Cyber Security

Software Security: Understanding the Platform

Dr Chris Willcocks

Let's take off our hats for Hilda

Computer architectures are mostly simple technologies with clever wiring

Durham University

Software Security

Zooming in on the threat landscape

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1. Understanding the computer architecture (getting close to the metal)
2. Understanding the stack
3. Stack and heap memory vulnerabilities
4. Smashing the stack
5. Dangerous system calls
6. Race condition attacks
7. Timing attacks

Today and in the practical

Coming up

Getting Close to the Metal

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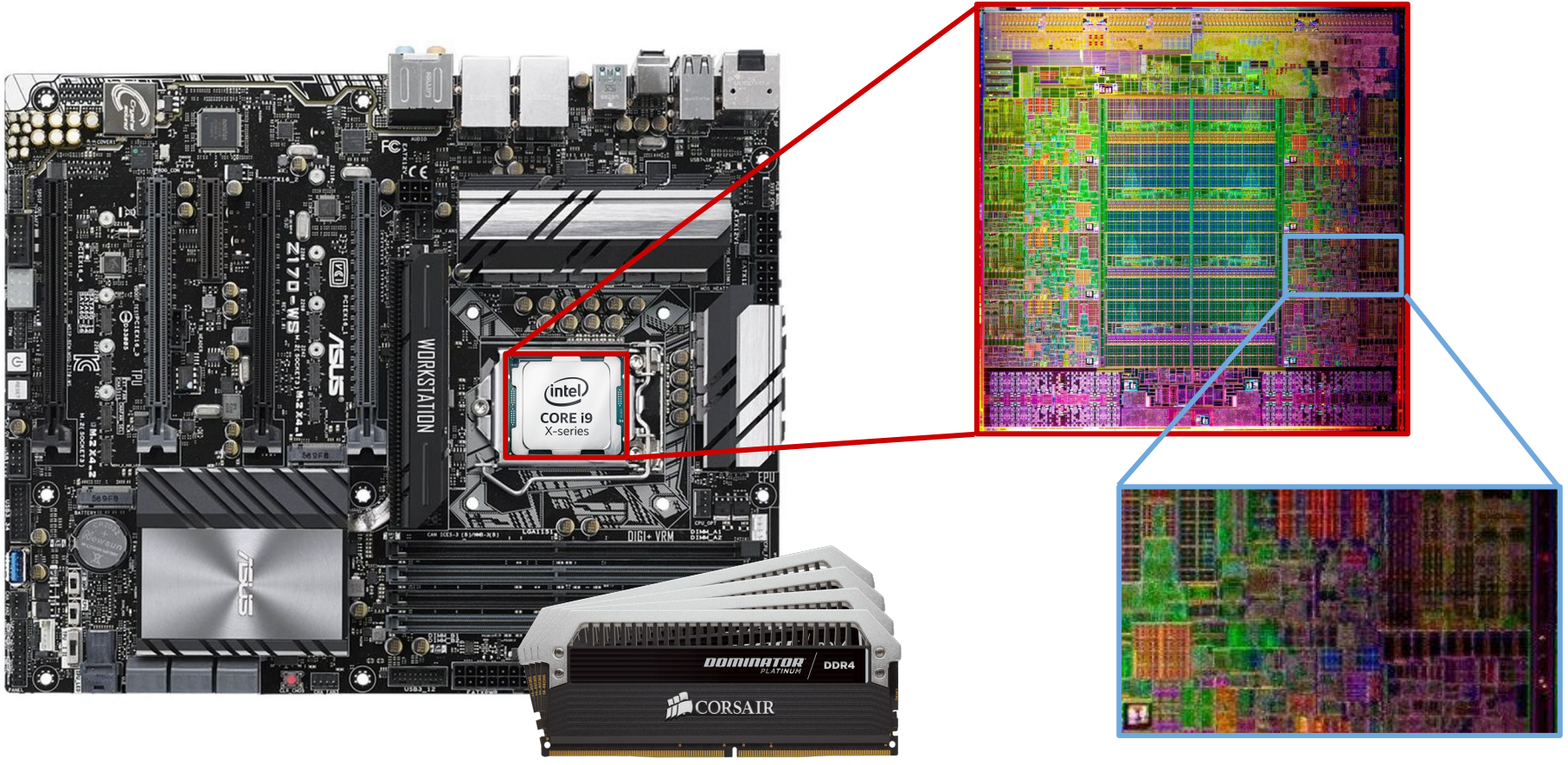
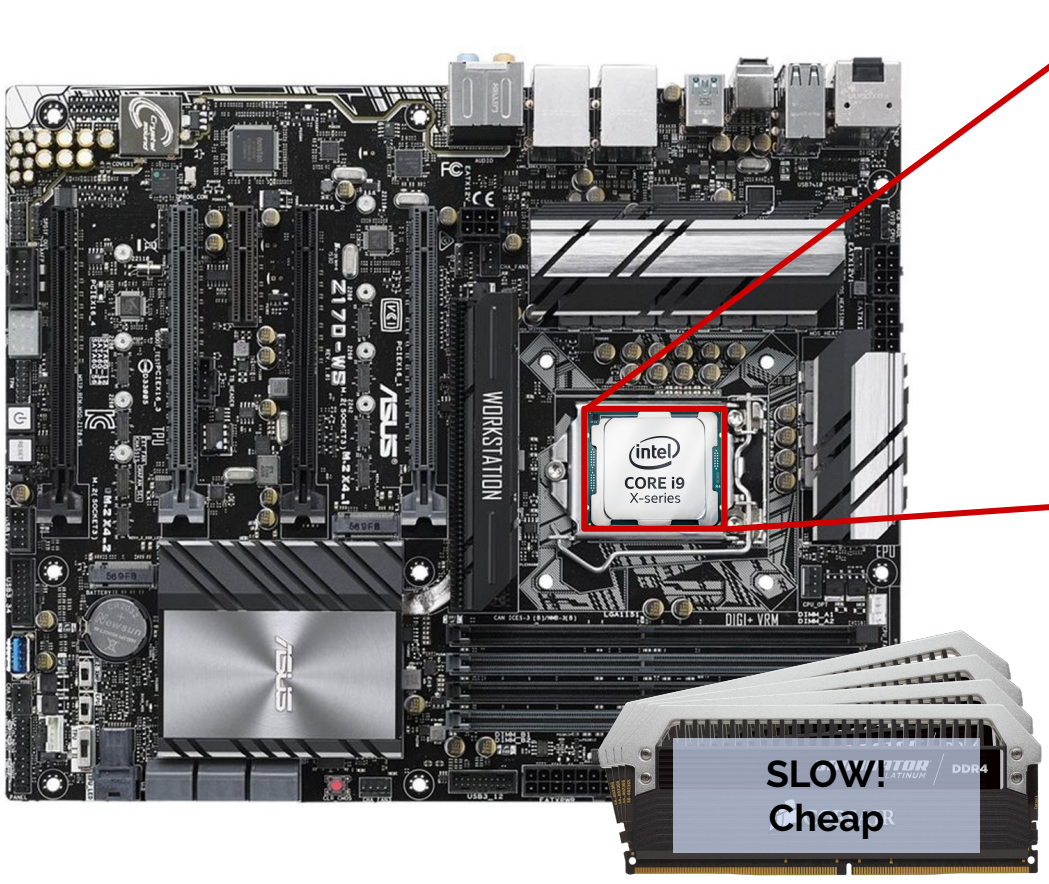
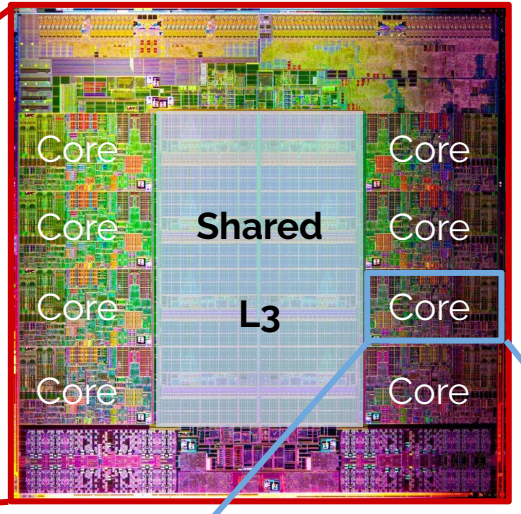
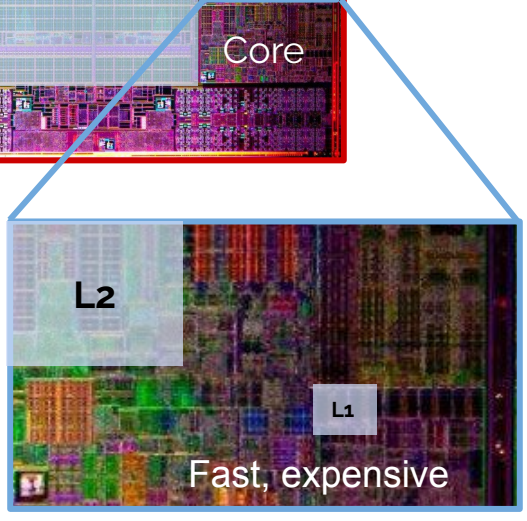


Getting Close to the Metal







Getting Close to the Metal

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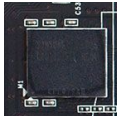
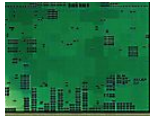
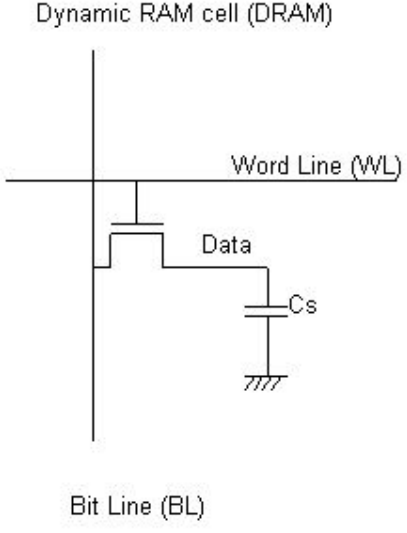
Two types of memory: DRAM & SRAM

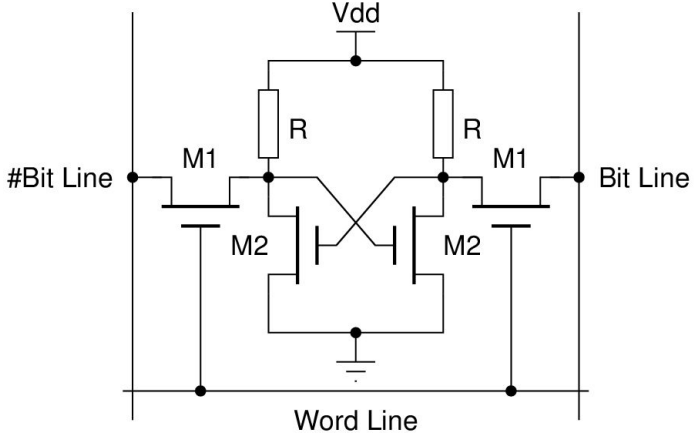


1 transistor per bit
- “slow”
- cheap



4+ transistors per bit
- fast (~4 clock cycles)
- expensive
- takes up space on die





