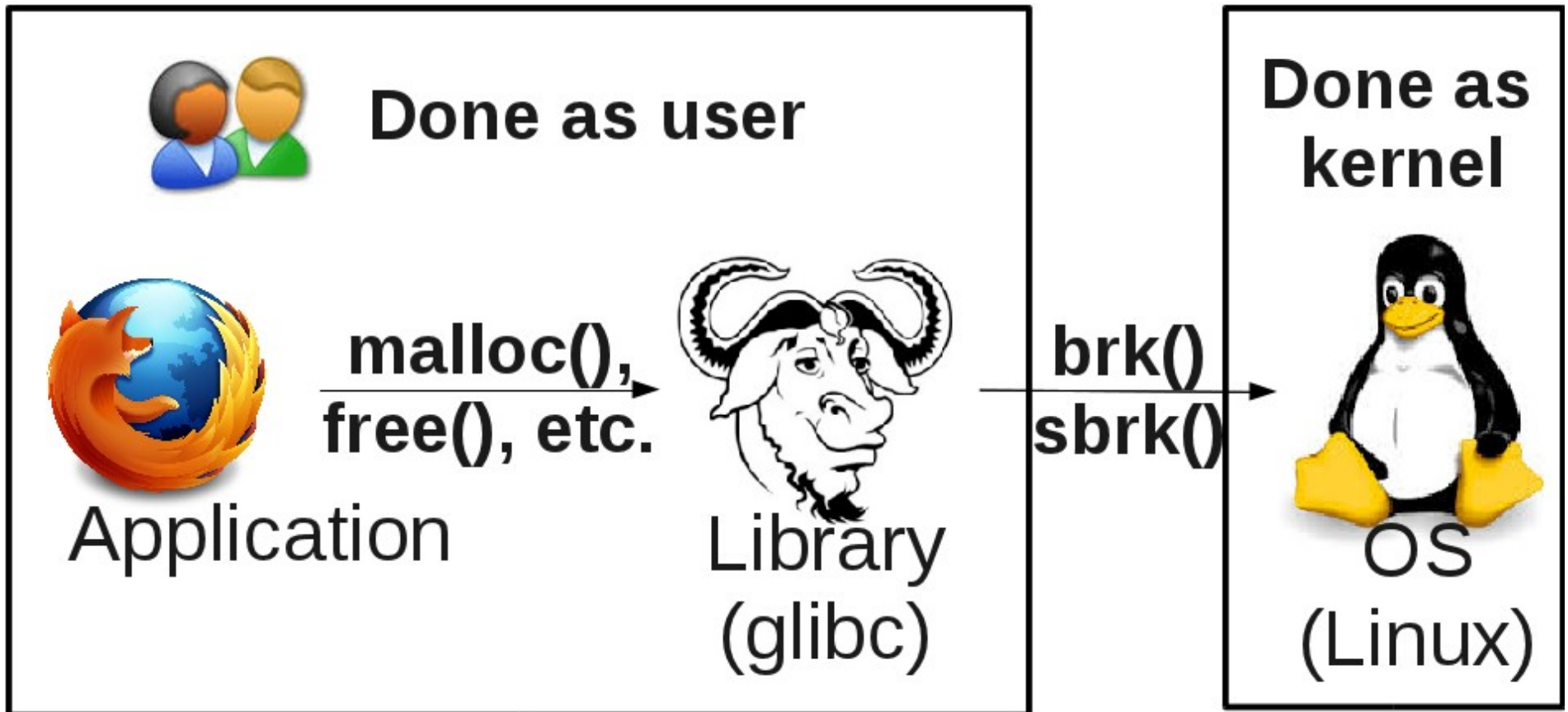
Put it  
on the  
*heap!*

```
MyClass* bar()  
{  
    return new MyClass(1,2);  
}
```

```
void foo()  
{  
    MyClass ptr;  
  
    ptr = bar();  
    . . .  
    delete(ptr);  
}
```



# Two “folks” we have to ask for heap memory:



# First: Ordinary C heap programming (glibc)



# Heap Programming

- ◆ ***void\* malloc(size\_t numBytes)***

- ◆ Allocate ***numBytes*** bytes from heap and return pointer (allocates in ***page table***, not necessarily ***main memory!***)
- ◆ Returns ***NULL*** if error like not enough space.
- ◆ Returned pointer should be cast to a more specific type before using:

```
int*   intPtr   = (int*)malloc(sizeof(int));  
char*  charPtr  = (char*)malloc(strlen(sourcePtr)+1);
```

- ◆ ***void free (void\* ptr)***

- ◆ Return memory back to system

# malloc() and free() example

```
#include <stdlib.h>
#include <stdio.h>

int      main      ( )
{
    int*   iPtr;

    iPtr   = (int*)malloc(sizeof(int));
    *iPtr  = 14;
    printf("iPtr = %p, *iPtr = %d\n",
           iPtr,*iPtr
           );
    free(iPtr);    // Very important!
    return(EXIT_SUCCESS);
}
```

# realloc() and calloc()

- ♦ ***void\* calloc(size\_t nmemb, size\_t size);***
  - ♦ Allocates an array of ***nmemb*** members, each of ***size*** bytes.
  - ♦ Initializes memory to byte all 0's
  - ♦ (Some claim this wastes time.)
- ♦ ***void\* realloc(void \*ptr, size\_t size);***
  - ♦ “Re-allocates” by extending memory allocated at pointer, or by (1) getting ***size*** bytes, (2) copying from ***ptr*** into new memory, and (3) ***free()***-ing old memory

# realloc() and calloc() example

```
#include <stdlib.h>
#include <stdio.h>
#define NUM_ELE 4
int      main      ( )
{
    int*   iPtr;
    int*   iPtr2;
    int    i;

    iPtr   = (int*)calloc(NUM_ELE,sizeof(int));
    iPtr2  = (int*)calloc(NUM_ELE,sizeof(int));

    for    (i = 0;   i < NUM_ELE;   i++)
    { // Any other ways to access?
        iPtr[i] = i*10;
    }
}
```

# realloc() and calloc(), contd

```
for (i = 0; i < NUM_ELE; i++)
    printf("%3d is at %p\n",
           *(iPtr+i), (iPtr+i)
    );
printf("Uh-oh, not enough space!\n");
iPtr=(int*)realloc(iPtr, 4*NUM_ELE*sizeof(int));

for (i = 0; i < 4*NUM_ELE; i++)
    printf("%3d is at %p\n",
           *(iPtr+i), (iPtr+i)
    );

free(iPtr2); // Very important!
free(iPtr);  // Very important!
return(EXIT_SUCCESS);
}
```

# realloc() and calloc(), contd

```
[instructor@localhost Lecture06]$ ./reallocAndCalloc1
```

```
0 is at 0x84f2008
```

```
10 is at 0x84f200c
```

```
20 is at 0x84f2010
```

```
30 is at 0x84f2014
```

```
Uh-oh, not enough space!
```

```
0 is at 0x84f2038
```

```
10 is at 0x84f203c
```

```
20 is at 0x84f2040
```

```
30 is at 0x84f2044
```

```
0 is at 0x84f2048
```

```
0 is at 0x84f204c
```

```
0 is at 0x84f2050
```

```
0 is at 0x84f2054
```

```
0 is at 0x84f2058
```

```
0 is at 0x84f205c
```

```
0 is at 0x84f2060
```

```
0 is at 0x84f2064
```

```
0 is at 0x84f2068
```

```
0 is at 0x84f206c
```

```
0 is at 0x84f2070
```

```
0 is at 0x84f2074
```

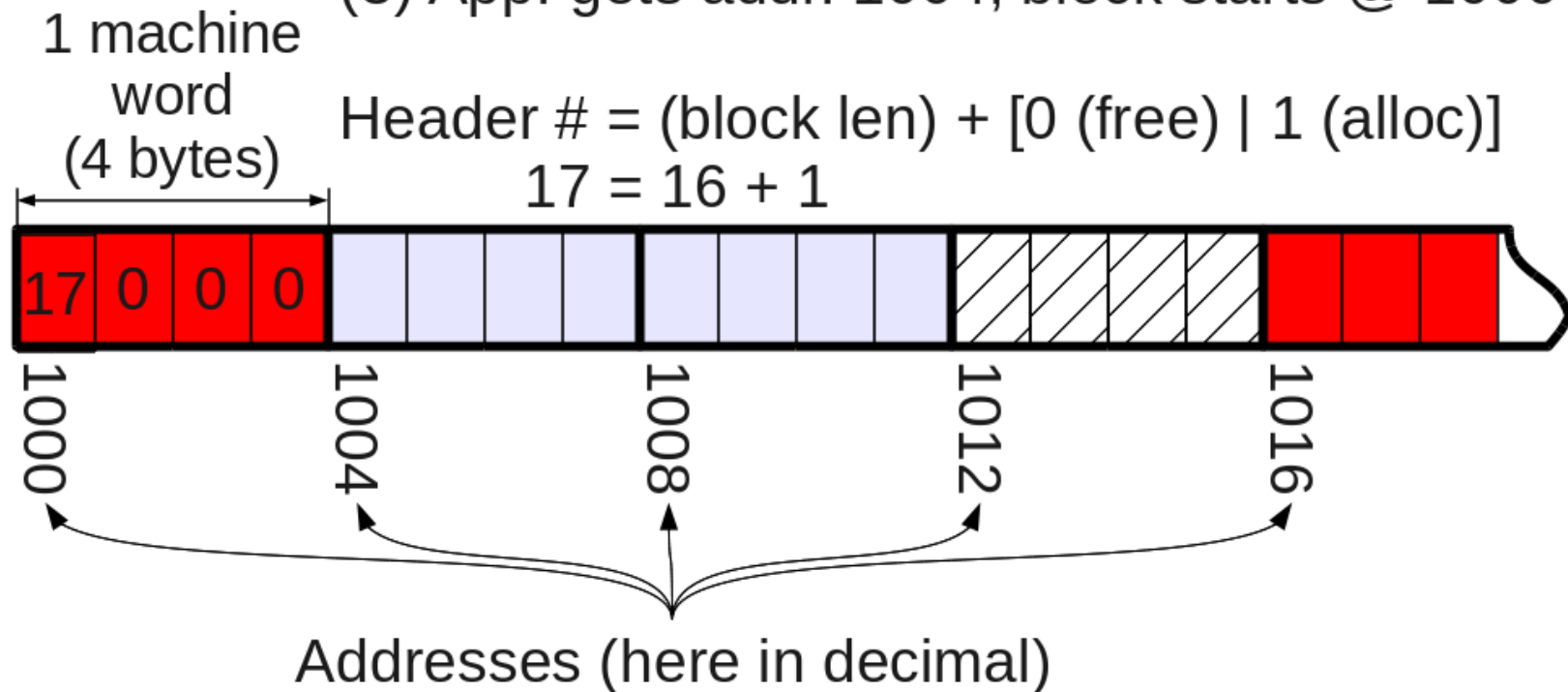


# Datastructure for heap management

(1) App. does ***malloc(6)***

(2) 6 rounded up to 8

(3) App. gets addr. 1004, block starts @ 1000



Byte used by header (int. frag.)



Byte given to application



Byte used for padding  
(int. frag.)

# Algorithm for heap management

- How do we keep track of malloc()s and free()s in heap?
- Desireable algorithms should:
  - 1) Be efficient (maximize space for app. data)
    - 1) Minimize internal fragmentation (space used in allocated block for bookkeeping and padding)
    - 2) Minimize external fragmentation (unused space between allocated blocks)
  - 2) Be fast!
  - 3) Be robust (detect app errors)
  - 4) Be sensitive to spatial locality (put similar sized items “close” to each other)
  - 5) Be thread safe

# Your turn!

- ◆ Question 1:
  - ◆ Why do you think it changed addresses between the `calloc()` and the `realloc()`?
  - ◆ Can you test that hypothesis?
- ◆ Question 2:
  - ◆ Do you think the newly allocated space is guaranteed to be initialized to 0?
  - ◆ Can you test that hypothesis?

