Systems Programming & Computer Architecture
HS2023 Essentials

Simon Sure
info@simonsure.com / simon.sure@inf.ethz.ch

January 8, 2024

This is an unofficial script containing information from the Systems Programming & Computer Architecture course as taught in HS of 2023. Although I am fairly confident that this contains everything mentioned in the lecture videos, ... - there is no guarantee for correctness of completeness!

If you have remarks or questions, or find any mistakes, don't hesitate to send me a mail to info@simonsure.com.

Also, feel free to share this script via https://simonsure.com/ethz which will always contain a link to the newest version. Use the date of this document to identify the newest version.

Contents

1 Introduction

Systems Programming describes programming on and above the hw/sw boundary. With systems, one always has to balance between theory and engineering (practical use). Specifically, we consider programs in the context of the real-world. While much of CS assumes many abstractions (data types, algorithms as mathematical objects, performance as asymptotic analysis, ...) systems recognizes the limitations of this as those abstractions do not really match reality, which can lead to bugs etc. when not having the proper knowledge. Systems Programmer understand the underlying reality to enable optimizations by recognizing that programs are more than just the algorithmic ideas.

Among the specialties which we will discuss in the following are:

- Computers don't really deal with numbers. Integers have an upper and lower bound. And floating point numbers are discrete.
- Understanding and writing (limited) assembly is important to fully grasp performance behavior and enable special functionality not accessible through a programming language.
- Memory is not a nice array that just stores data. It is finite. It must be managed (allocated & freed). There are caches, prefetching, virtual memory, ... Those all are deviations from the ideal simplified understanding. Performance depends on those factors. Adapting a program to the given environment can yield great improvements.
- Performance is about much more than asymptotic complexity. We must consider different latencies of different instructions, vector instructions, loop orders, ... Despite having the same asymptotic complexity, such simple changes may increase program performance by 160x.
- Computers don't just execute programs. They are a very complex and intricate piece of machinery. There is the Operating System, external devices (I/O), concurrent operations, different platforms, ... The generic programmer only knows a small fraction of the whole system. But knowing the entire systems structure enables a great systems programmer to unlock additional performance.
- Programs are not semantic specifications. Much behavior is implementation defined and we rely on the compiler to map operations in the program to the most natural operations in hardware.

Another reason for the relevance of Systems Programming is that Moore's Law does not continue to imply an increase in single-core performance as it has done in the past. To combat this decline, more specialized compute units (GPUs, TPUs, NPUs, ...) are developed. Programming those is a systems software problem.

2 Introduction to C

This course discusses C on a practical level. There won't be a formal introduction or formal definitions. Instead, we see the different properties of C introduced through example and applications.

2.1 History

C is an old language. It was developed quickly by Dennis Ritchie with the purpose to reimplement the Unix kernel in C instead of Assembly as it had been done before. At that time, C was considered a high-level language. Many characteristics of (even modern) C can be traced back to the properties of architecture used at the time of the inception of C.

The C language was influenced by other earlier languages, which preceded C: CPL (Combined Programming Language), BCPL (Basic Combined Programming Language), and B. CPL was so complex that nobody ever managed to implement a compiler for it.

By its design, C was portable across many architectures. Accordingly, there were numerous debates on the C standard. As C was and is used on many different platforms, it is often difficult to agree on a shared definition for a standard. Hence, many features of C are stated to be implementation-defined. Chronologically, those are the relevant C standards:

- K&R C (the standard was not defined in plain English, instead the compiler was the standard)
- ANSI C
- C99 (from 1999, will be used in this course)
- C11
- C17
- C23 (?) to be released in 2024

2.2 Characteristics of C

Compared to other languages, C is very fast. The reason that C is so fast is that (a) it is close to the hardware and writing C code is hence very optimized for the used hardware, and (b) C compilers are very, very sophisticated. It is almost impossible to write as good assembly code manually.