Computer Architecture

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Fast, expensive, close to core(s)

Cheap, slow, far from core(s)

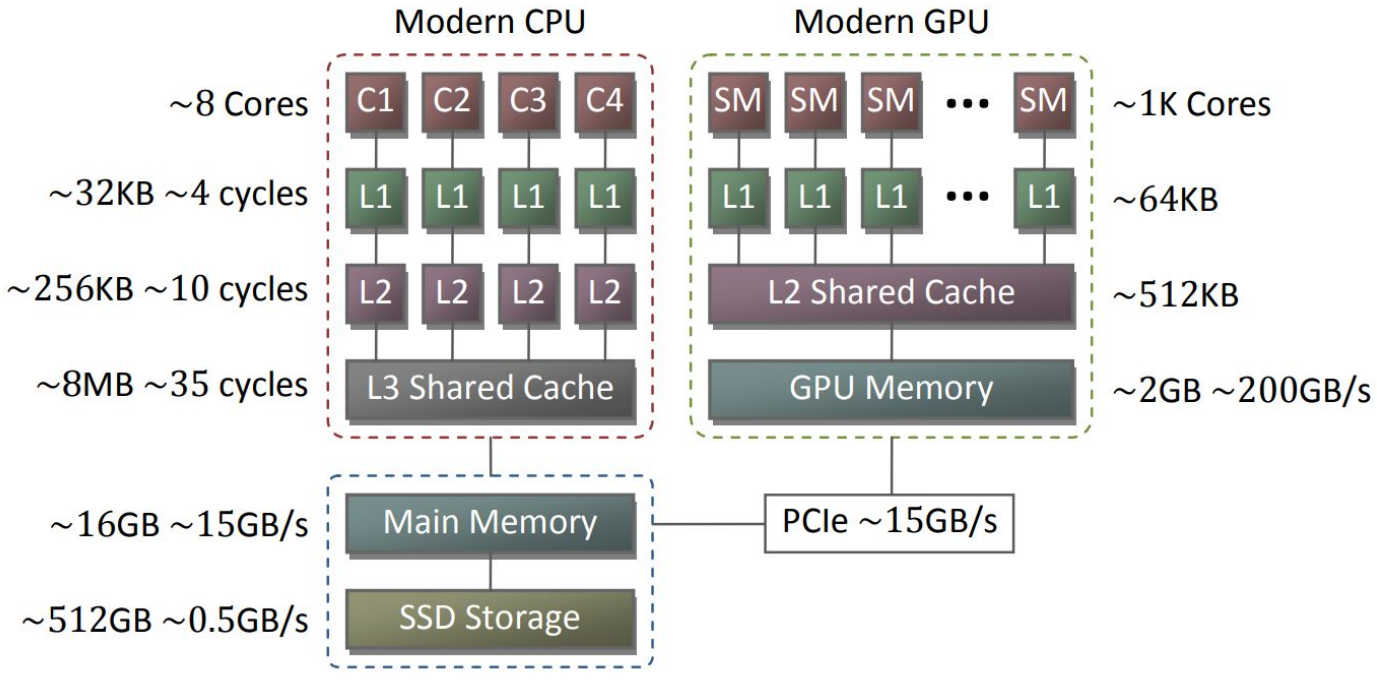

Figure 11: Abstraction of the basic memory hierarchy for a modern CPU and GPU.

Getting Close to the Metal (GPU)

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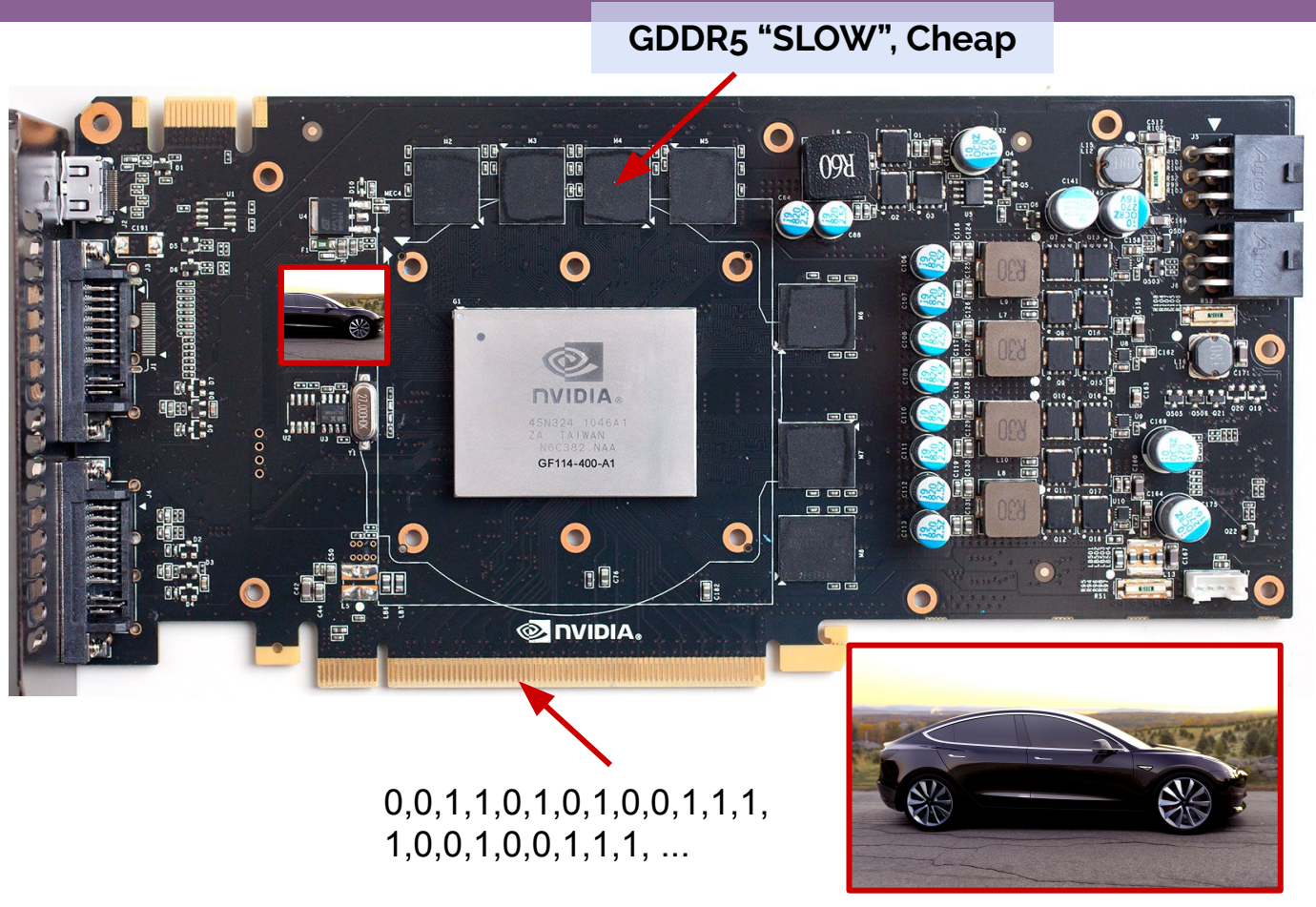

Getting Close to the Metal (GPU)

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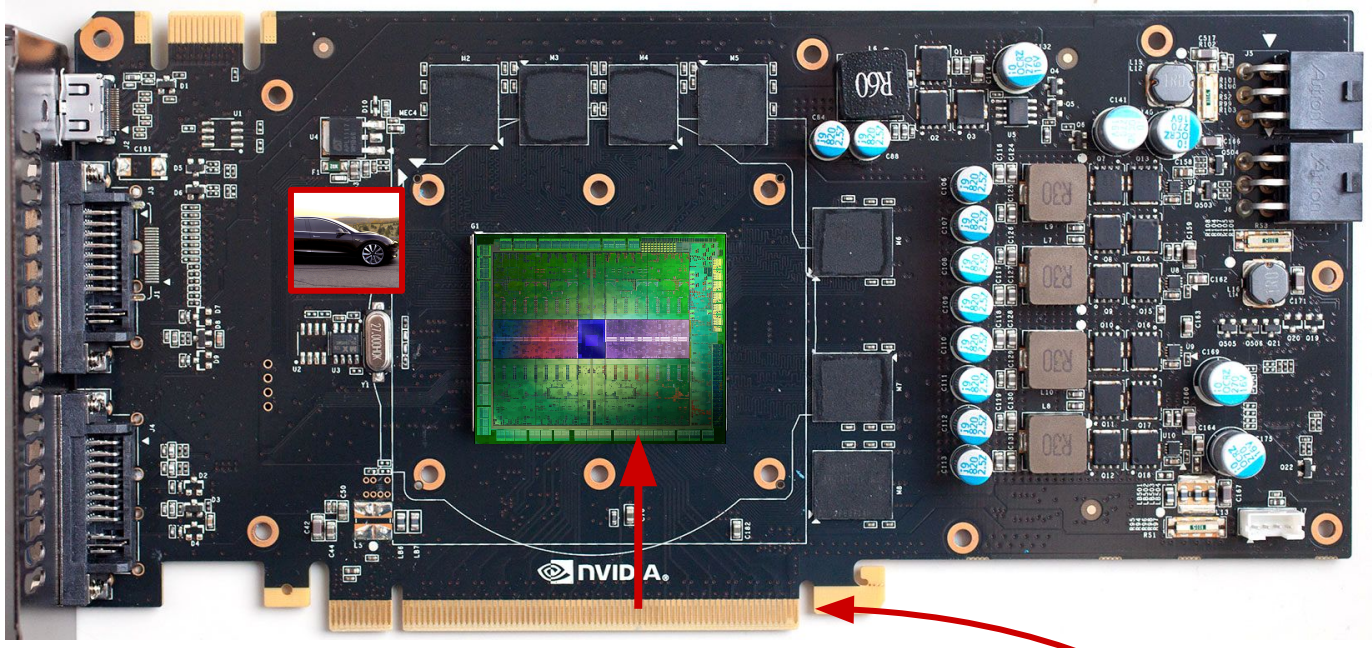


```
Vector car_image
Vector output
Kernel( int core_index )
{
        float some_value = 0.001 * ...
```

compile

```
TEMP temp
ATTRIB col0 = fragment.color
OUTPUT out = result.color
TEX temp, tex0, texture[0], 2D
MUL out, col0, temp
...
```

0,0,1,1,0,1,0, ...