# ***A Rogue's Gallery of the *All-Time WORST* memory offenses***

***Enter at your  
own risk!***



# How NOT to use the heap: Memory leak

// Very subtly wrong. What are the symptoms?

```
#include <stdlib.h>
```

```
#include <stdio.h>
```

```
int      main      ()
```

```
{
```

```
    int*   iPtr;
```

```
    iPtr   = (int*)malloc(sizeof(int));
```

```
    *iPtr  = 14;
```

```
    printf("iPtr = %p, *iPtr = %d\n",  
           iPtr,*iPtr
```

```
        );
```

```
    return(EXIT_SUCCESS);
```

```
}
```

# How NOT to use the heap:

## Double free

```
#include <stdlib.h>
#include <stdio.h>

int      main      ()
{
    int*   iPtr;

    iPtr   = (int*)malloc(sizeof(int));
    *iPtr  = 14;
    printf("iPtr = %p, *iPtr = %d\n",
           iPtr,*iPtr
           );
    free(iPtr);
    free(iPtr);
    return(EXIT_SUCCESS);
}
```

# How NOT to use the heap: Wild-write 1

```
#include <stdlib.h>
#include <stdio.h>

int      main      ()
{
    int*   iPtr;

    iPtr    = (int*)malloc(sizeof(int));
    *(iPtr-1) = 14;
    printf("iPtr = %p, *iPtr = %d\n",
           iPtr,*iPtr
           );
    free(iPtr);
    return(EXIT_SUCCESS);
}
```

# How NOT to use the heap:

## Freed memory access

```
#include <stdlib.h>
#include <stdio.h>

int      main      ()
{
    int*   iPtr;

    iPtr   = (int*)malloc(sizeof(int));
    *iPtr  = 14;
    printf("iPtr = %p, *iPtr = %d\n",
           iPtr,*iPtr
           );
    free(iPtr);
    (*iPtr)++; // Not yet finished
    return(EXIT_SUCCESS);
}
```



# How NOT to use the heap: Uninitialized mem access

```
#include <stdlib.h>
#include <stdio.h>

int      main      ()
{
    int*   iPtr;

    *iPtr = 14;
    printf("iPtr = %p, *iPtr = %d\n",
           iPtr,*iPtr
           );
    return(EXIT_SUCCESS);
}
```

# This is how glibc complains:

```
*** glibc detected *** wildwrite: munmap_chunk():
invalid pointer: 0x08f71008 ***
===== Backtrace: =====
/lib/libc.so.6[0x49b8b9f2]
/lib/libc.so.6[0x49b8bc6b]
wildwrite[0x8048524]
/lib/libc.so.6(__libc_start_main+0xf3)
[0x49b2c6b3]
wildwrite[0x8048441]
===== Memory map: =====
08048000-08049000 r-xp 00000000 fd:03 397997
    ./wildwrite
08049000-0804a000 rw-p 00000000 fd:03 397997
    ./wildwrite
08f71000-08f92000 rw-p 00000000 00:00 0      [heap]
. . .
```

**And this is how Linux  
complains:**

Segmentation fault (core dumped)

# Your turn!

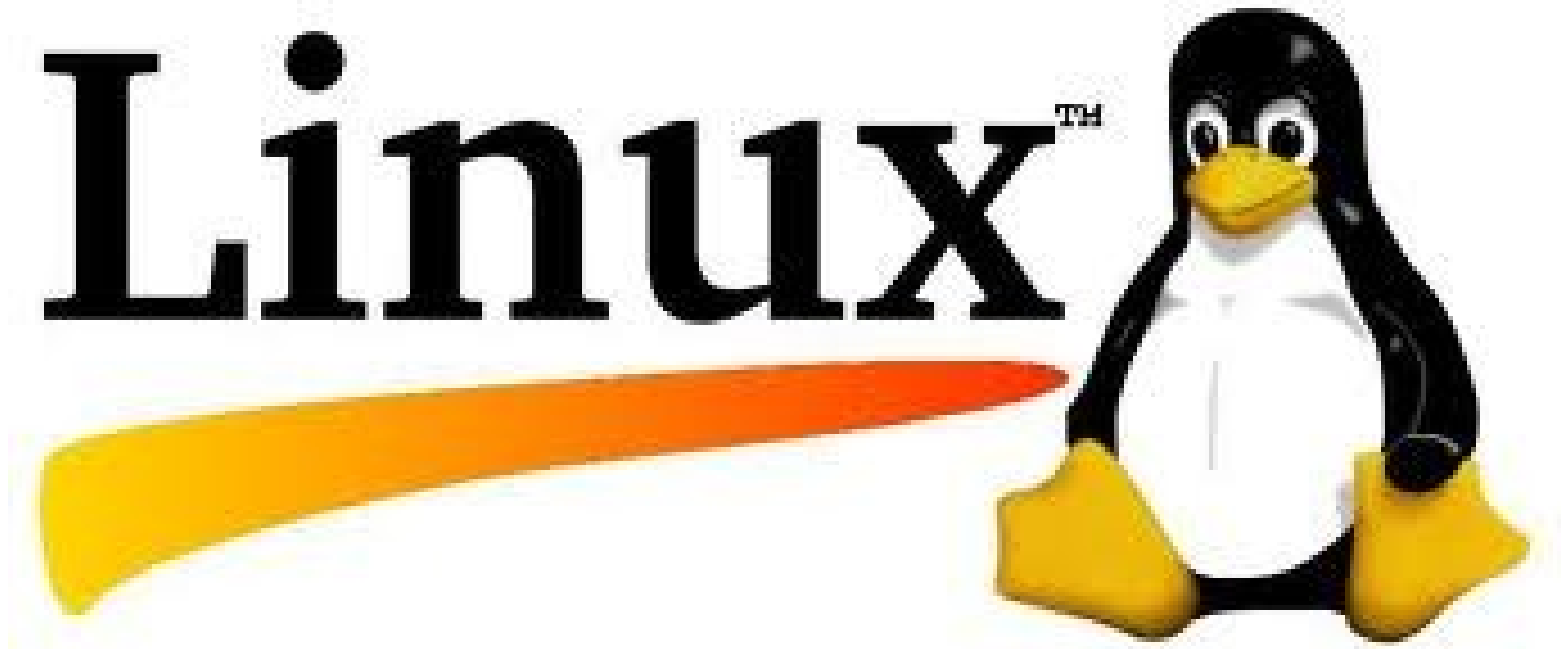
- ◆ Fix the following function that should copy a string into memory allocated from the heap:

```
char* naughtyCopy (const char* fromP)
{
    char* toP;

    for ( ; *fromP != '\0'; fromP++, toP++)
        *toP = *fromP;

    free(fromP);
    return(toP);
}
```

## Second: OS's heap interface



# OS's heap tools

- ♦ A process can put limits on how big it's heap is allowed to grow
  - ♦ **getrlimit()**, **setrlimit()**
  - ♦ **Soft-limit:** limits how much heap (or stack, CPU, *etc.*) a process is allowed to use
    - ♦ Any process can set
  - ♦ **YOUR TURN:** Why would a process want to do this?
  - ♦ **Hard-limit:** limits the soft limit
    - ♦ Only privileged processes may set
- ♦ A process can get heap pages directly from OS:
  - ♦ **brk()**, **sbrk()**

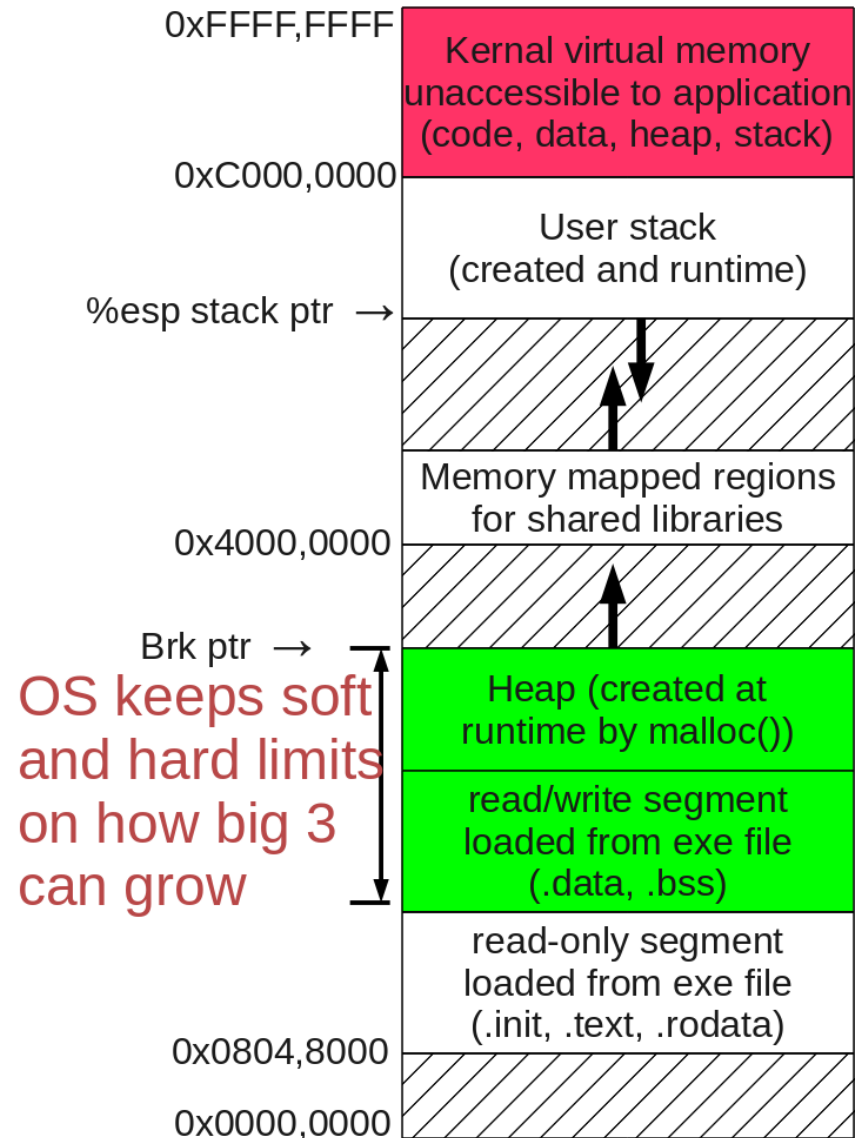
# OS's view of heap

```
#include <stdlib.h>
#include <stdio.h>
#include <sys/resource.h>
#include <errno.h>
int main ()
{
    struct rlimit    resouceLimit;
    if ( getrlimit(RLIMIT_DATA, &resouceLimit) ) {
        perror("getrlimit(RLIMIT_DATA) failed");
        return(EXIT_FAILURE);
    }

    printf("Process' combined max Data,"
           " ROData and heap sizes:\n");

    printf("Soft:\t");
    if (resouceLimit.rlim_cur == RLIM_INFINITY)
        puts("(Unlimited)");
    else
        printf("%lu\n",resouceLimit.rlim_cur);

    printf("Hard:\t");
    if (resouceLimit.rlim_max == RLIM_INFINITY)
        puts("(Unlimited)");
    else
        printf("%lu\n",resouceLimit.rlim_max);
    return(EXIT_SUCCESS);
}
```



# OS's view of heap, cont'd

- ◆ ***#include <unistd.h>***
- ◆ ***int brk(void \*endDataSeg);***
  - ◆ sets end of data segment when
    - ◆ (1) value is reasonable,
    - ◆ (2) system has memory,
    - ◆ (3) process doesn't exceed max data size
- ◆ ***void \*sbrk(intptr\_t inc);***
  - ◆ increments data space by *inc* bytes
  - ◆ Not a system call, it is just a C library wrapper.
  - ◆ `sbrk(0)` finds current ptr value.
- ◆ WARNING: YOU ARE ***malloc()*** and ***free()***!
  - ◆ Manually do what GNU C Library (glibc) does for you