For the above reasons (speed and hardware closeness) C is the language of choice for OS developers, embedded systems, speed-critical applications, security exploits, ... despite its age. Moreover, C is a very simple language by itself. Simple not meaning it is simple to write good C code, but that the count of language constructs is rather small. There are no objects, classes, traits, features, methods, interfaces, ... We only really have functions, variables, and pointers. There are also no fancy build-in types. We mostly deal with what the hardware provides. Boolean are just integers with an easier to read name, for example. Exceptions do also not exist. Nevertheless, objects, polymorphism etc. can still be used in C because those concepts can of course be implemented.

Because C is so close to the hardware, writing C programs is about caring about data organization. C is about directly building and manipulation structures in main memory. In C, one must manually manage the memory. That unlocks great potential for optimization. We mostly store things on the stack. When we want to use the heap, we need to manually allocate memory and free it after we have used it as there is no garbage collection. Pointers (weakly types) enable us to directly access memory addresses.

While those concepts are different from Java, JavaScript, C++, and other languages, the syntax is fairly similar. Comments, identifiers, blocks,..., they all work basically the same. Still, as C has less language constructs, the list of reserved words is different. Also, there is a powerful macro pre-processor, which is used for string and file substitution, conditional compilation, etc. Such pre-processors are not present in other relevant languages.

2.3 C Program Structure

Listing 1: Simple C Program

```
1 int main() {
2   return 0;
3 }
```

Without relying on default type definitions etc., one will struggle to write a shorter C program. But for illustratory purposes we will consider a slightly more elaborate program.

Listing 2: Basic C Program

```
1 #include <stdio.h>
2
3 int main(int arc, char *argv[])
4 {
5   printf("hello, world\n");
6   return 0;
7 }
```

- The `#include<...>` can be understood as an import. The `#` indicates a pre-processor instruction. What is actually done is that the contents of the specified file, here the stdio.h header file, is pasted to replace the include during compilation.
- The `main()` function is the entry point of the program. Its arguments are the command line arguments. `argc` specifies the number of arguments and `*argv[]` is an array of strings.
- `printf()` is a generic function for printing formatted strings. The `\n` is required to add a line break. This function can only be used when importing `stdio.h`.

In C, the program always returns an integer. By convention, 0 tells the operating system that the program terminated successfully. Anything else indicates some sort of error. One can use different integers for different errors. But notice that also returning `void` will likely compile correctly due to compiler defaults.

2.4 Toolchain/Workflow

If the reader is familiar with languages such as `Python`, one probably knows that it is an interpreted language. During execution the program is interpreted and executed at runtime. C (and other languages such as C++) are different. Those are compiled languages. Before execution, C is compiled into assembly, which can then directly be executed. This removes a runtime performance overhead.

Compilation is done in different steps. In the early times of C, the linking as part of loading did not exist. But today, the assembly being executed is different from the binary assembly on disk. Dynamic linking (linking during load) is discussed in the section on linking.

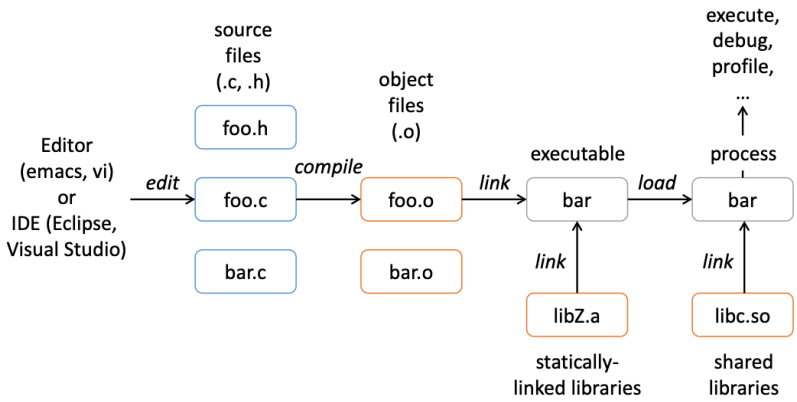


Figure 1: C Workflow

1. Editing the raw .c files.
2. Pre-processing as part of compilation with `cpp` generates new .c files.
3. The pre-processed .c files are compiled into assembly using `cc1`. The assembly is still stored in human-readable form in .s files. This finishes the compilation step.
4. The .s files are then assembled into .o object files. This now corresponds to assembly as defiend by the ISA and is not human friendly to read. This is done with the `as` tool.
5. Various object files and statically linked libraries are then linked to create an executable using `ld`. Executables often have the ending .a.
6. During execution, the loader loads an executable and finishes to link dynamically linked libraries.