Getting Close to the Metal (GPU)

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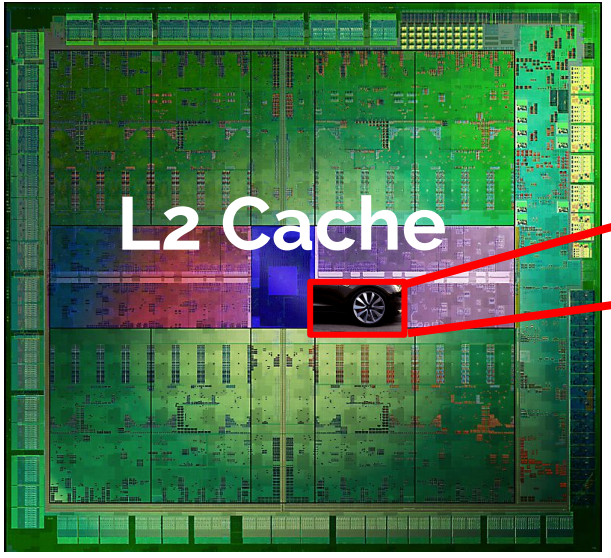
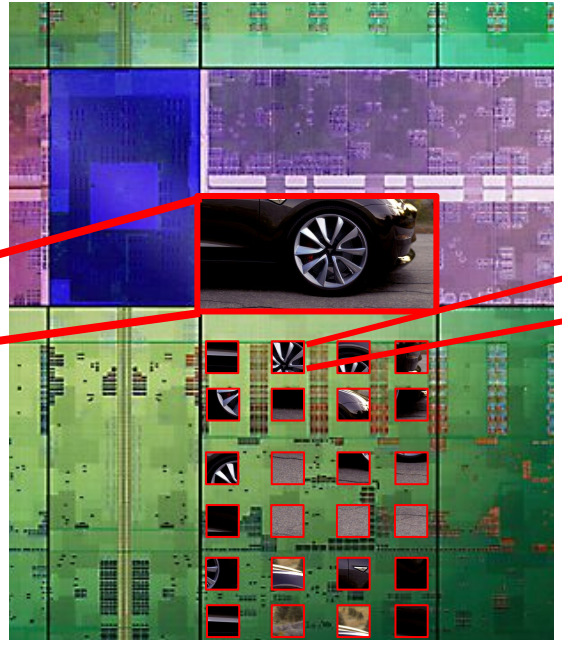
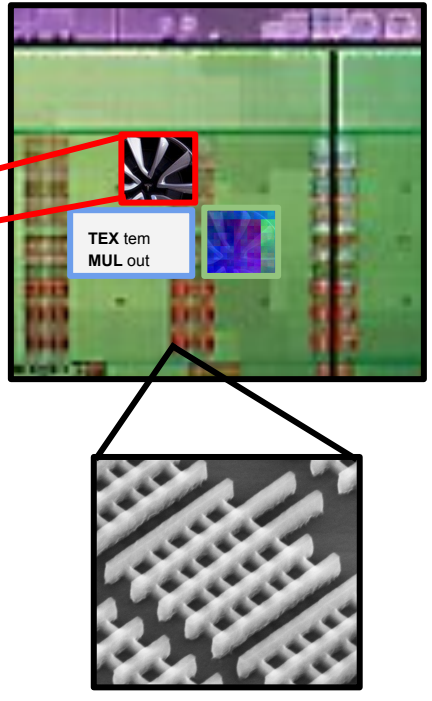




L1 Cache

Instruction State + Data State + Clock = Output State



~15 billion transistors on 2017 GPU die

Getting Close to the Metal (GPU)

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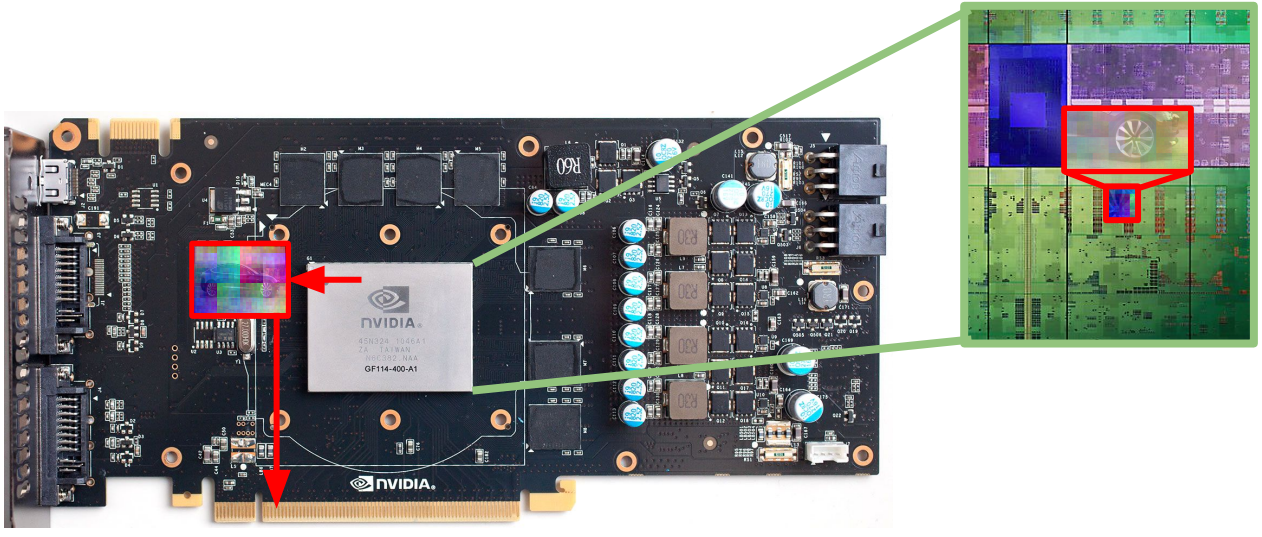

0,0,1,1,0,1,0,1,0,0,1,1,1,
1,0,0,1,0,0,1,1,1, ...

Program output:

Data, Instructions & Transforms

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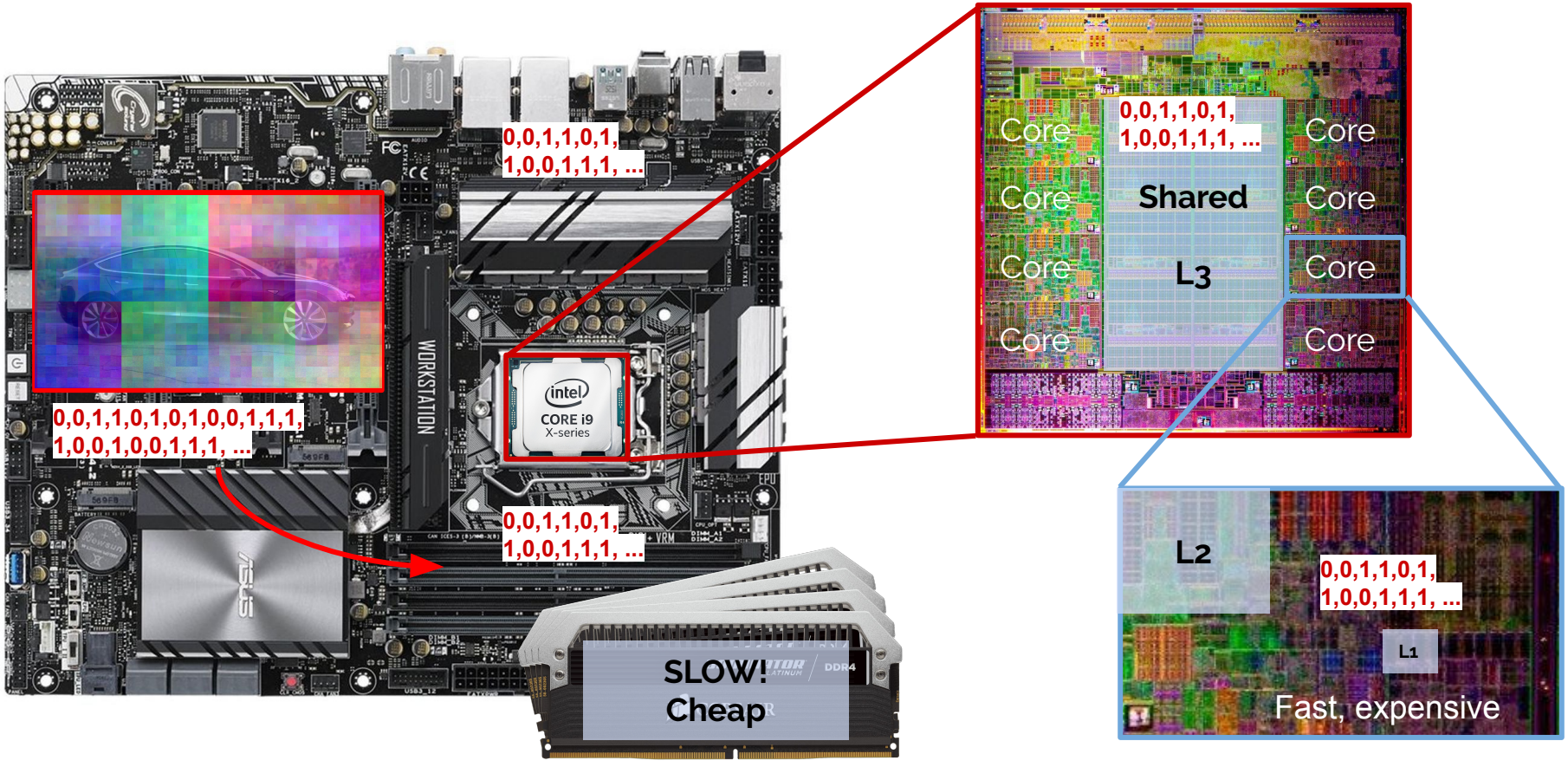

A simple C program

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```c
#include <stdio.h>

int w;

int absolute(int x)
{
   if (x<0)
       return -x;
   return x;
}

int abs_mul(int x, int y)
{
   return absolute(x*y);
}

int main()
{
   int a;
   int b;

   a = 5;
   b = -2;
   w = abs_mul(a,b);
   printf("output = %d\n", w);

   return 0;
}
```

Global variable

Function

Local variables

```
 chris@chris-lab  ~/security  master ●  ls
main.c
 chris@chris-lab  ~/security  master ●  gcc -std=c89 -pedantic main.c -o main.o
 chris@chris-lab  ~/security  master ●  ls
main.c  main.o
 chris@chris-lab  ~/security  master ●  ./main.o
output = 10
 chris@chris-lab  ~/security  master ●  objdump -S -M intel main.o > main.asm
 chris@chris-lab  ~/security  master ●  ls
main.asm  main.c  main.o
 chris@chris-lab  ~/security  master ●
```

1. Compile .c source to object file
2. Execute program
3. Disassemble object to assembly form
4. View assembly

Compiling and Executing

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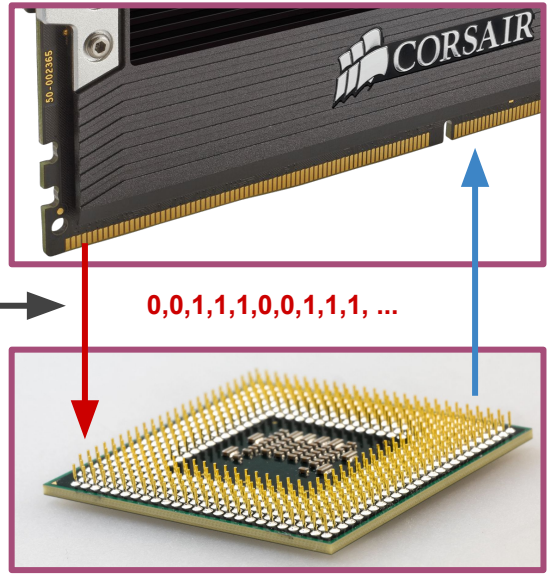
Source code