# Check this out!

- A program that recursively
  - 1) Prints the current value of the `brk` pointer.
  - 2) Asks (in hexadecimal) how many bytes to allocate
  - 3) Allocates those bytes
  - 4) Prints the difference between the `brk` pointer and the end of the allocated block
  - 5) Recursively goes back to (1)
- Useful stuff:
  - `strtol("FF", NULL, 16)` returns integer `0xFF`

# moveBrkPtr2.c

```
#include <stdlib.h>
#include <stdio.h>
#include <unistd.h>
#include <errno.h>
#include <string.h>

#define TEXT_LEN      10

void doIt ()
{
    char text[TEXT_LEN];

    printf("sbrk is now      "
           "      %010p\n",
           sbrk(0)
    );
    printf("How much mem IN HEXADECIMAL "
           "do you want (0-8000,0=quit)? "
    );
    fgets(text,TEXT_LEN,stdin);
    int size = strtol(text,NULL,16);

    if (size <= 0)
        return;

    void* ptr = malloc(size);

    if (errno == ENOMEM)
    {
        printf("Out of memory, Boss!\n");
        return;
    }

    printf("You just got addresses:"
           "      %010p - %010p.\n",
           ptr,ptr+(size-1)
    );
    printf("sbrk- blockEnd: %010p -"
           " %010p = %010p\n",
           sbrk(0),
           ptr+(size-1),
           sbrk(0)-(ptr+(size-1))
    );
}
```

# moveBrkPtr2.c, cont'd

```
doIt();  
printf("Now freeing %p\n",ptr);  
free(ptr);  
}
```

```
int      main      ()  
{  
    doIt();  
    return(EXIT_SUCCESS);  
}
```

# Using moveBrkPtr2.c

```
$ ./moveBrkPtr2
```

```
sbrk is now                                0x0957e000
How much mem IN HEXADEECIMAL do you want (0-8000, 0=quit)? 8000
You just got addresses:                    0x0957e008 - 0x09586007.
sbrk- blockEnd: 0x095a7000 - 0x09586007 = 0x00020ff9
sbrk is now                                0x095a7000 <= 1st malloc
How much mem IN HEXADEECIMAL do you want (0-8000, 0=quit)? 8000
You just got addresses:                    0x09586010 - 0x0958e00f.
sbrk- blockEnd: 0x095a7000 - 0x0958e00f = 0x00018ff1
sbrk is now                                0x095a7000
How much mem IN HEXADEECIMAL do you want (0-8000, 0=quit)? 8000
You just got addresses:                    0x0958e018 - 0x09596017.
sbrk- blockEnd: 0x095a7000 - 0x09596017 = 0x00010fe9
sbrk is now                                0x095a7000
```

# Using moveBrkPtr2.c

```
You just got addresses:      0x0958e018 - 0x09596017.
sbrk- blockEnd: 0x095a7000 - 0x09596017 = 0x00010fe9
sbrk is now                  0x095a7000
How much mem IN HEXADECIMAL do you want (0-8000, 0=quit)? 8000
You just got addresses:      0x09596020 - 0x0959e01f.
sbrk- blockEnd: 0x095a7000 - 0x0959e01f = 0x00008fe1
sbrk is now                  0x095a7000
How much mem IN HEXADECIMAL do you want (0-8000, 0=quit)? 8000
You just got addresses:      0x0959e028 - 0x095a6027.
sbrk- blockEnd: 0x095a7000 - 0x095a6027 = 0x00000fd9 <= too small
sbrk is now                  0x095a7000
How much mem IN HEXADECIMAL do you want (0-8000, 0=quit)? 8000
You just got addresses:      0x095a6030 - 0x095ae02f.
sbrk- blockEnd: 0x095cf000 - 0x095ae02f = 0x00020fd1
sbrk is now                  0x095cf000 <=sbrk changed
How much mem IN HEXADECIMAL do you want (0-8000, 0=quit)? 0
```

# Buffer overflow attacks

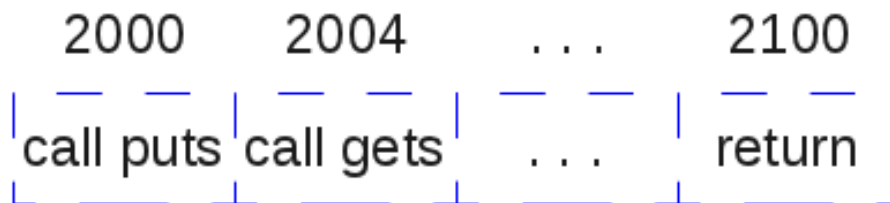
## Buffer overflow:

- Very common type of attack
- Exploits weakness in design of C with respect to:
  - implementation of arrays
  - Function calls
  - How values are saved in system stack
- So we'll have to review a wee bit of how function calls work . . .

# Buffer overflow attack (1)

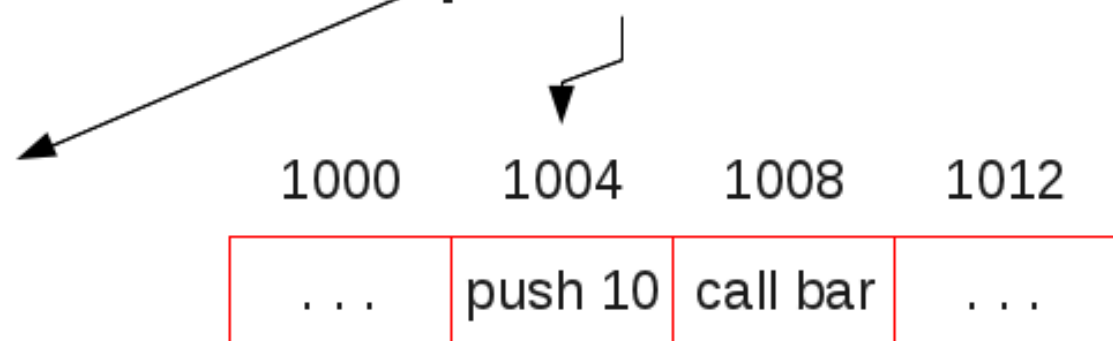
```
void bar(int i)
{
    char buf[100];
    puts("Name?");
    gets(buf);
    . . .
    return;
}
```

Each function is in its own strip of mem. Instruction pointer (*ip*) points to current instruction being done



```
void foo()
{
    . . .
    bar(10);
    . . .
}
```

*ip* = 1004



# Buffer overflow attack (2)

```
void bar(int i)
{
    char buf[100];
    puts("Name?");
    gets(buf);
    . . .
    return;
}
```

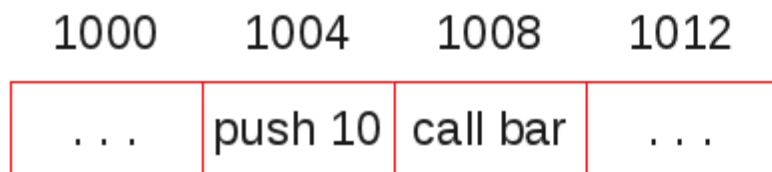
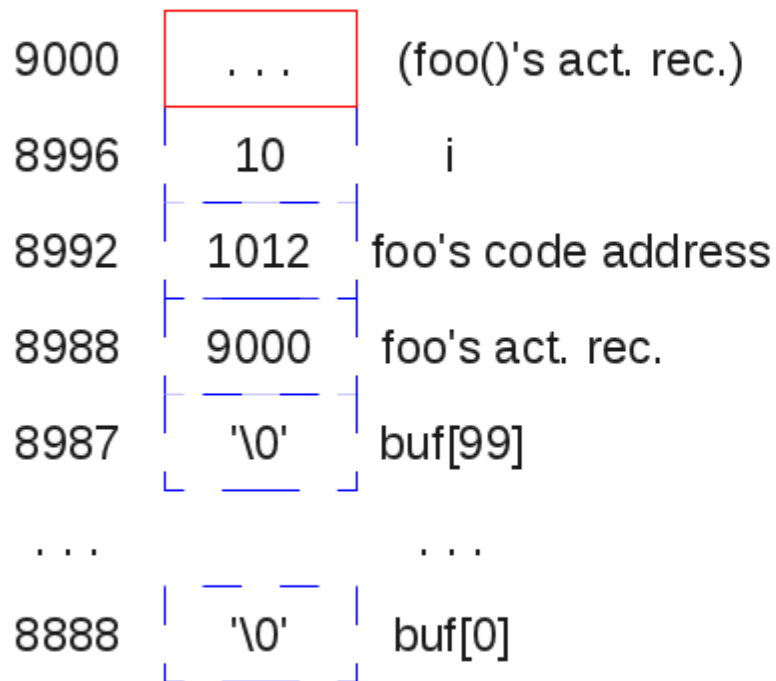
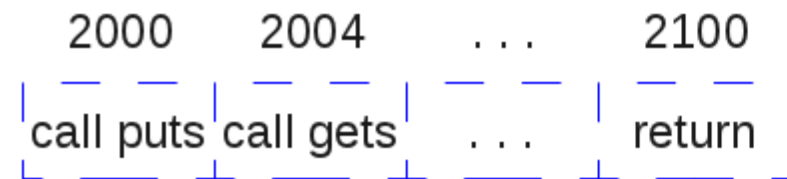
```
void foo()
{
    . . .
    bar(10);
    . . .
}
```

Local vars for each fnc are in an activation record on a sys stack, along with address of where to return in fnc that called you.

9000	...	(foo()'s act. rec.)
8996	10	i
8992	1012	foo's code address
8988	9000	foo's act. rec.
8987	'\0'	buf[99]
...	...	...
8888	'\0'	buf[0]



# Buffer overflow attack (3)



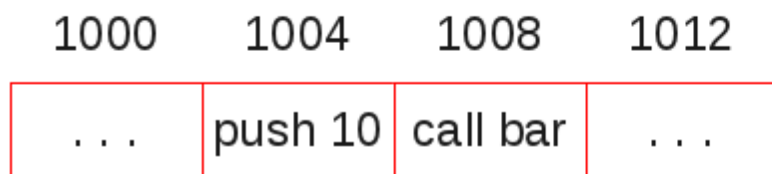
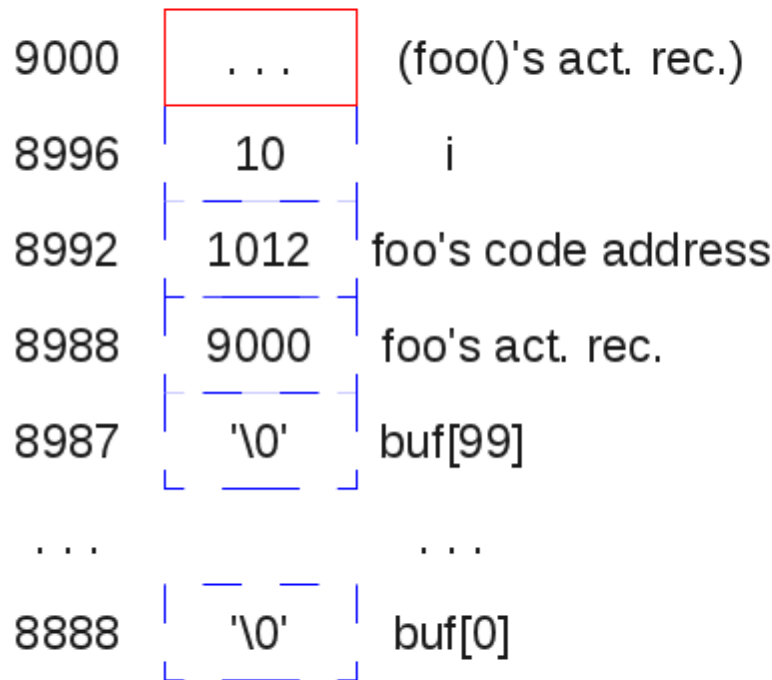
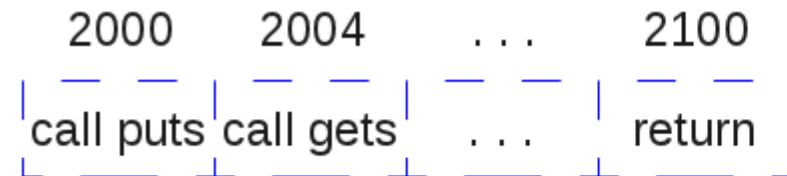
ip = 2100