The different steps of this pipeline could be done manually. But in practice, we use `gcc`, which combines all the above steps into a single tool. Gcc stands for GNU Compiler Collection. With different flags, one can instruct `gcc` to only perform some of the steps outlined above.

- `gcc -S`: Up to including step 3. Results in human-readable assembly.
- `gcc -c`: Up to including step 4. Results in non-human-readable machine code.
- `gcc -o`: Up to including step 5. This creates the executable.

2.5 Control Flow

`if`, `switch`, `for`, `while`, `do-while`, `return`, ... all have basically the same semantics and syntax as in Java or C++. Hence, we will not elaborate them here. Notice that for `switch` we need a `break;` in each case if we would rather not fall through and continue executing the next case. We also have `break` and `continue`. But there are no labels, so we can always only affect the innermost loop.

Also, we have `goto`, which we can use to jump to a specific label, i.e., point in the code. This is a remnant from early programming. It should only be used in a few specific cases. Using `goto` almost never increases program performance and it is very confusing to understand programs using C.

2.6 Functions

Functions work mostly as in Java/C++. We won't explain them explicit.y

Listing 3: Functions in C

```
returnType fucntionName(parameterType parameterName, /* ... */ )
{
  // ...
  return returnType;
}
```

2.7 Basic I/O

Using I/O to interact with devices is complicated. It will be discussed in the last section. But more basic I/O is printing to the console and reading input from the console. To print to the console we use `printf();` which may only be used when importing `stdio.h`. It is a variadic function, meaning it accepts a variable number of arguments.

The first argument is the format string. The remaining arguments are arbitrary but must fit the what we indicated to insert into the format string. Inside the format string, we use `%d` to insert a decimal, `%s` to insert a string, ... The following arguments then specify those values in the corresponding order.

2.8 Basic Types

Variable declaration works as known: `type name;`. Together with initialization: `type name = value;`. Furthermore, we may add additional keywords such as `static` or `volatile`. The latter is discussed as part of multiprocessing.

	inside a block	**outside a block**
static	value persists between calls	scope limited to compilation unit
non-static	scope is just the block	scope is the entire program

Figure 2

The compilation unit is what is being compiled after the pre-processing. I.e., the unit that is actually being compiled and not all files that are separately compiled but only combined during linking.

Besides basic types as `int`, `float`, `double`, `char`, ..., we also have `void`. It has no value and is used for untyped pointers (`void *`) or declaring functions with no return value. `char` can be signed or unsigned. It is basically a byte of memory. `float` is always signed. Integer types can be signed or unsigned.

We usually distinguish between integers and floating point types. Chars and booleans are also just integers under the hood. Thus, we can all discuss them as being the same. They only correspond to different sizes/amounts of bits in memory. Integers are stored in 2s complement format. Floating point types will be discussed in a separate section.

Booleans are integers as they are an integer-type. In basic C there even isn't a bool type. We just use small ints. A 0 is interpreted as false and anything else means true. One can use `!` to convert true/false to false/true. When one wants to use a type bool, one has to import `stdbool.h`.

2.8.1 Type Width

The width (i.e., size) of types is not defined in the C standard. It is implementation-defined. However, it is defined that integers are signed by default.

C Data Type	typical 32-bit	ia32 (intel x86)	intel x86-64
char	1	1	1
short	2	2	2
int	4	4	4
long	4	4	8
long long	8	8	8
float	4	4	4
double	8	8	8
long double	8	10/12	10/16

Figure 3: Default Type Widths in Bytes

”Native” types are accessible by just writing `int` or similar. However, one may import `stdint.h`, which provides additional type definitions. This is also helpful, because `int` may have different sizes on different platforms. But with the definitions from `stdint.h` one can specify specific sizes etc. We may use types such as `uint_32, uint_8, int_64, ....`

2.8.2 Conversion/Casting

Between different integer-type types we have ’implicit’ conversion in a sense that we just reinterpret the bits without changing them. If we change the size of the integer, more interesting things happen. Reducing the size just corresponds to truncation, i.e., only the unaltered fitting lower bits are kept. (For a signed original int, this technically is implementation defined.) Increasing the size differs depending on whether the original value is signed or unsigned. If the original value is signed, the new value will be sign extended. If the original value is unsigned, the new value will be zero extended.