```c
#include <stdio.h>

int w;

int absolute(int x)
{
   if (x<0)
       return -x;
   return x;
}

int abs_mul(int x, int y)
{
   return absolute(x*y);
}

int main()
{
   int a;
   int b;

   a = 5;
   b = -2;
   w = abs_mul(a,b);
   printf("output = %d\n", w);

   return 0;
}
```

Machine Instructions

```
0000000000000681 <main>:
681:   55                      push   rbp
682:   48 89 e5                mov    rbp,rsp
685:   48 83 ec 10             sub    rsp,0x10
689:   c7 45 f8 05 00 00 00    mov    DWORD PTR [rbp-0x8],0x5
690:   c7 45 fc fe ff ff ff    mov    DWORD PTR [rbp-0x4],0xfffffffe
697:   8b 55 fc                mov    edx,DWORD PTR [rbp-0x4]
69a:   8b 45 f8                mov    eax,DWORD PTR [rbp-0x8]
69d:   89 d6                   mov    esi,edx
69f:   89 c7                   mov    edi,eax
6a1:   e8 bd ff ff ff          call   663 <abs_mul>
6a6:   89 05 88 09 20 00       mov    DWORD PTR [rip+0x200988],eax
6ac:   8b 05 82 09 20 00       mov    eax,DWORD PTR [rip+0x200982]
6b2:   89 c6                   mov    esi,eax
6b4:   48 8d 3d 99 00 00 00    lea    rdi,[rip+0x99]
6bb:   b8 00 00 00 00          mov    eax,0x0
6c0:   e8 6b fe ff ff          call   530 <printf@plt>
6c5:   b8 00 00 00 00          mov    eax,0x0
6ca:   c9                      leave
6cb:   c3                      ret
6cc:   0f 1f 40 00             nop    DWORD PTR [rax+0x0]
```

Voltage signals



Understanding Application memory

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```c
#include <stdio.h>

int w;

int absolute(int x)
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   if (x<0)
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}

int abs_mul(int x, int y)
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int main()
{
   int a;
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   a = 5;
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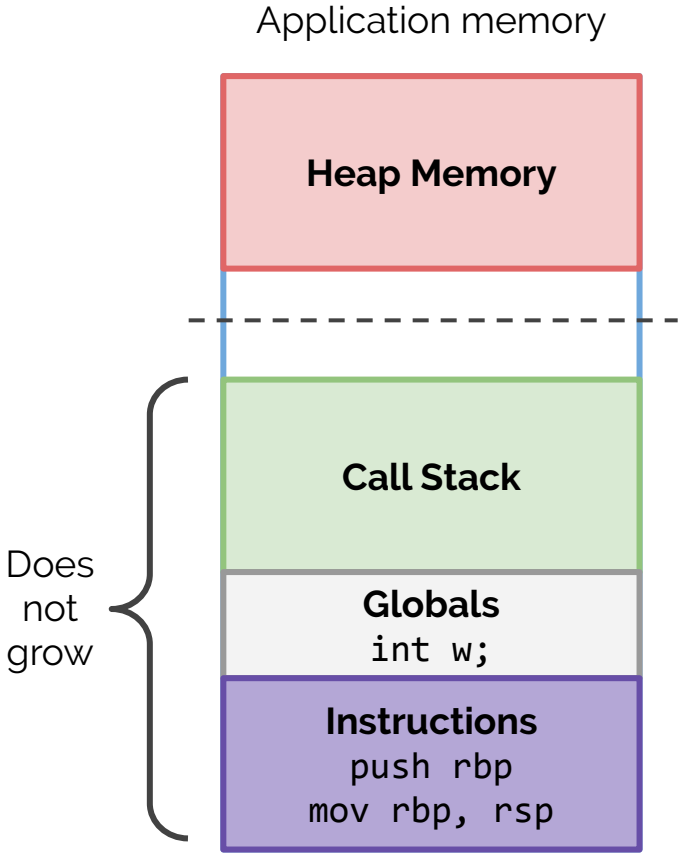
   w = abs_mul(a,b);
   printf("output = %d\n", w);

   return 0;
}
```



Understanding the Stack

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69f:   89 c7                   mov    edi,eax
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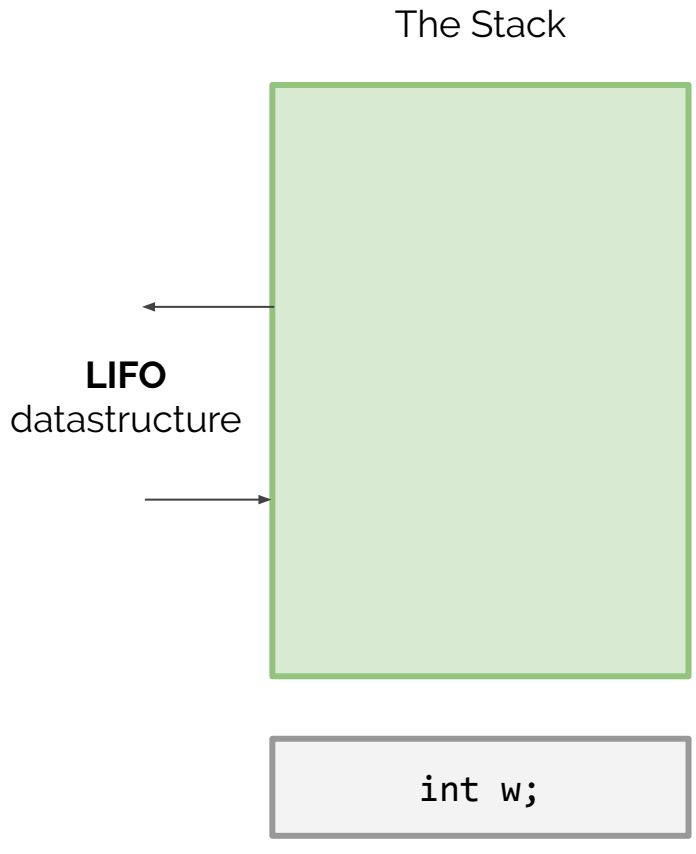
6bb:   b8 00 00 00 00          mov    eax,0x0
6c0:   e8 6b fe ff ff          call   530 <printf@plt>
6c5:   b8 00 00 00 00          mov    eax,0x0
6ca:   c9                      leave
6cb:   c3                      ret
6cc:   0f 1f 40 00             nop    DWORD PTR [rax+0x0]
```



Understanding the Stack

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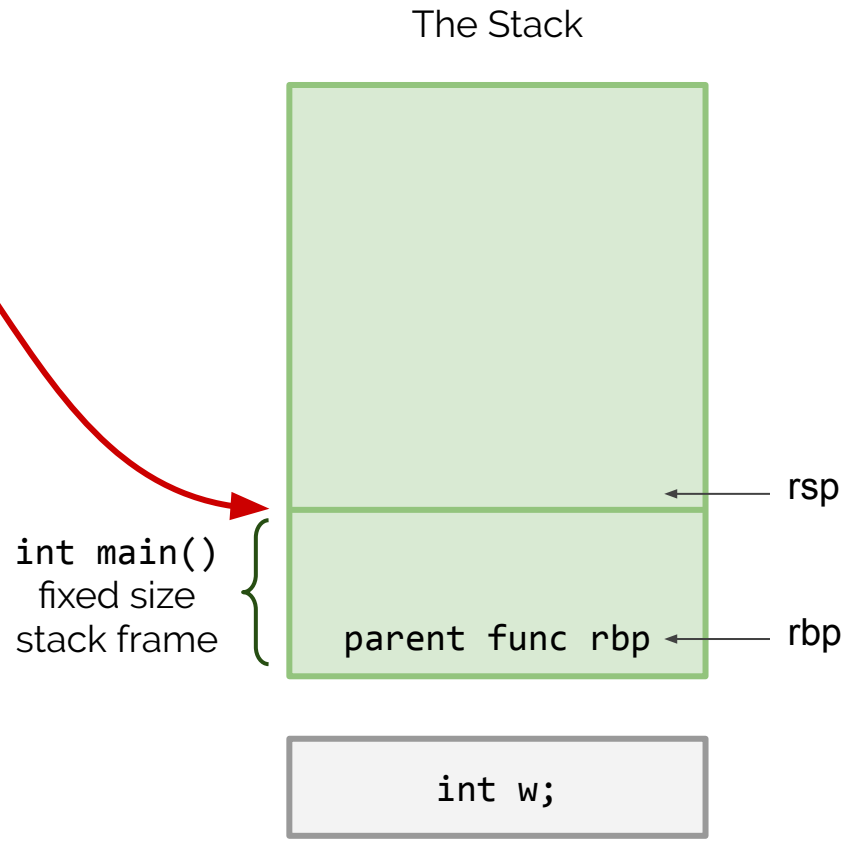

Understanding the Stack

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6bb:   b8 00 00 00 00          mov    eax,0x0
6c0:   e8 6b fe ff ff          call   530 <printf@plt>
6c5:   b8 00 00 00 00          mov    eax,0x0
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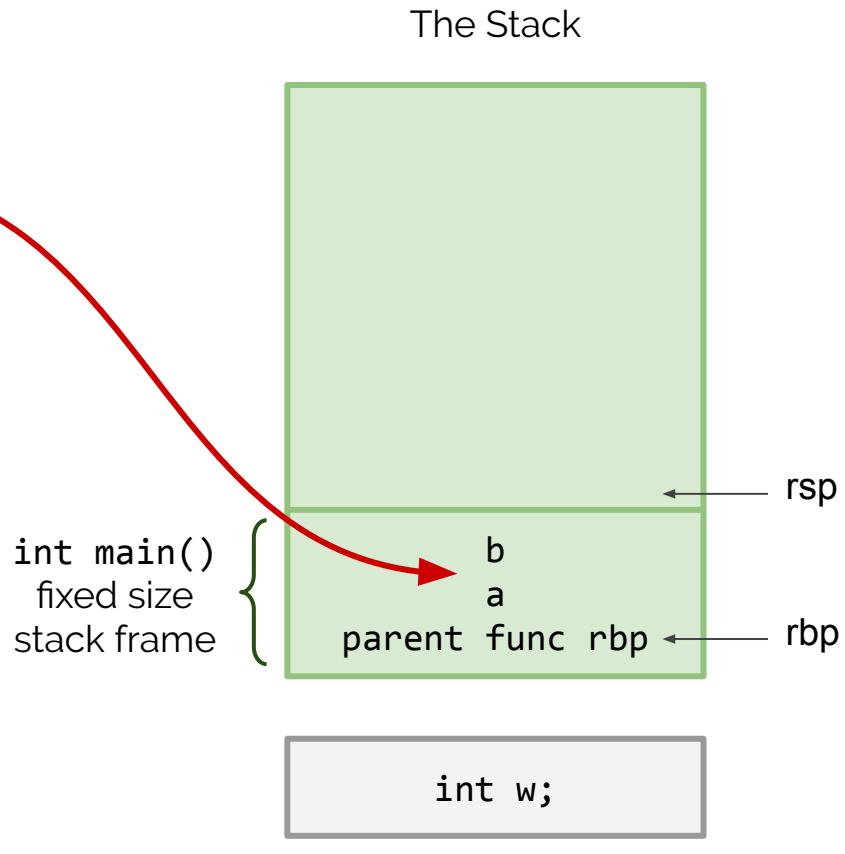

Understanding the Stack

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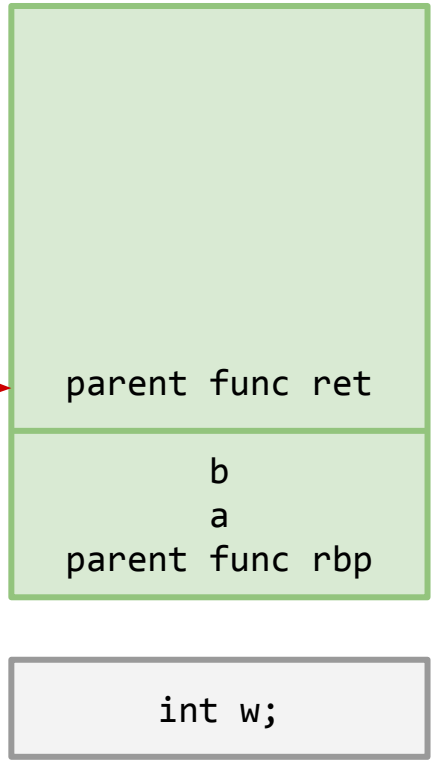
```