(1) Instruction pointer gets to bar()'s return.

```
void bar(int i)
{
    char buf[100];
    puts("Name?");
    gets(buf);
    . . .
    return;
}
```

```
void foo()
{
    . . .
    bar(10);
    . . .
}
```

# Buffer overflow attack (4)



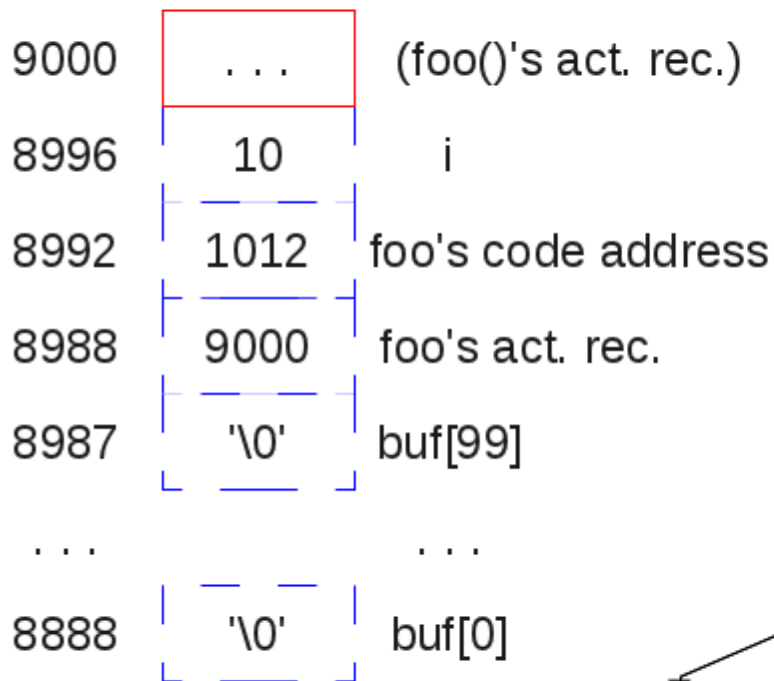
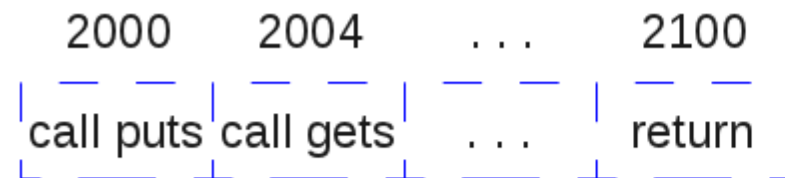
ip ← 1012

(2) Instruction pointer reads from `bar()`'s act. record address in `foo()` to return to.

```
void bar(int i)
{
    char buf[100];
    puts("Name?");
    gets(buf);
    . . .
    return;
}
```

```
void foo()
{
    . . .
    bar(10);
    . . .
}
```

# Buffer overflow attack (5)

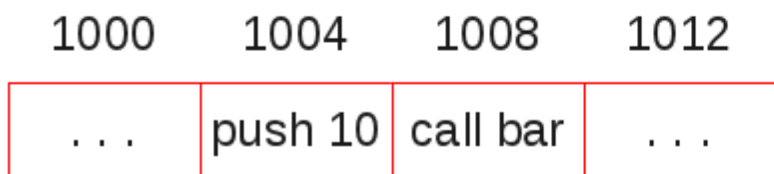


(3) Program resumes where it left off in `foo()`.

ip = 1012

```
void bar(int i)
{
    char buf[100];
    puts("Name?");
    gets(buf);
    ...
    return;
}
```

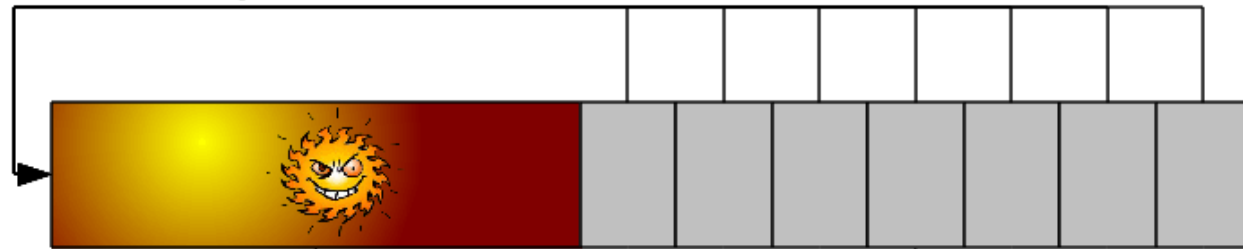
```
void foo()
{
    ...
    bar(10);
    ...
}
```



# Buffer overflow attack (6)



(1) Malfoy writes a small bit of code to run a shell, and some extra code as pointers to beginning of the shell code.



Code that does something bad! (like run a command line shell)

A bunch of pointers to the beginning of the bad part

# Buffer overflow attack (7)

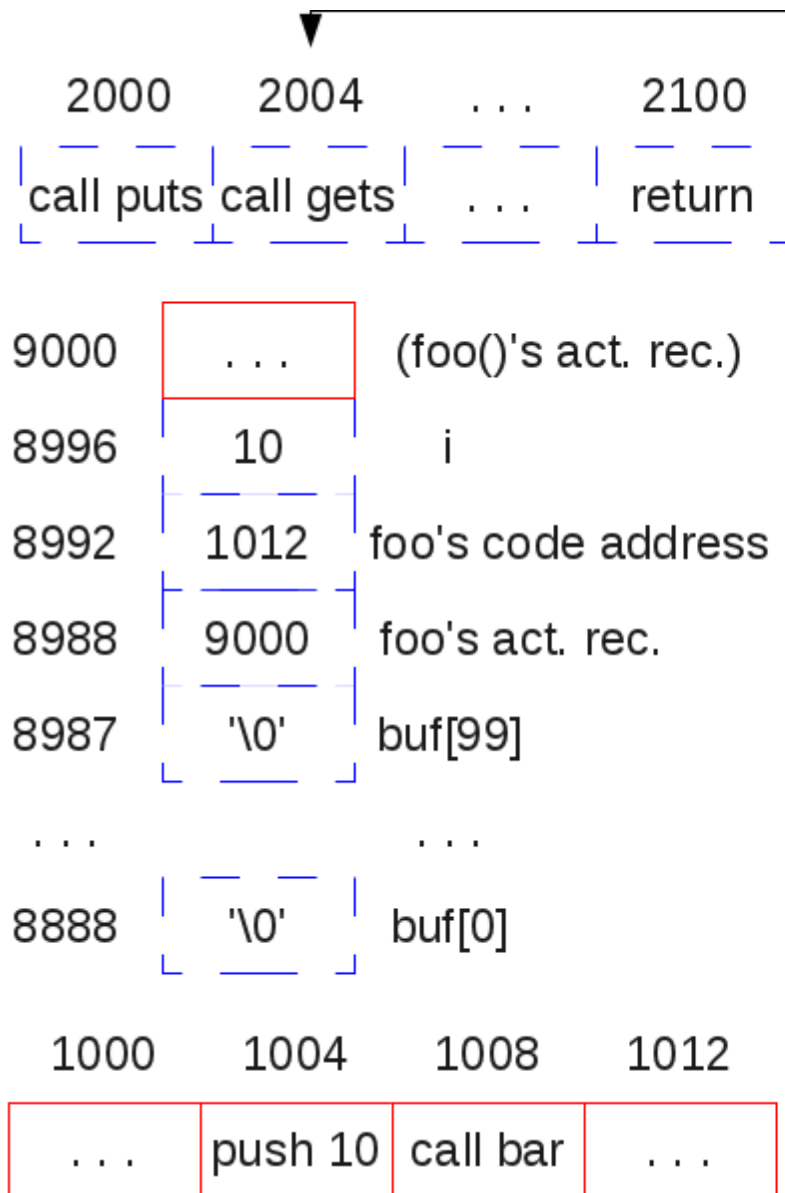


(2) Malfoy gets machine code of the string

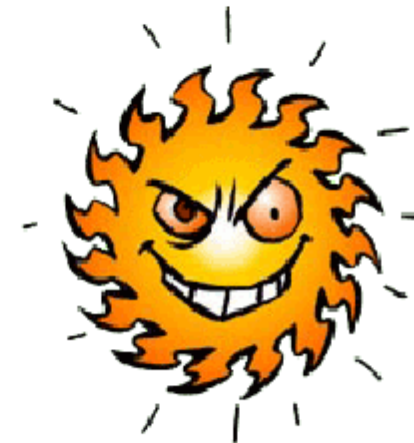


10 2E 4C B2 C4 07 08 . . .