Between integers and floating-point types are also is implicit conversion. But that conversion actually changes the bit representation of a number so that it is best approximated in the other number type. In the floating point section the details of this conversion will be discussed in detail. Similarly, one can also implicitly convert between floating point types.

2.9 Statements as Expressions

In C, any statement is also an expression. Assignments etc. all evaluate to a value. Assignments specifically, evaluate to the new/assigned value.

2.10 Operators

As with other properties too, operators in C are similar in other languages such as C++ or Java as those are heavily inspired by C. For all operators, we shall remember their associativity, i.e., whether it is left-to-right or right-to-left associative. If there are multiple occurrences of the same operator, right-to-left means that we start evaluating on the right, while left-to-right means that we start evaluating on the left.

The following list shows operators in C in order of their presedence.

- `()`, `[]`, `->` are left-to-right

- unary operators: `!`, `~`, `++`, `--`, `+`, `-`, `*`, `&`, `(type)`, `sizeof` are right-to-left
- binary operators: `*`, `/`, `%` are left-to-right
- binary operators: `+`, − are left-to-right
- `<<`, `>>` are left-to-right
- `<`, `<=`, `>`, `>=` are left-to-right
- `==`, `!=` are left-to-right
- `&` is left-to-right
- `^` is left-to-right
- `|` is left-to-right
- `&&` is left-to-right
- `||` is left-to-right
- `?` (ternary operator) is right-to-left
- `=`, `+=`, `*=`, `/=`, `%=`, `&=`, `^=`, `|=`, `<<=`, `>>=` are right-to-left
- `,` is left-to-right

Almost all of those operators should be known. Only `,` may be unfamiliar as it is not common in other languages. It can chain two instructions together but discard the value of the left expression as it returns the value of the right expression.

Notice the difference between pre- and post-increment and -decrement.

2.11 Arrays

Arrays are finite vectors of variables of the same type. An N-element array is indexed from 0 to N-1. In contrast to high-level languages, the C compiler does not check for array bounds.

In memory, an array just is a contiguous block of memory. With N elements, we have `N * sizeof(type)` contiguous types, where the array elements are just lined up. Indexing the array corresponds to specifying an offset from the first element. If we give some bogus offset (too large, some negative number, ...) we just offset to some memory location which has nothing to do with the array. This may lead to program failure.

Listing 4: C Array Example

```
1  #include <stdio.h>
2
3  //creating array
4  float data[5];
5
6  int main()
7  {
8    data[0] = 34.0;
9    data[1] = 27.0;
10   data[2] = 45.0;
11   data[3] = 82.0;
```

```
  data[4] = 22.0;
  total = data[0] + data[1] + data[2] + data[3] + data[4];
  return (0);
}
```

We can also create multi-dimensional arrays.

C is row major. So access pattern should look like `arr[0][0],arr[0][1],...,arr[1][0],arr[1],[1],...`. Always remember row-majority when iterating over arrays!

Listing 5: Multi-Dimensional Arrays in C

```
int array[3][3];
for(int i = 0; i<3; i++) {
  for(int j = 0; j<3; j++)
    array[i][j] = i+j;
}
```

For multi-dimensional arrays in C there also is another option. Instead of storing all elements contiguously, one may also store a pointer to the row for each row. So we basically have an 'outer' array `void* array[length]` and length many inner arrays `type inner[length2]` with length2 being the size in the second dimension. This has fundamentally different memory (latency) behavior. What's most confusing about this in practice is that both types of arrays are indexed in the same way.