The Stack



Understanding the Stack

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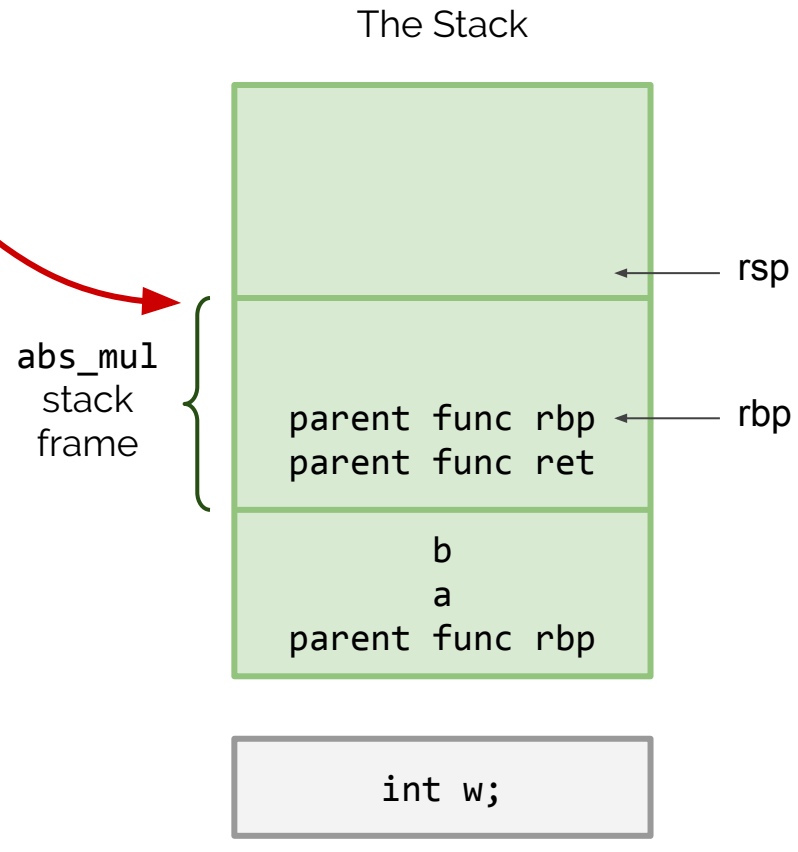
667:   48 83 ec 08             sub    rsp,0x8
66b:   89 7d fc                mov    DWORD PTR [rbp-0x4],edi
66e:   89 75 f8                mov    DWORD PTR [rbp-0x8],esi
671:   8b 45 fc                mov    eax,DWORD PTR [rbp-0x4]
674:   0f af 45 f8             imul   eax,DWORD PTR [rbp-0x8]
678:   89 c7                   mov    edi,eax
67a:   e8 cb ff ff ff          call   64a <absolute>
67f:   c9                      leave
680:   c3                      ret
```



Understanding the Stack

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67a:   e8 cb ff ff ff          call   64a <absolute>
67f:   c9                      leave
680:   c3                      ret
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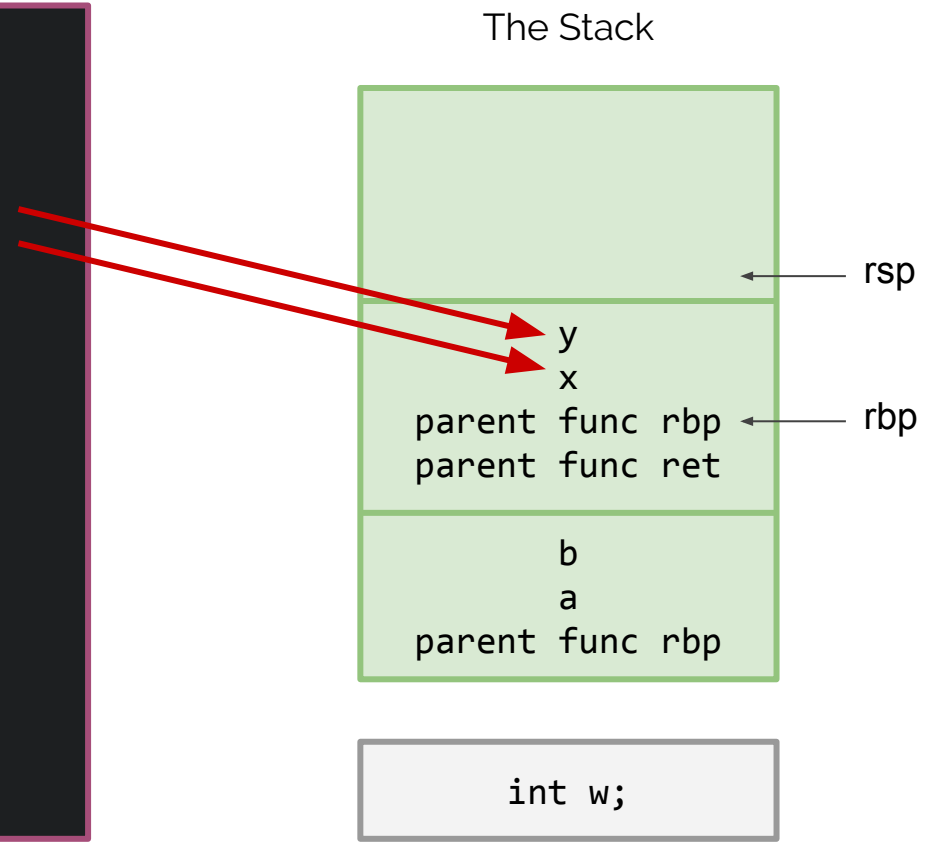

Understanding the Stack

Durham University

```
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663:   55                      push   rbp
664:   48 89 e5                mov    rbp,rsp
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66b:   89 7d fc                mov    DWORD PTR [rbp-0x4],edi
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67a:   e8 cb ff ff ff          call   64a <absolute>
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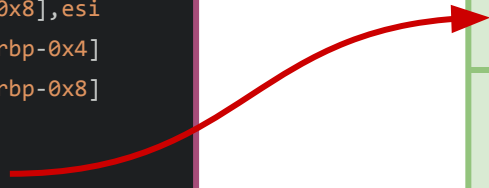
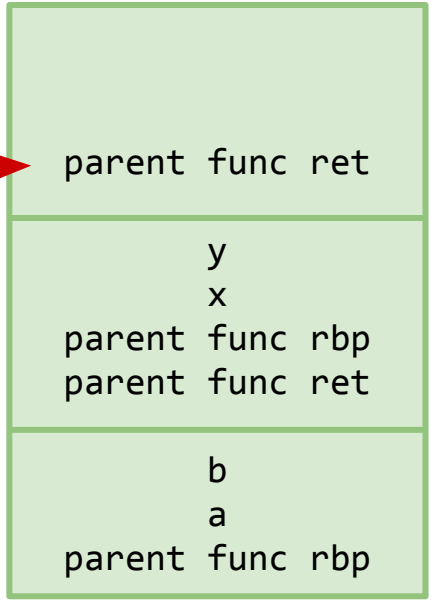
680:   c3                      ret
```



The Stack

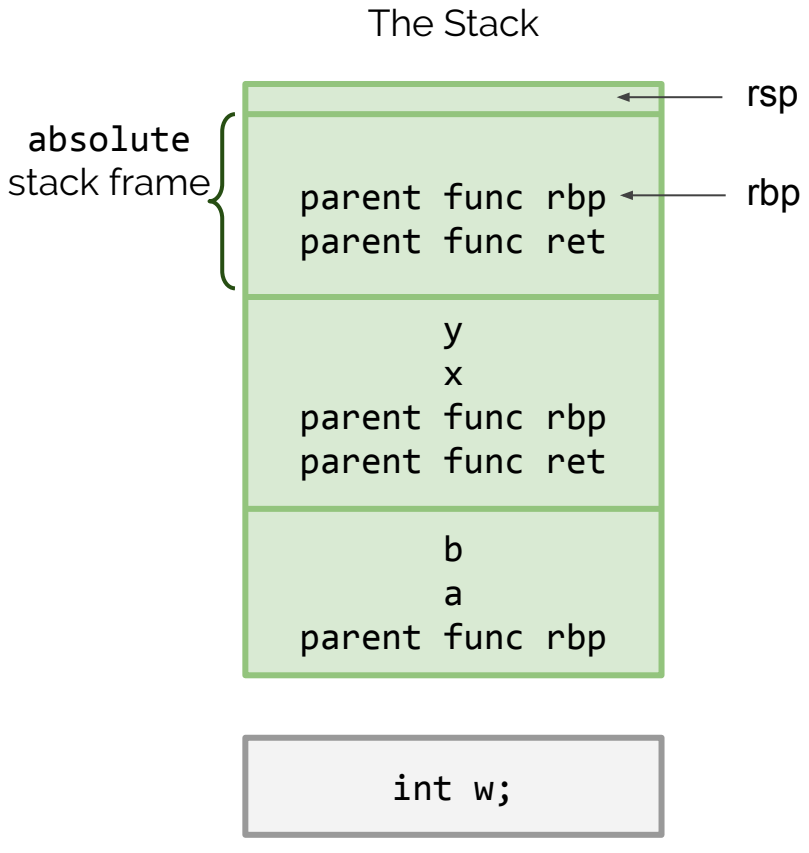