# Buffer overflow attack (8)



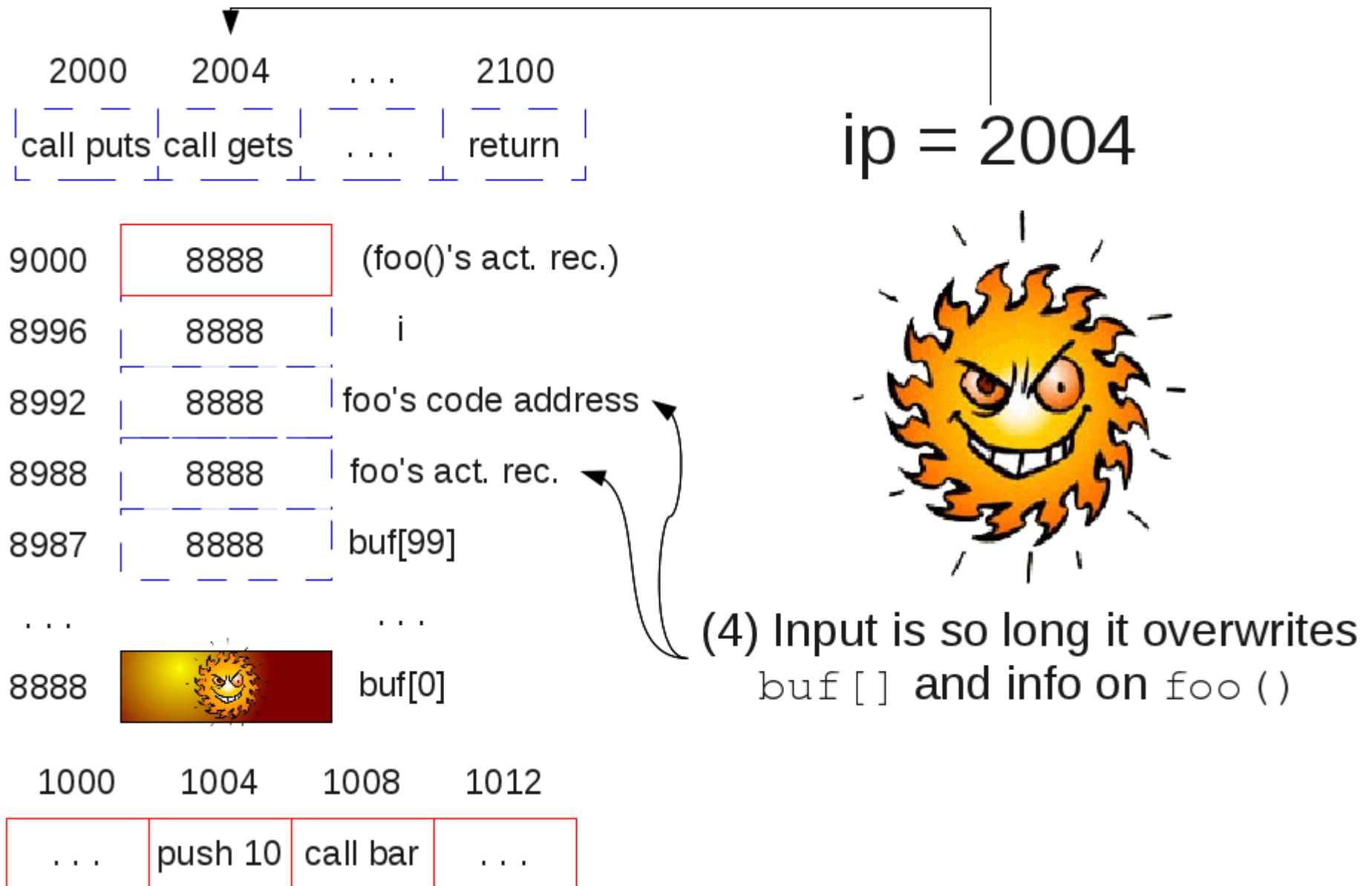
ip = 2004



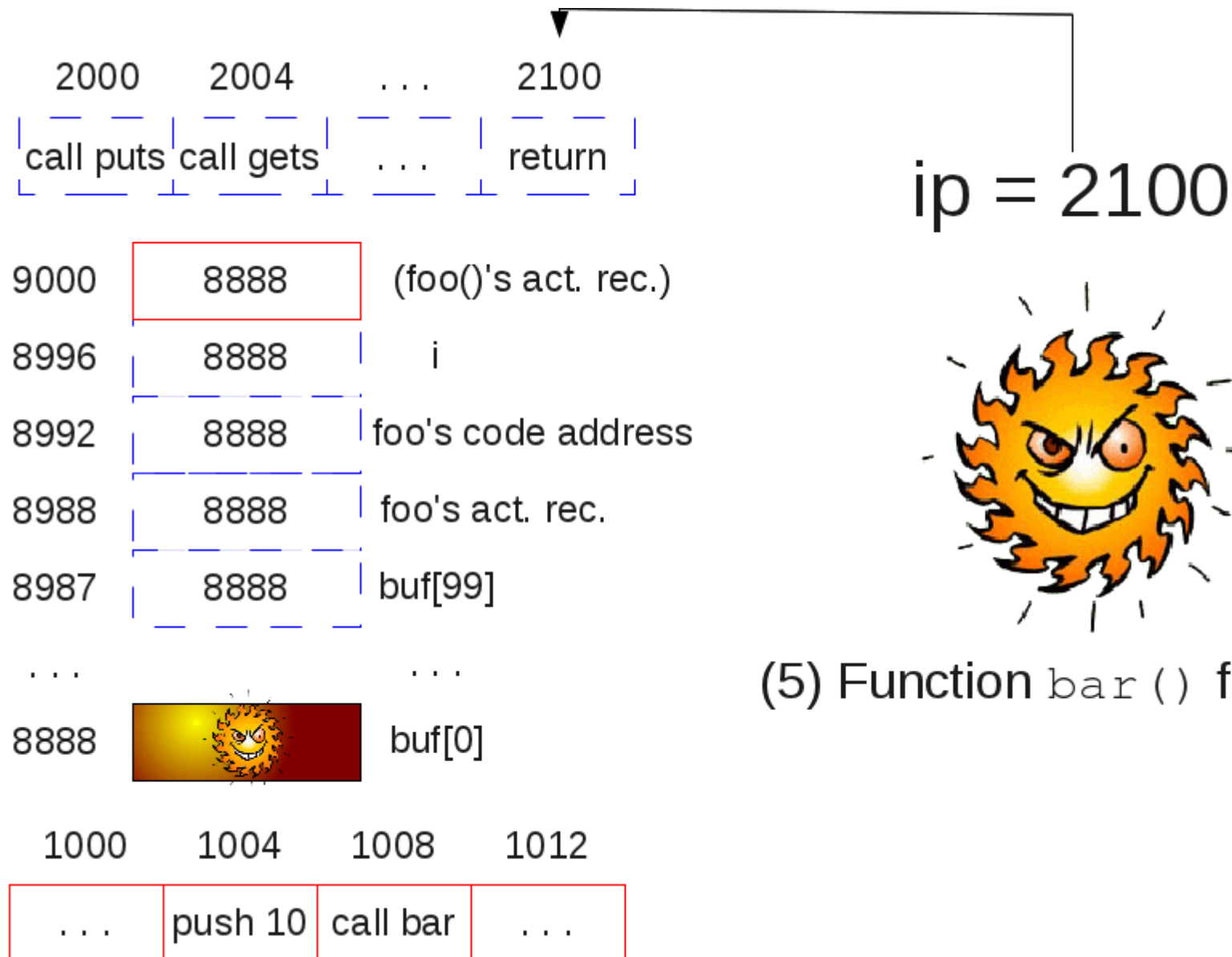
***“10 2E 4C B2 C4 07 08 ...”***

(3) Malfoy inputs string as input to “Name?” request.

# Buffer overflow attack (9)



# Buffer overflow attack (10)





# Buffer overflow attack (11)

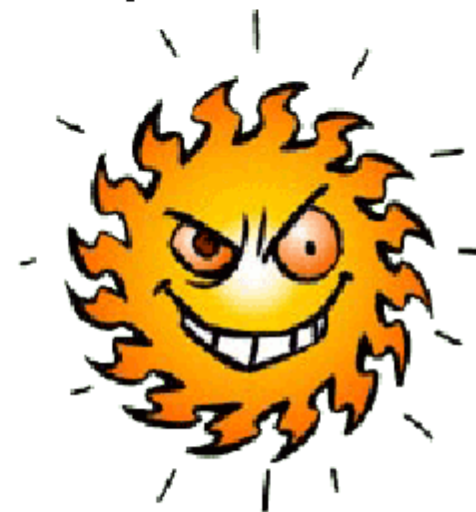
2000	2004	...	2100
call puts	call gets	...	return

9000	8888	(foo()'s act. rec.)
8996	8888	i
8992	8888	foo's code address
8988	8888	foo's act. rec.
8987	8888	buf[99]

...		...
8888		buf[0]

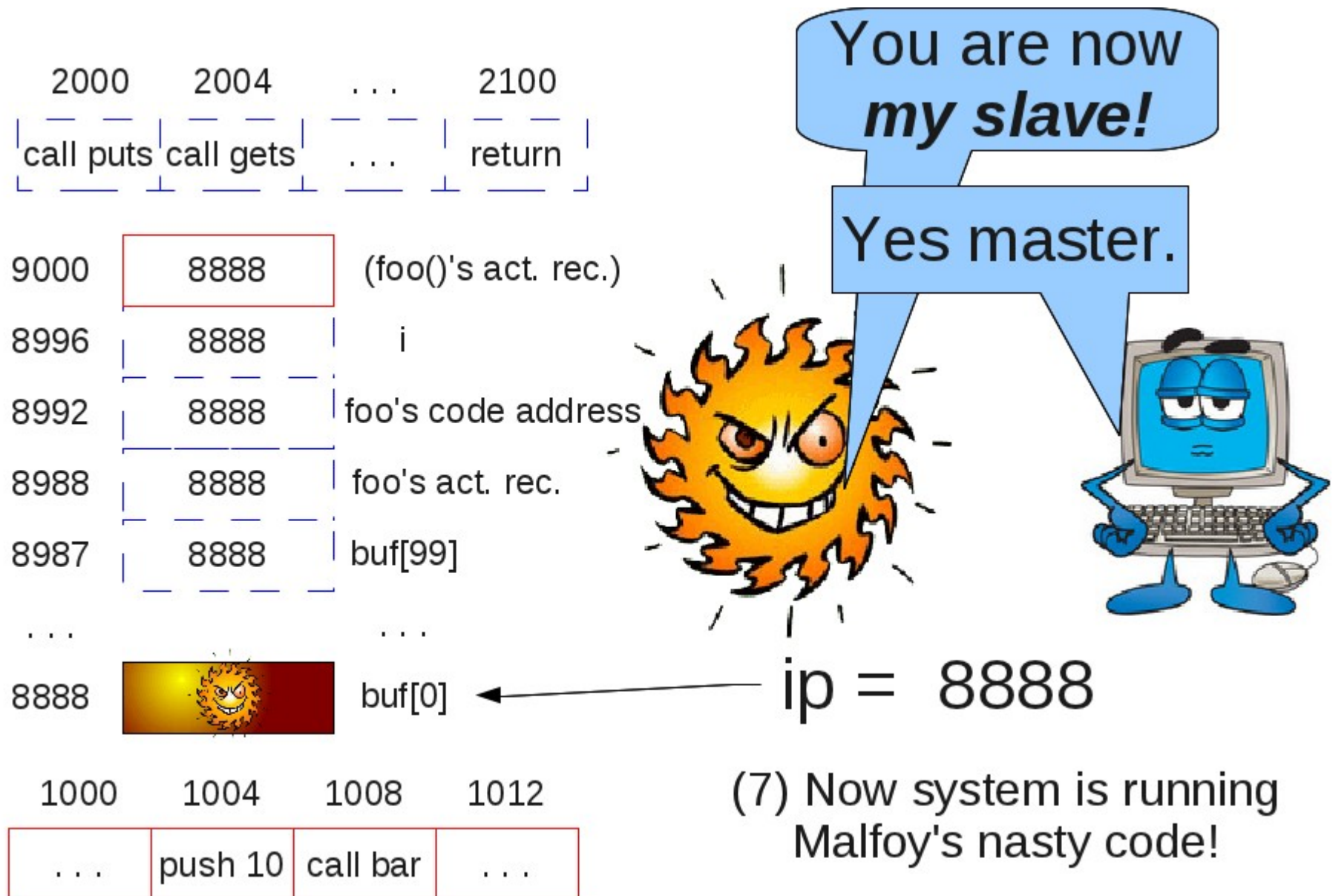
1000	1004	1008	1012
...	push 10	call bar	...

ip ← 8888



(6) CPU gets `ip`'s next value from where `foo()`'s return address should be

# Buffer overflow attack (12)



# Preventing Buffer Overflow

- ◆ Solution #1: Use C++ string objects.
  - ◆ `const char* string::c_str();`
  - ◆ Returns C-string representation of C++ string
- ◆ Solution #2: Use safe C-string fncls

**Bad:** `gets(char* buf)`

**Good:** `fgets(char* buf, int size, FILE* filePtr)`

**Bad:** `sprintf(char* buf, . .)`

**Good:** `snprintf(char* buf, int size, . .)`

**Bad:** `strcpy(char* to, const char* from)`

**Good:** `strncpy(char* to, const char* from, int size)`

**Bad:** `strcat(char* to, const char* from)`

**Good:** `strncat(char* to, const char* from, int size)`

**Bad:** `strcmp(const char* p0, const char* p1)`

**Good:** `strncmp(const char* p0, const char* p1, int size)`

# Your turn! Fix this program!

```
#include <stdlib.h>
#include <stdio.h>
#include <string.h>
#define STRING_LEN 20 /*Assumed char array len */
#define NUMBER_LEN 3

void enterName(char* nPtr)
{ printf("Your name: ");
  gets(nPtr);
}

void enterAge(int* agePtr)
{ char numberText[NUMBER_LEN];
  printf("Your age: ");
  gets(numberText);
  *agePtr=strtol(numberText,0,0);
}
```

# Your turn! Fix this (cont'd)

```
void enterFavoriteColor (const char* itemNamePtr,
                        char*      entryPtr)
{ printf("Fav. color for %s.",itemNamePtr);
  gets(entryPtr);
}
```

```
void printInfo (char*  nameP, int y,
               char*  carCP,char*  houseCP)
{
  char  text[STRING_LEN];
  sprintf(text,"%s who's %d yrs old",nameP,y);
  printf ("%s likes car color %s",text,carCP);
  if(strcmp(carCP,houseCP) == 0)
    puts("They like same color for houses");
  else
    printf("They like house color %s",houseCP);
}
```

# Your turn again!

- ◆ Revise the `naughtyCopy( )` to copy at most `size_t n` chars.

```
char* naughtyCopy(const char* fromP, size_t n)
{
    char* toP;

    for ( ; *fromP != '\0'; fromP++, toP++)
        *toP = *fromP;

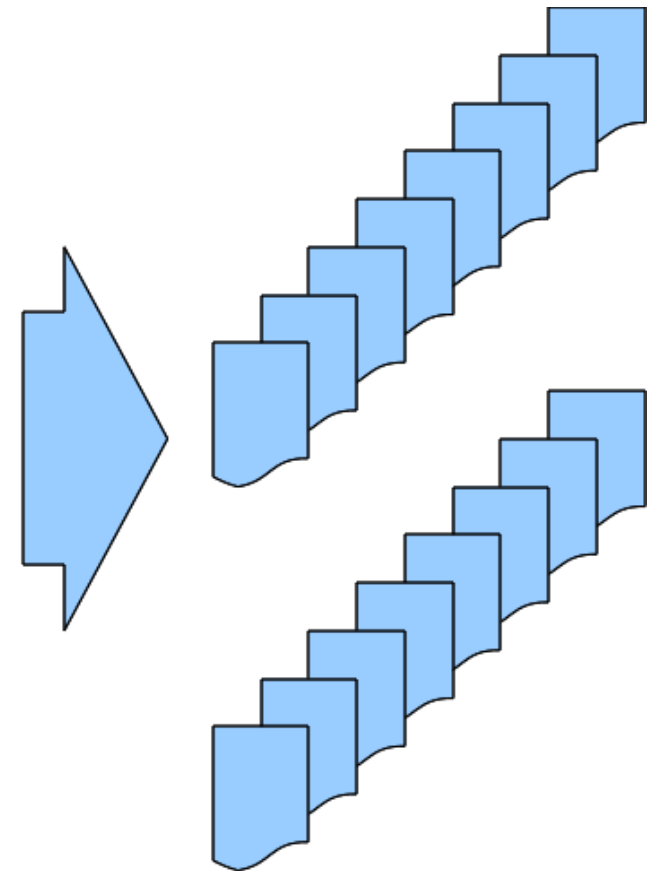
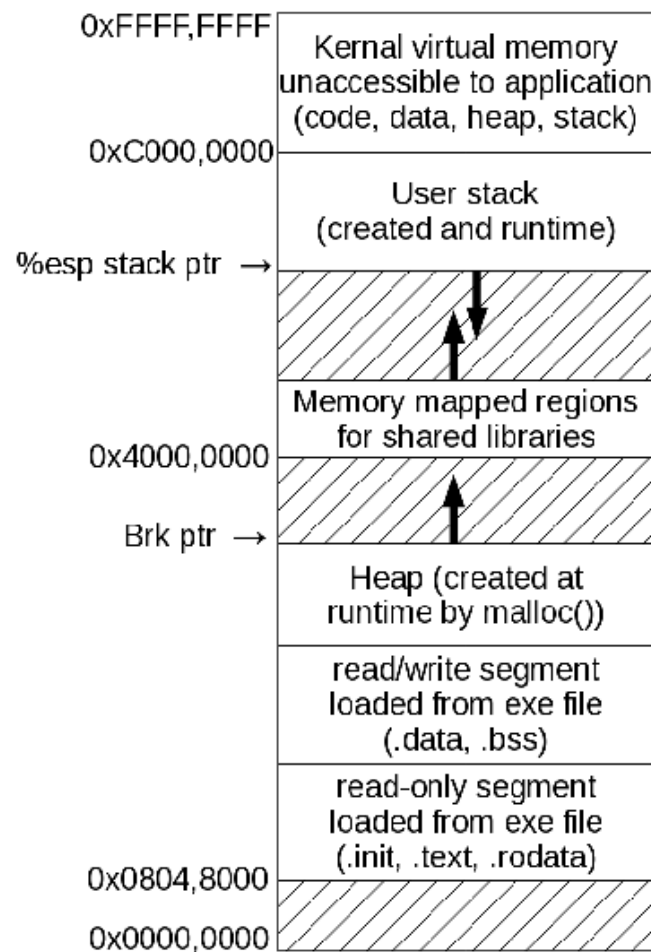
    free(fromP);
    return(toP);
}
```

# Virtual Memory and Paging

- ◆ Advantages of virtual memory
  1. Access to more memory than just DRAM
  2. Easier memory management, let's processes share pages
  3. Increased protection for a process' memory: either a process has access to a page or it does not.

# But first, how does virtual memory work?

- Each process' memory divided into pages.
- Pages 4 kb each.
- Process' *page table* tells which pages it owns.





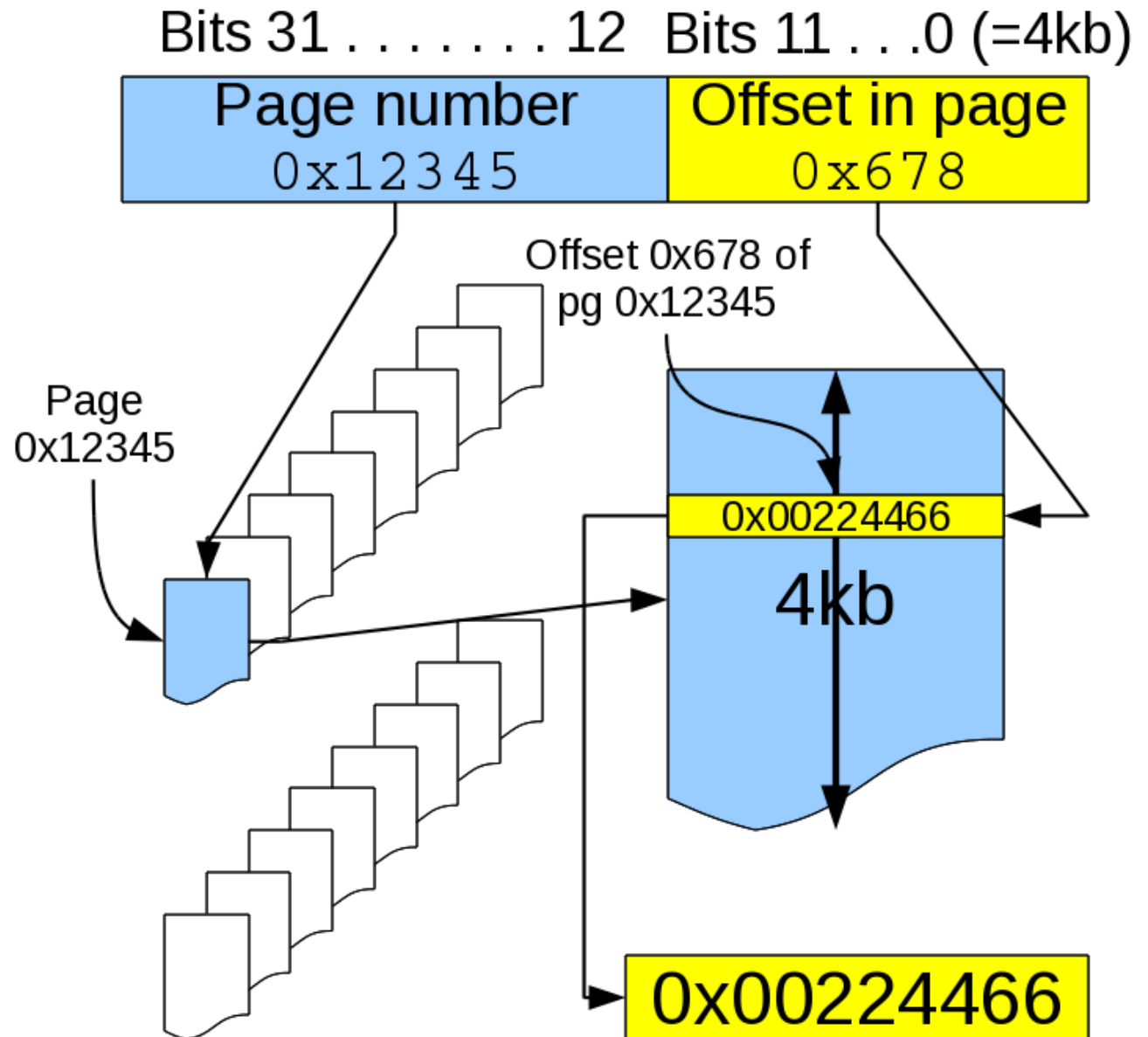
# Getting mem in a paging sys

High bits 12..31  
tell the *page number*.

Low bits 0..11  
tell the *offset within the page*.

Pages can be:

- ◆ In RAM
- ◆ On disk

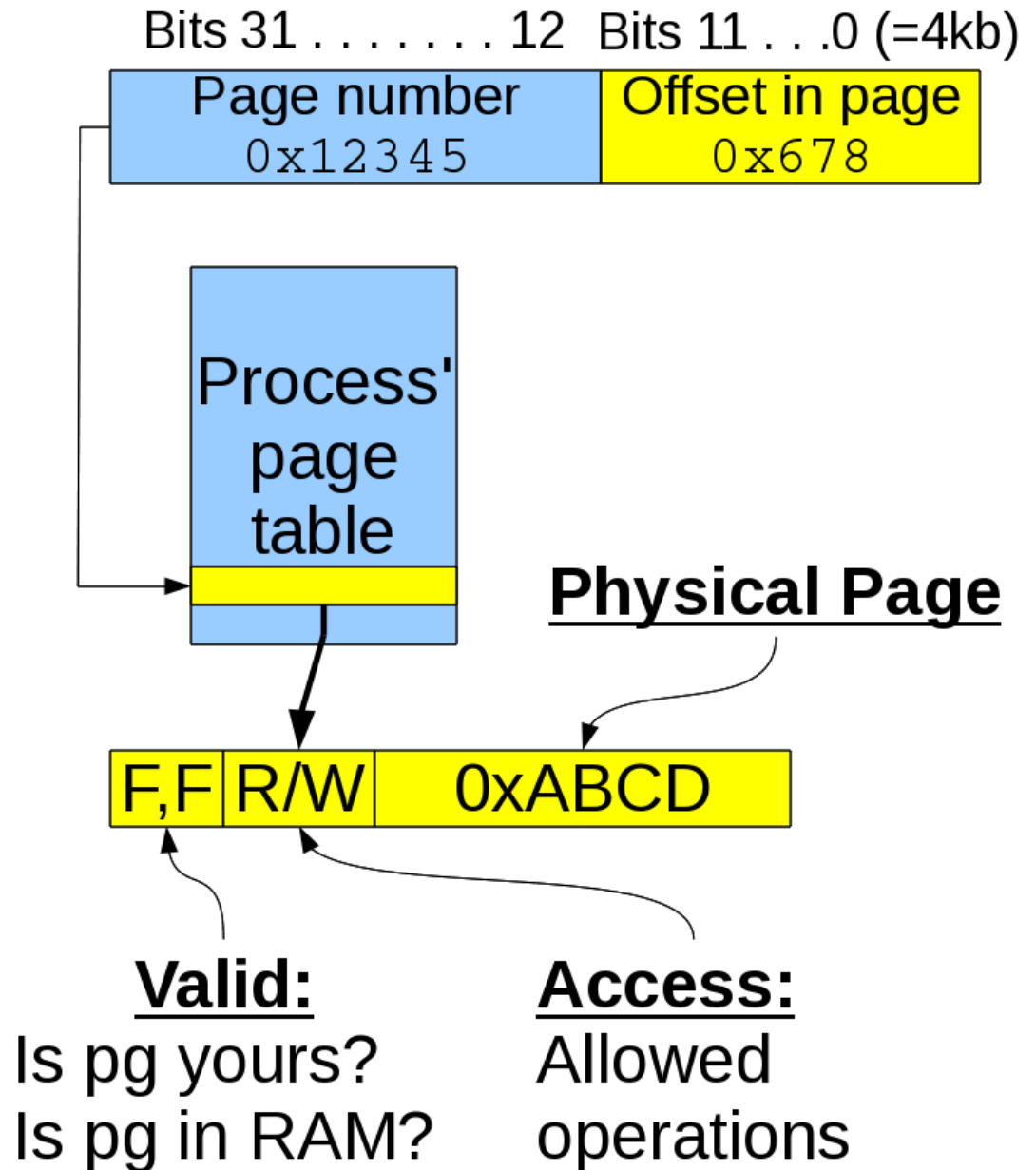


# Virtual memory details

Each process has a page table.