```
int w;
```

Understanding the Stack

Durham University

```
000000000000064a <absolute>:
64a:   55                    push   rbp
64b:   48 89 e5              mov    rbp,rsp
64e:   89 7d fc              mov    DWORD PTR [rbp-0x4],edi
651:   83 7d fc 00           cmp    DWORD PTR [rbp-0x4],0x0
655:   79 07                 jns    65e <absolute+0x14>
657:   8b 45 fc              mov    eax,DWORD PTR [rbp-0x4]
65a:   f7 d8                 neg    eax
65c:   eb 03                 jmp    661 <absolute+0x17>
65e:   8b 45 fc              mov    eax,DWORD PTR [rbp-0x4]
661:   5d                    pop    rbp
662:   c3                    ret
```



Understanding the Stack

Durham University

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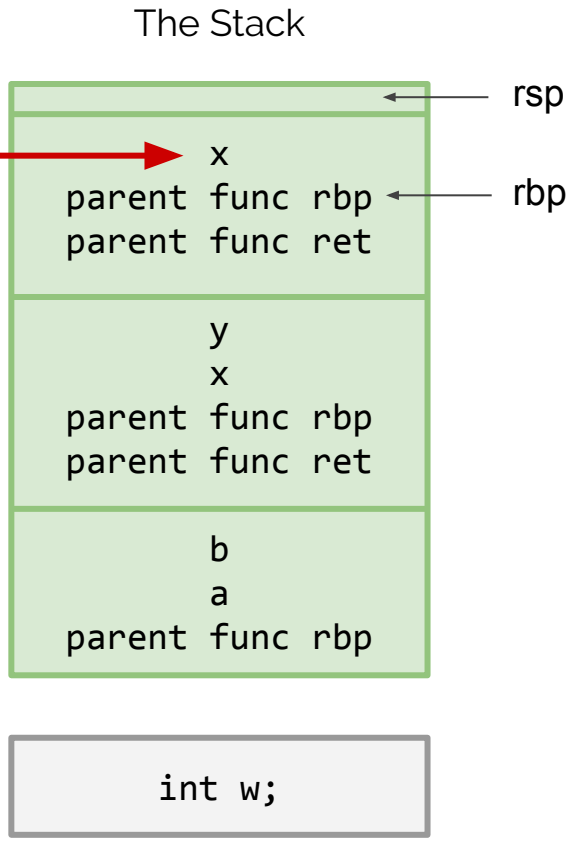
```



Understanding the Stack

Durham University

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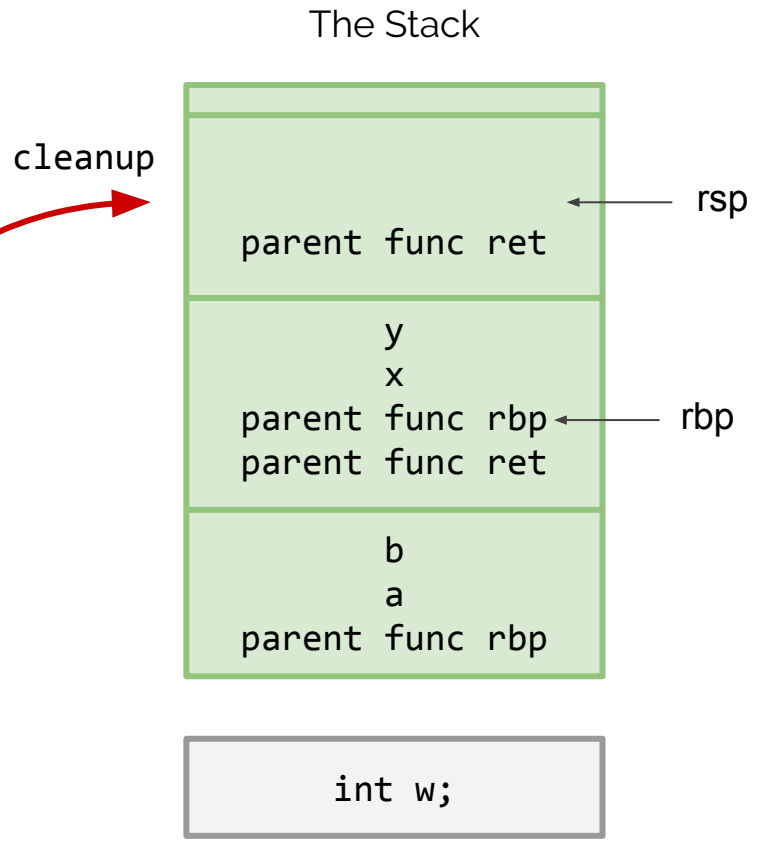
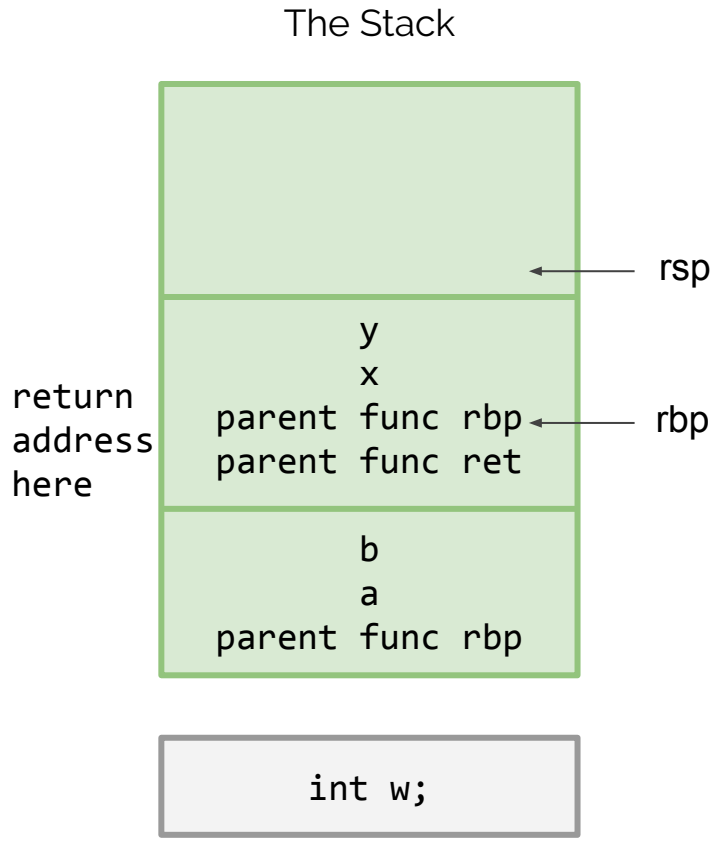
```



Understanding the Stack

```
0000000000000663 <abs_mul>:
663:   55                      push   rbp
664:   48 89 e5                mov    rbp,rsp
667:   48 8d a4 24 d8 ef ff    lea    rsp,[rsp-0x1028]
66e:   ff
66f:   48 83 0c 24 00          or     QWORD PTR [rsp],0x0
674:   48 8d a4 24 20 10 00    lea    rsp,[rsp+0x1020]
67b:   00
67c:   89 7d fc                mov    DWORD PTR [rbp-0x4],edi
67f:   89 75 f8                mov    DWORD PTR [rbp-0x8],esi
682:   8b 45 fc                mov    eax,DWORD PTR [rbp-0x4]
685:   0f af 45 f8             imul   eax,DWORD PTR [rbp-0x8]
689:   89 c7                   mov    edi,eax
68b:   e8 ba ff ff ff          call   64a <absolute>
690:   c9                      leave
691:   c3                      ret
```



Understanding the Stack

Durham University

```
0000000000000663 <abs_mul>:
663:   55                      push   rbp
664:   48 89 e5                mov    rbp,rsp
667:   48 8d a4 24 d8 ef ff    lea    rsp,[rsp-0x1028]
66e:   ff
66f:   48 83 0c 24 00          or     QWORD PTR [rsp],0x0
674:   48 8d a4 24 20 10 00    lea    rsp,[rsp+0x1020]
67b:   00
67c:   89 7d fc                mov    DWORD PTR [rbp-0x4],edi
67f:   89 75 f8                mov    DWORD PTR [rbp-0x8],esi
682:   8b 45 fc                mov    eax,DWORD PTR [rbp-0x4]
685:   0f af 45 f8             imul   eax,DWORD PTR [rbp-0x8]
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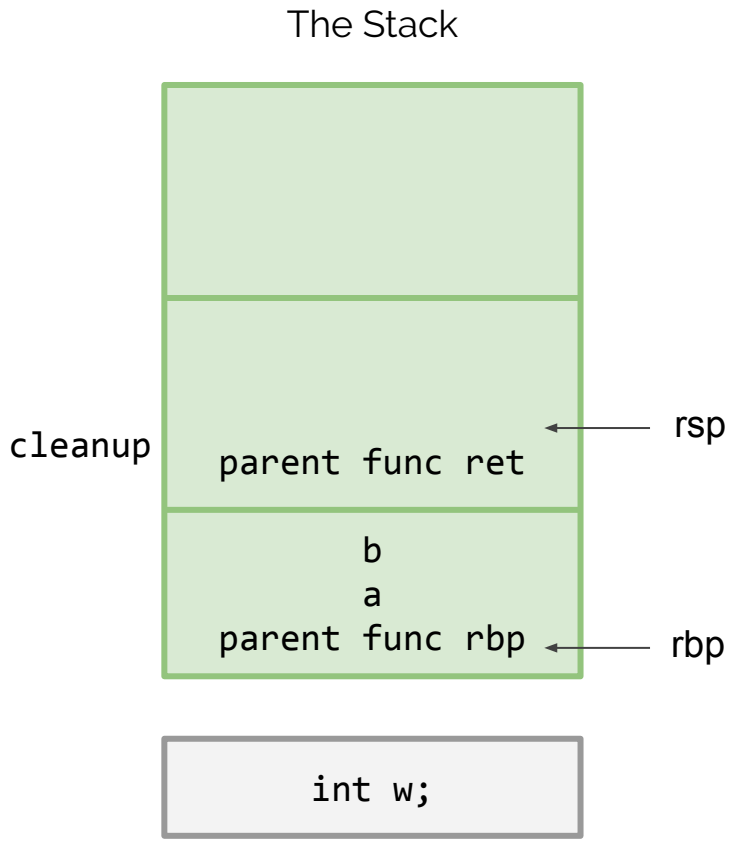
```

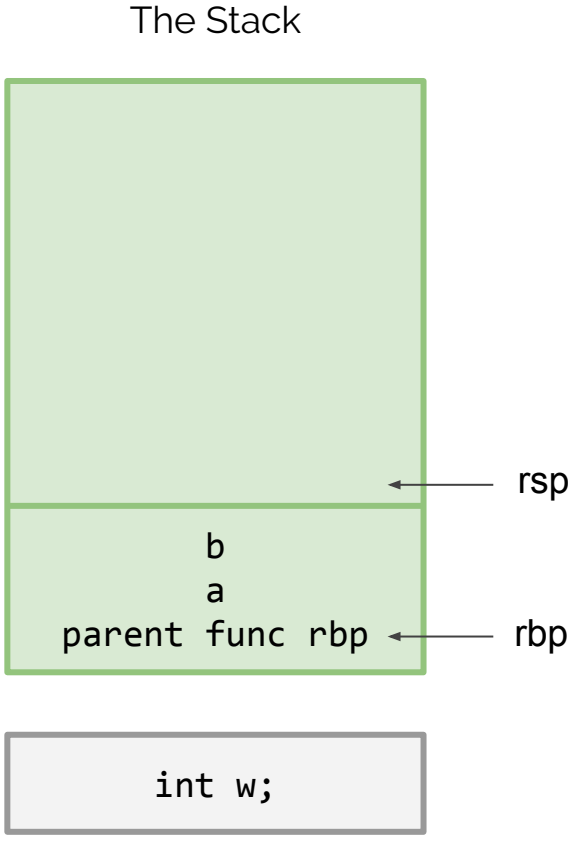


Understanding the Stack

Durham University

```
0000000000000681 <main>:
681:   55                      push   rbp
682:   48 89 e5                mov    rbp,rsp
685:   48 83 ec 10             sub    rsp,0x10
689:   c7 45 f8 05 00 00 00    mov    DWORD PTR [rbp-0x8],0x5
690:   c7 45 fc fe ff ff ff    mov    DWORD PTR [rbp-0x4],0xfffffffe
697:   8b 55 fc                mov    edx,DWORD PTR [rbp-0x4]
69a:   8b 45 f8                mov    eax,DWORD PTR [rbp-0x8]
69d:   89 d6                   mov    esi,edx
69f:   89 c7                   mov    edi,eax
6a1:   e8 bd ff ff ff          call   663 <abs_mul>
6a6:   89 05 88 09 20 00       mov    DWORD PTR [rip+0x200988],eax
6ac:   8b 05 82 09 20 00       mov    eax,DWORD PTR [rip+0x200982]
6b2:   89 c6                   mov    esi,eax
6b4:   48 8d 3d 99 00 00 00    lea    rdi,[rip+0x99]
6bb:   b8 00 00 00 00          mov    eax,0x0
6c0:   e8 6b fe ff ff          call   530 <printf@plt>
6c5:   b8 00 00 00 00          mov    eax,0x0
6ca:   c9                      leave
6cb:   c3                      ret
6cc:   0f 1f 40 00             nop    DWORD PTR [rax+0x0]
```

return address here



Understanding the Stack

```
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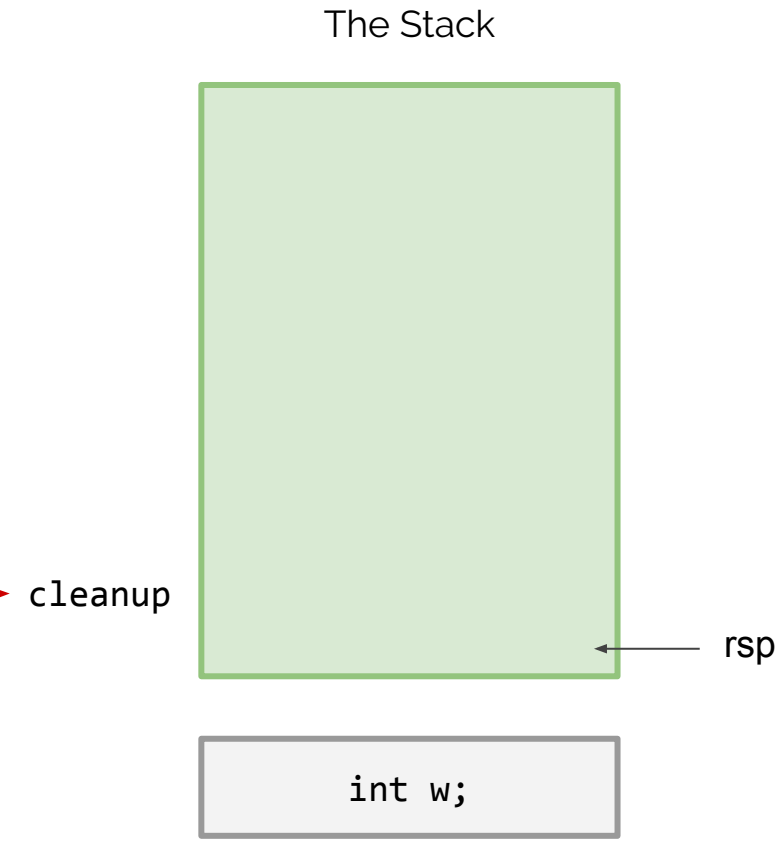
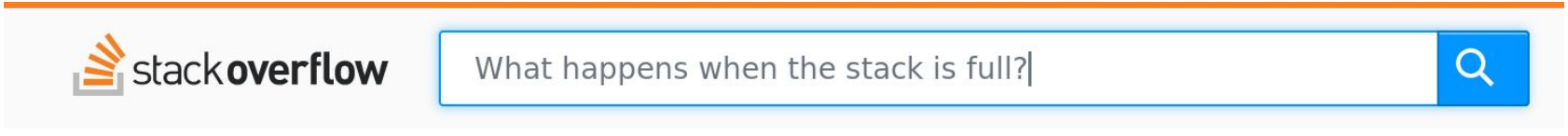
69d:   89 d6                   mov    esi,edx
69f:   89 c7                   mov    edi,eax
6a1:   e8 bd ff ff ff          call   663 <abs_mul>
6a6:   89 05 88 09 20 00       mov    DWORD PTR [rip+0x200988],eax
6ac:   8b 05 82 09 20 00       mov    eax,DWORD PTR [rip+0x200982]
6b2:   89 c6                   mov    esi,eax
6b4:   48 8d 3d 99 00 00 00    lea    rdi,[rip+0x99]
6bb:   b8 00 00 00 00          mov    eax,0x0
6c0:   e8 6b fe ff ff          call   530 <printf@plt>
6c5:   b8 00 00 00 00          mov    eax,0x0
6ca:   c9                      leave
6cb:   c3                      ret
6cc:   0f 1f 40 00             nop    DWORD PTR [rax+0x0]
```



Understanding the Stack

- When program thread starts, the operating system reserves some amount of space for the stack.
  - Stack memory does not grow during runtime.




```
int stack_overflow() {
    return stack_overflow();
}
```

```
chris@chris-laptop ~/security master • gcc main.c -o main.o
chris@chris-laptop ~/security master • ./main.o
[1]    11796 segmentation fault (core dumped)  ./main.o
✘ chris@chris-laptop ~/security master •
```

- Caused by…
  - Badly written recursive functions
  - Too much local memory allocated (esp with multi-threading)
- What happens if we need to allocate a large amount of local memory?
  - We would need to know the size of it at compile time.
  - But what if you wanted it to grow dynamically at runtime without know it beforehand?

Introducing the Heap

also called Dynamic Memory (not related to the heap data structure)

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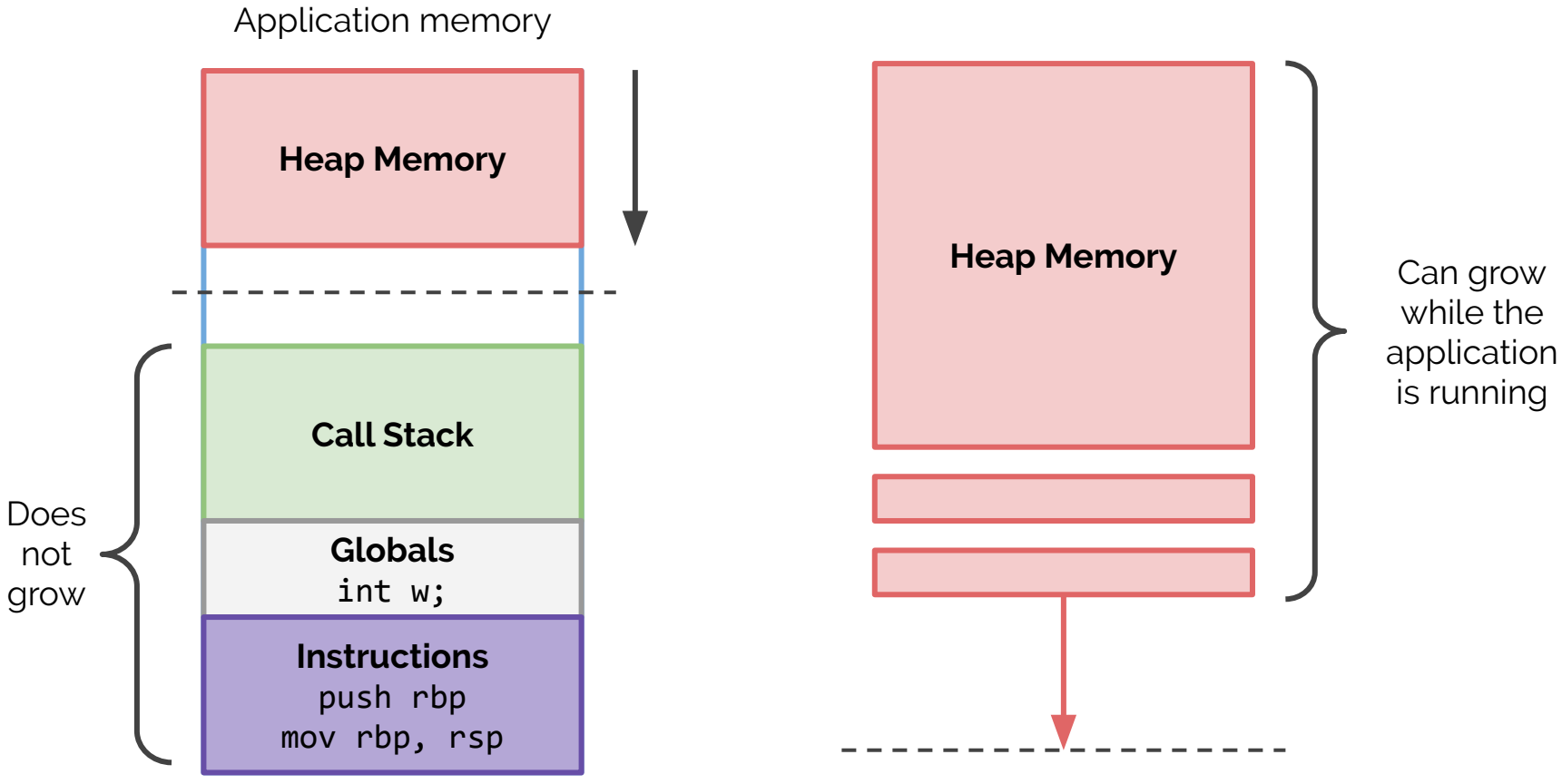

Pointers

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

int main()
{
   int *p;
   int x;

   p = &x;
   x = 4;

   printf("ex1 = %p\n", p);
   printf("ex2 = %d\n", *p);
   printf("ex3 = %d\n", p[0]);
   printf("ex4 = %d\n", p[ 1]);
   printf("ex5 = %d\n", p[-1]);
   printf("ex6 = %p\n", &p[1]);
   printf("ex7 = %p\n", &p[2]);

   return 0;
}
```