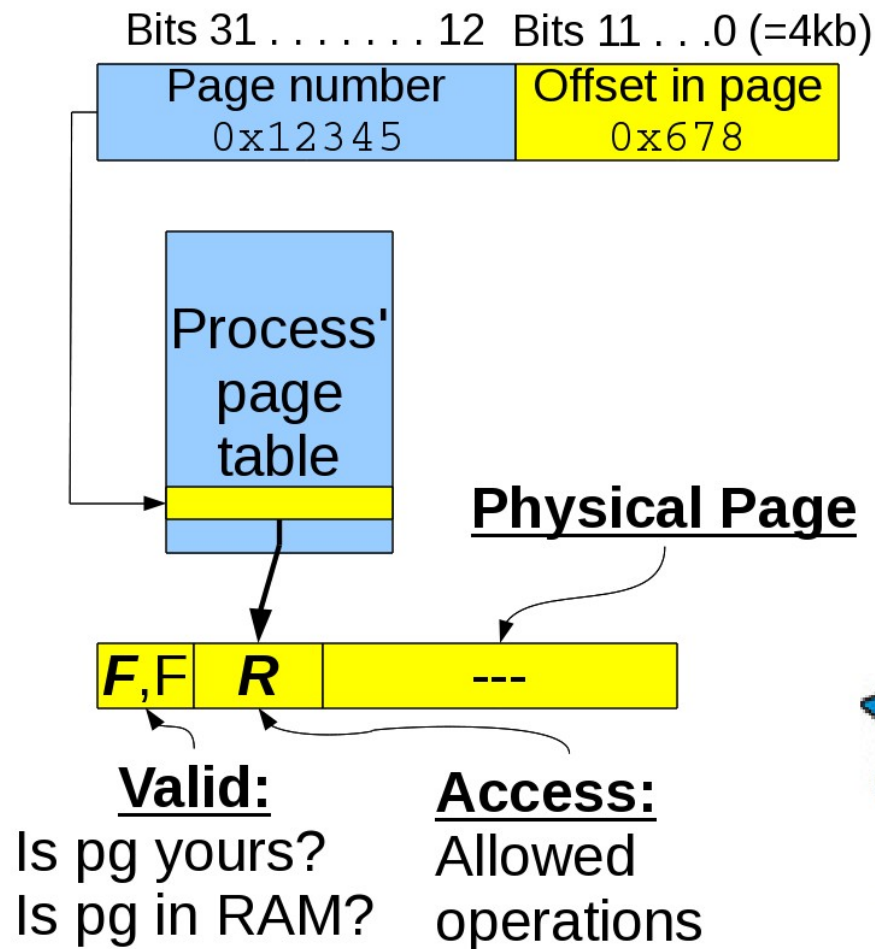
Page table tells page's

- ◆ Validity
- ◆ Allowed access
- ◆ Physical page (or location on disk)



# Virtual Memory Operation 1

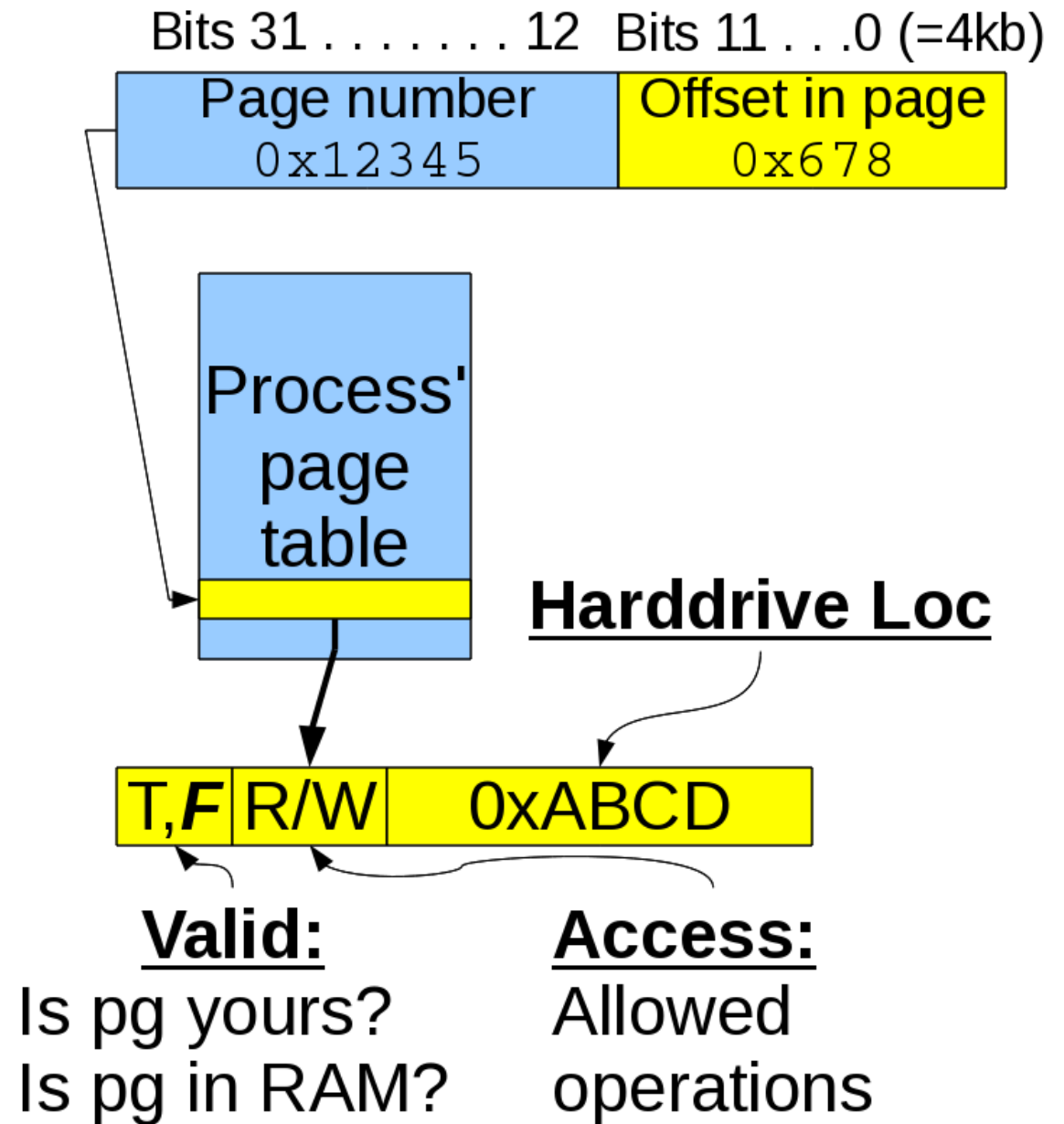
**Case 1:** You don't own the page, or try to write to read-only page



# Virtual Memory Operation 2

**Case 2:** Page is yours but not in RAM.

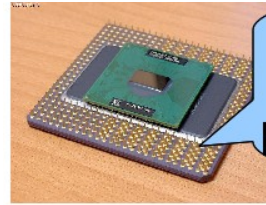
Have to load from hard drive.



# Virtual Memory Operation 2, cont'd

**Case 2:** Page is yours but not in RAM.

Harddrive (and network card, and flash drive, and DVD, *etc.*) writes data directly to RAM. Interrupts CPU when done.

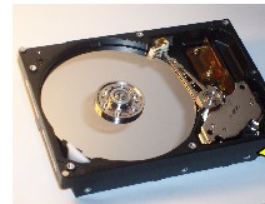


Please read sector 0xAB track 0xCD.  
Put in phy pg 0x0022



Many msec  
of reading hd

Tick tock,  
Tick tock,



Hey memory!  
Put this data in  
Page 0x0022 . . .



Sending you an  
Interrupt Ms. CPU,  
The data is in mem!