- Pointers ***x** are just integer numbers that point to the memory address.
- We can assign pointers to “the address of” **&x** variables.

```
 chris@chris-lab  ~/security  master •  ls
main.c
 chris@chris-lab  ~/security  master •  gcc main.c -o main.o
 chris@chris-lab  ~/security  master •  ./main.o
ex1 = 0x7fff398c4f2c
ex2 = 4
ex3 = 4
ex4 = 965496620
ex5 = 1733957040
ex6 = 0x7fff398c4f30
ex7 = 0x7fff398c4f34
 chris@chris-lab  ~/security  master •
```

- We can read memory from outside

Using the Heap

- C
  - **malloc**
  - **free**

  } functions
- C++
  - **new**
  - **delete**

  } operators
- Java
  - **new**
  - lots of stuff resides on the heap
- Python
  - In CPython, all objects live on the heap

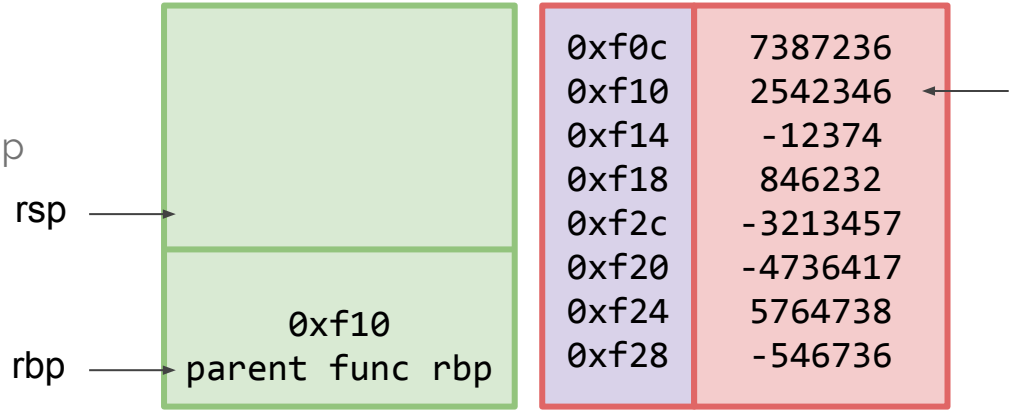
malloc manages a pool of memory and *sometimes* makes calls to **sbrk** which zeros out new requests

```c
#include <stdlib.h>

int main()
{
   float *ptr;

   ptr = (float*)malloc(3*sizeof(float));
   *ptr = 42;
   free(ptr);

   return 0;
}
```



Using the Heap

- C
  - **malloc**
  - **free**

  } functions
- C++
  - **new**
  - **delete**

  } operators
- Java
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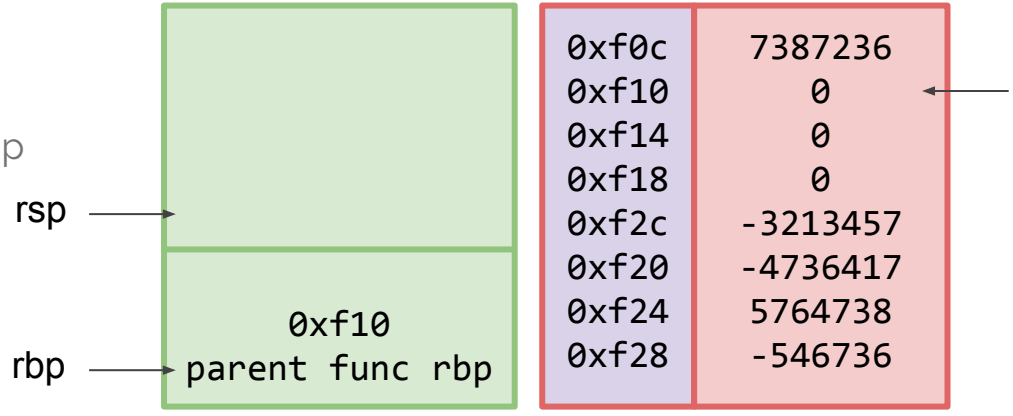
```



Using the Heap

- C
  - **malloc**
  - **free**

  } functions
- C++
  - **new**
  - **delete**

  } operators
- Java
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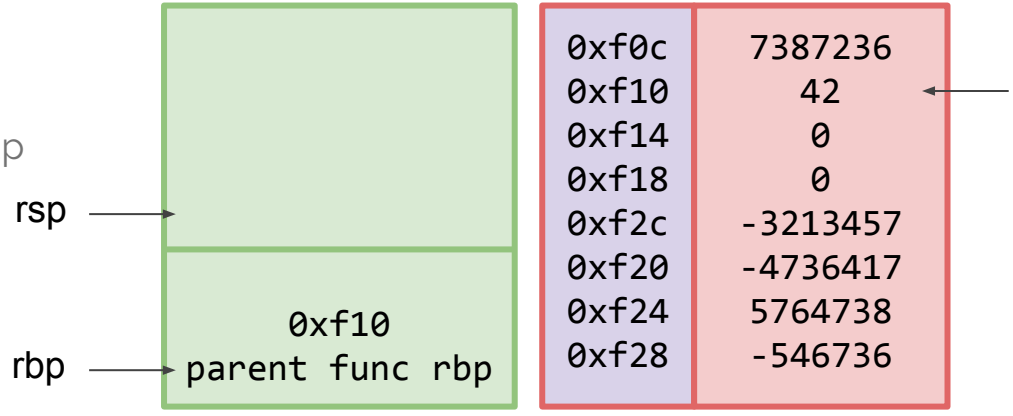

Using the Heap

Durham University

```c
#include <stdio.h>
#include <stdlib.h>
int main()
{
   float *p;
   int i;

   p = (float*)malloc(100*sizeof(float));
   for (i=0; i<100; ++i)
       p[i] = (float)rand()/(float)RAND_MAX;
   free(p);

   p = (float*)malloc(100*sizeof(float));
   p[0] = 6.283185;
   p[3] = 5.0;

   printf("p[0] = %f\n", p[0]);
   printf("p[1] = %f\n", p[1]);
   printf("p[2] = %f\n", p[2]);
   printf("p[3] = %f\n", p[3]);

   free(p);
   return 0;
}
```

- Memory not guaranteed to be initialized to zero
- Can malloc memory to same size of some sensitive data

Same size, so likely to get same memory

```
 chris@chris-lab  ~/security  master •  ls
main.c
 chris@chris-lab  ~/security  master •  gcc main.c -o main.o
 chris@chris-lab  ~/security  master •  ./main.o
p[0] = 6.283185
p[1] = 0.000000
p[2] = 0.783099
p[3] = 5.000000
 chris@chris-lab  ~/security  master •
```

Where did that come from?

Questions

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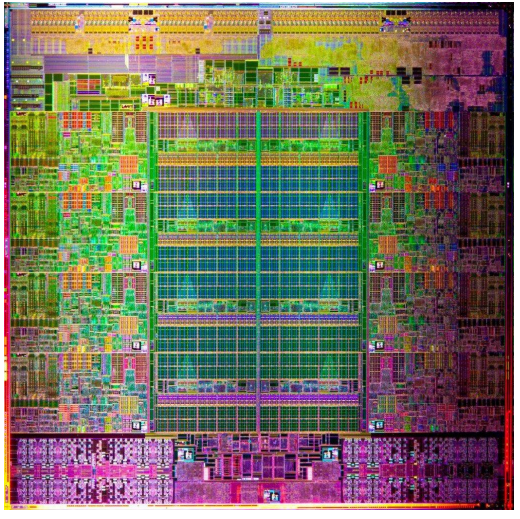
- Which memory type is faster?
  - Stack or Heap?
- Where does heap memory reside physically?
- Where does stack memory reside physically?
- What happens when stack memory leaves scope?
- What happens when heap memory leaves scope?
  - In Java?
    - **ArrayList**<Integer> v = **new ArrayList**<Integer>();
    - v.add(1); v.add(2); v.add(3); … ;
  - In C++?
    - **std::vector**<int> v;
    - v.push_back(1); v.push_back(2); v.push_back(3); …



Principles of good software?

… fast, secure, efficient, withstands the test of time, simple, intuitive, …

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- https://www.owasp.org/index.php/Security_by_Design_Principles
  - Minimize attack surface area, fail securely, keep security simple, …
- https://github.com/nothings/stb
  - Sean Barrett, a legendary software veteran, creator of the famous stb libraries such as stb_image, a tiny single file public domain header that enables you to read JPG, PNG, TGA, BMP, PSD, … instead of including huge monolithic libraries.
  - **“Make it easily usable”.**
  - **“Do anything you want with it”.**
- https://suckless.org/philosophy
  - The suckless group, developers of well-written and extendable software, such as the DWM window manager - just 2149 lines of easy-to-understand C code.
    - “**Simplicity, clarity, frugality**”
    - **“Do one task, do it well”**
- https://www.archlinux.org/ “Keep It Simple, Stupid!”
- **Writing secure software involves understanding the platform, and all the things that come between you (the developer) and the platform.**

Understanding the Platform

- The key to writing good, secure, software is to understand the platform.
- Hardware is the base platform (for software).
- Lots of things get in the way:
  - Compilers, Abstractions, Software Libraries, GUIs,
  - Operating Systems, User Patches, Web Browsers, ...

Offtopic but relevant, assuming Lemi was a Durham University computer science student, what should Lemi have done?

- "Stealing Webpages Rendered on Your Browser by Exploiting GPU Vulnerabilities"
  - http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=6956554

Optional Practicing Software Security

Durham University

- Download this specially prepared Kali VM from Ross Bradley at SRM:
  - Link 1
  - Link 2
- Start:
  - **Username**: level1
  - **Password**: level1
  - Double-click README and exploit.py in files.
- Also have a go at: https://www.hackthebox.eu/invite
  - You need to hack your way in