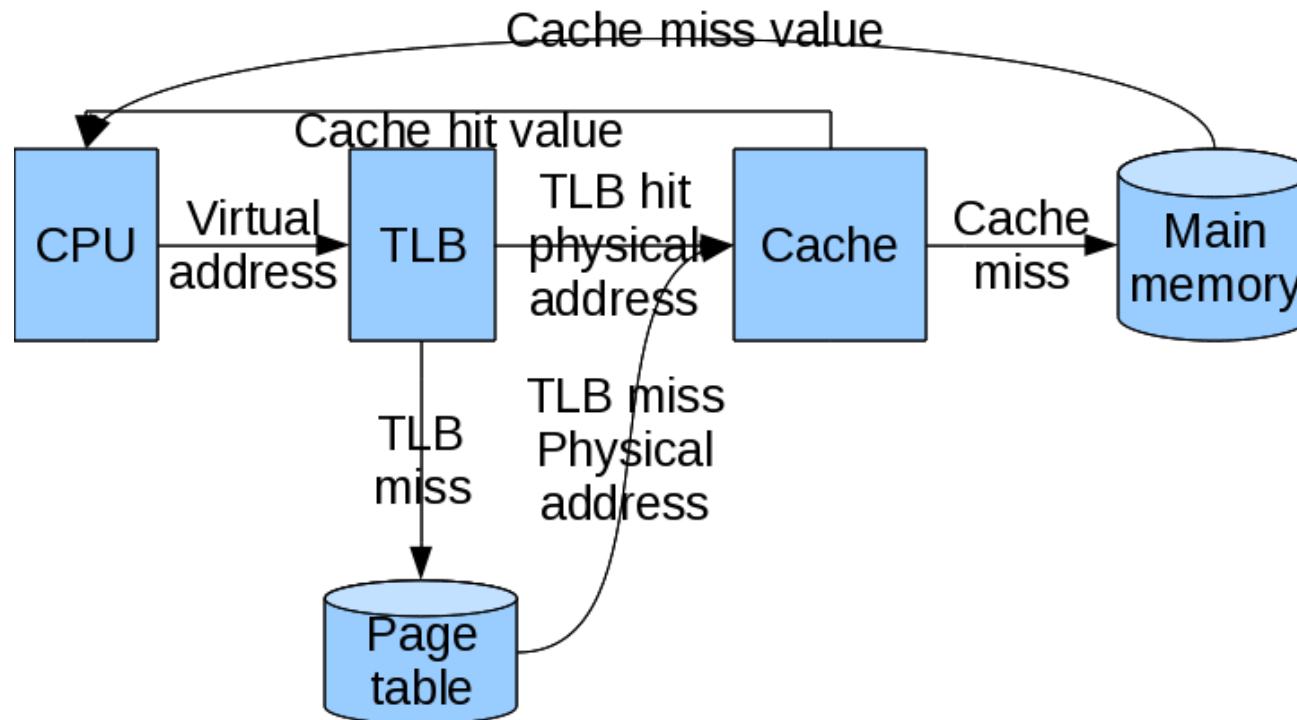


# Virtual Memory Operation 3

**Case 3:** Page is yours and is in RAM. Go to cache (or RAM) and get it!

**Problem:** Page table could be huge!

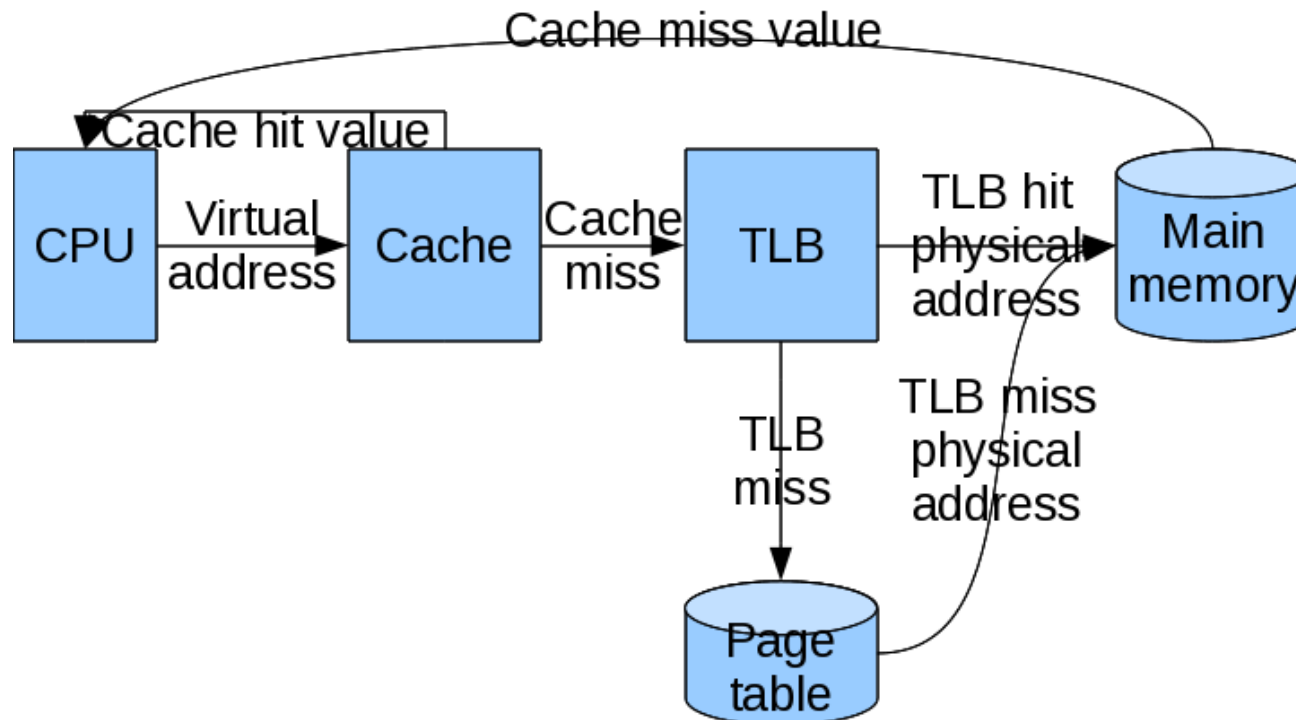
**Solution:** TLB (Translation Lookaside Buffer) is a hardware cache of page table



# Your turn!

You could put the **cache** before the **TLB**.

Caching **virtual addresses** would be **faster** for CPU. *Why is caching physical addresses still preferred? Hint: There's more than 1 process.*



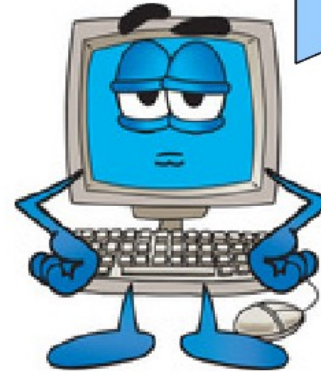


# Advantage #1 of Paging Sys

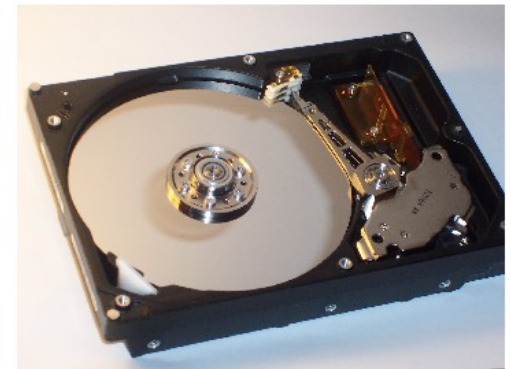
Ability to use  
harddrive as  
memory, not just  
file storage.

**Question:** Nothing is  
free! What did we  
sacrifice?

I can use my cheap 512 Gbyte  
harddrive as extra memory for  
my expensive 4 Gbyte RAM



4 Gbyte  
expensive!



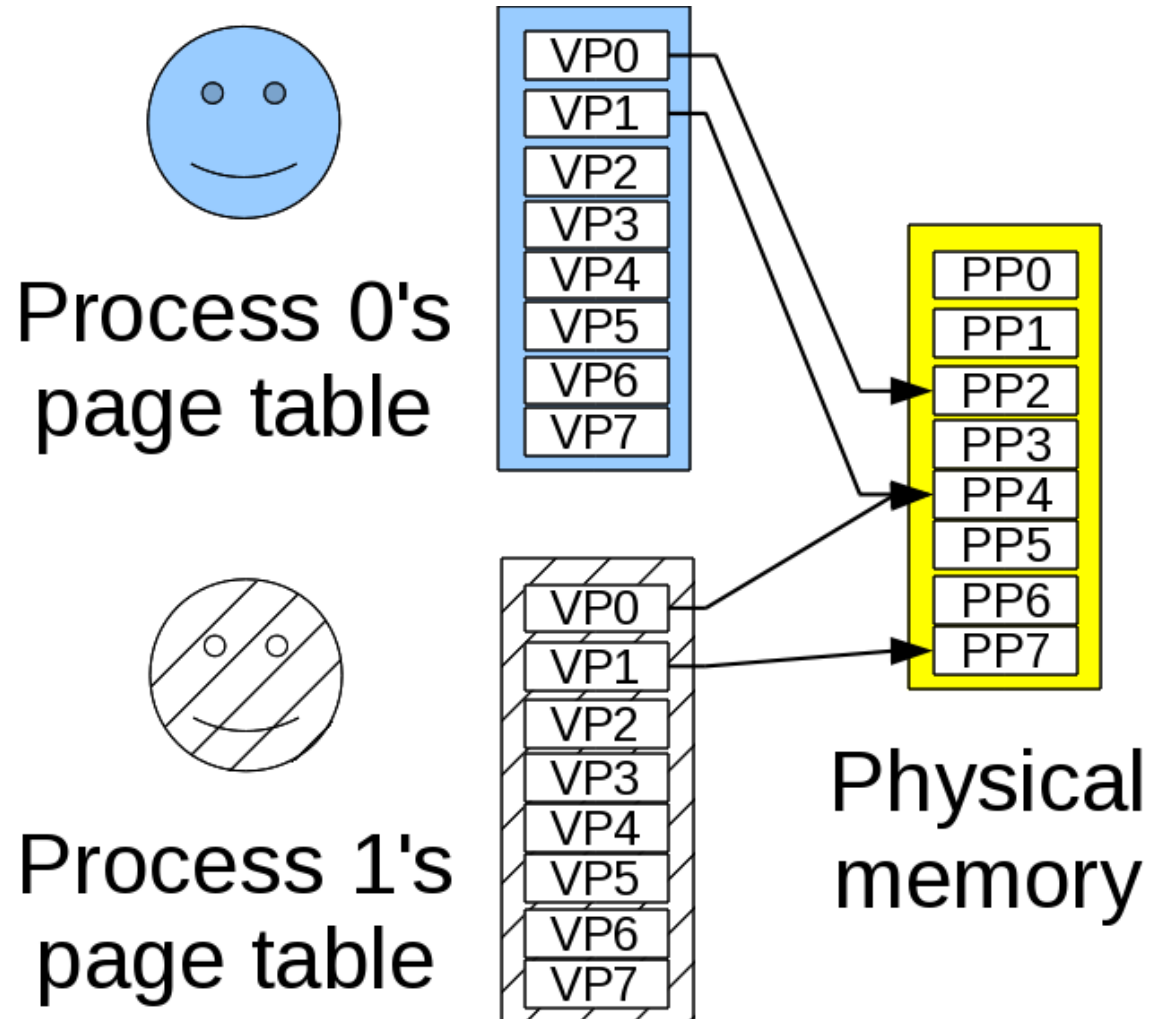
512 Gbyte, cheap!



# Advantage #2 of Paging Sys

Ability of processes to share pages, and flexibility for OS about where virtual pages are in phys mem.

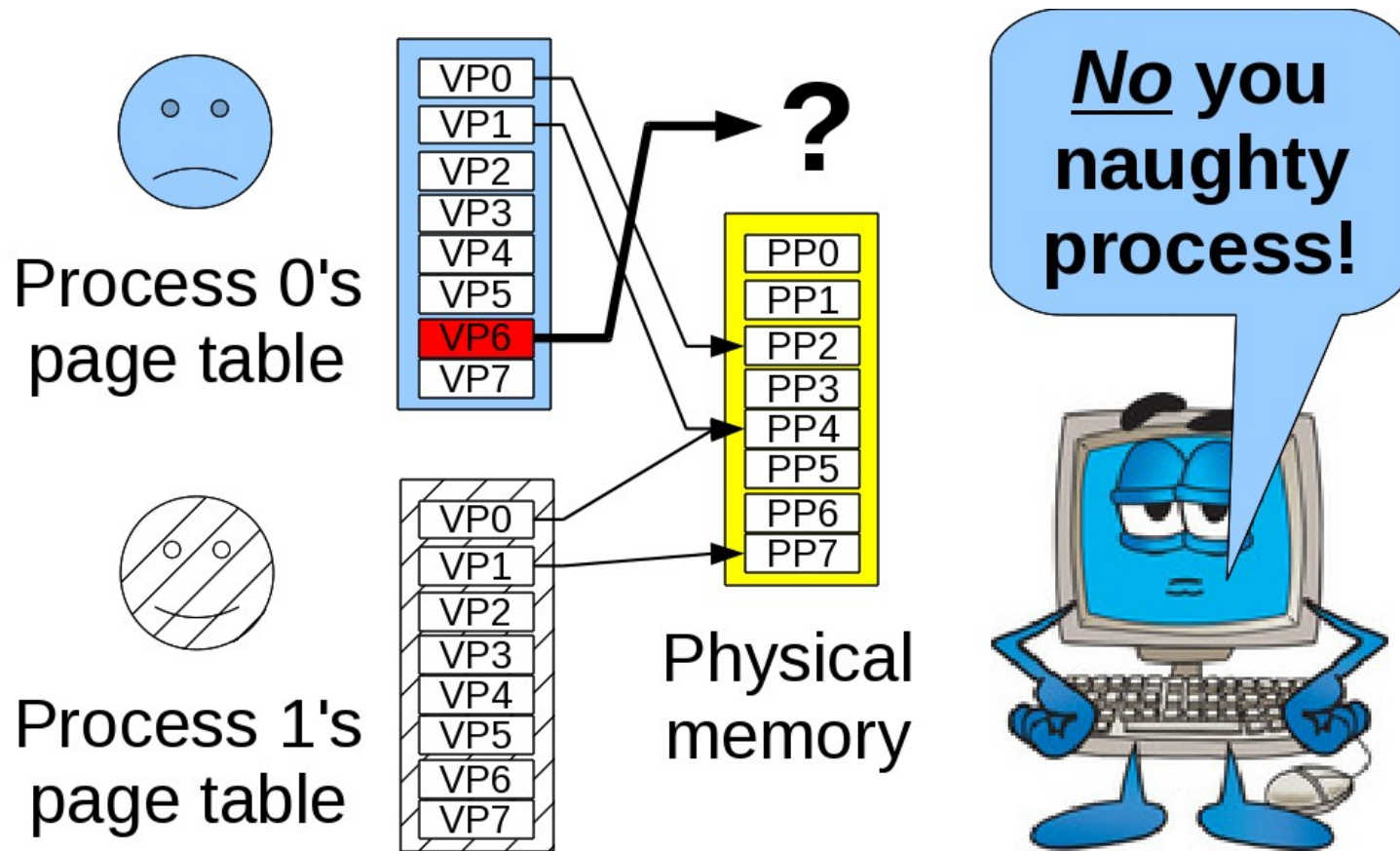
**Question:** Which segment pages can be safely shared?



# Advantage #3 of Paging Sys

Ability to protect processes from each other.

**Question:** What must the OS do when process makes illegal memory access?



# Effective main memory use

Stay on the same page!

# Your turn!

Which has better spatial locality?

// Option 1:

```
int sum=0;
```

```
for (int i=0; i<NUM_ROW; i++)
```

```
    for (int j=0; j<NUM_COLS; j++)
```

```
        sum+=array[i][j];
```

// Option 2:

```
int sum=0;
```

```
for (int j=0; j<NUM_COLS; j++)
```

```
    for (int i=0; i<NUM_ROW; i++)
```

```
        sum+=array[i][j];
```

Next time:  
Input/Output!