Finally, arrays can be initialized while being created:

Listing 6: Array Initialization during Declaration in C

```
int a[3] = {3, 7, 9};
int b[3][3] = {
  { 1, 2, 3 },
  { 4, 5, 6 },
  { 7, 8, 9 },
};
```

2.12 Strings

In C there isn't a special type for strings. Instead, strings are just arrays or characters terminated with a null byte `0x0` or `\0` (this is different from 0 itself!). So strings are `char string[length];`. Thus, in a string, i.e., a char array, not an arbitrarily long text can be stored. It can be at most length-1 long as we still need to add the null byte. Forgetting the null byte is fatal because the null byte stops functions to continue processing the string. If it is missing, they will likely run beyond the bounds of the char array.

To then use strings as one would use strings in other languages (copying, concatenation, getting the length, ...) one has to import `string.h`.

Listing 7: C String Example

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

int main(int argc, char *argv[])
{
  char name1[12], name2[12];
```

```
7   char mixed[25], title[20];
8
9   //strcpy(name1, "Rosalinda");
10  strncpy(name1, "Rosalinda", sizeof(name1)-1);
11  //strcpy(name2, "Zeke");
12  strncpy(name2, "Zeke", sizeof(name2)-1);
13  //strcpy(title, "This is the title.");
14  strncpy(title, "This is the title.", sizeof(title)-1);
15
16  printf("%s\n\n", title);
17  printf("Name 1 is %s\n", name1);
18  printf("Name 2 is %s\n", name2);
19
20  /* returns 1 if name1 > name2 */
21  if (strcmp(name1, name2) > 0) {
22    //strcpy(mixed, name1);
23    strncpy(mixed, name1, sizeof(mixed)-1);
24  } else {
25    //strcpy(mixed, name2);
26    strncpy(mixed, name2, sizeof(mixed)-1);
27  }
28  printf("The biggest name alphabetically is %s\n", mixed);
29
30  //strcpy(mixed, name1);
31  strncpy(mixed, name1, sizeof(mixed)-1);
32  //strcat(mixed, " ");
33  strncat(mixed, " ", sizeof(mixed)-strlen(mixed)-1);
34  //strcat(mixed, name2);
35  strncat(mixed, name2, sizeof(mixed)-strlen(mixed)-1);
36  printf("Both names are %s\n", mixed);
37  return 0;
38 }
```

We use `strncpy` instead of `strcpy` to avoid going over the bounds of the target buffer by specifying the maximum string size allowed.

- `strlen(char[])`: returns the length of a string
- `strncpy(char[], char[], size_t)`: copies the second array to the first array upu to a given length
- `strncat(char[], char[], size_t)`: concatenates the second string to the first string, adds at most the specified number of chars
- `strcmp(char[], char[])`: compares the two strings by comparing their chars one by one

  returns 0 if identical

  returns value > 0 if: with first different char, the first string's char is larger in ASCII OR the first string is longer if no different up to then

  returns value < 0 if: with first different char, the second string's char is larger in ASCII OR the second string is longer if no difference up to then

3 Representing Integers in C

3.1 Representing Numbers

In modern machines, integers are usually stored as several bytes. With little-endian systems, we store the least significant byte first/at the low address. With big-endian systems, we store the most significant byte first/at the low address.

Integers are just a sequence of bits. Their decimal value interpretation depends on whether we consider signed or unsigned integers. For unsigned integers, we consider standard binary representation:

$$\text{binary2unsigned}(x) = \sum_{i=0}^{w-1} x_i \cdot 2^i$$

For signed integers, we use two's complement:

$$\text{binary2signed}(X) = -x_{w-1} \cdot 2^{w-1} + \sum_{i=0}^{w-2} x_i \cdot 2^i$$

	8 bit decimal	16 bit decimal	16 bit hexadecimal	16 bit binary	32 bit decimal	64 bit decimal
UMax	255	65,535	FF FF	11111111 11111111	4,294,967,295	18,446,744,073,709,551,615
TMax	127	32,767	7F FF	01111111 11111111	2,147,483,657	9,223,372,036,854,775,807
TMin	-128	-32,768	80 00	10000000 00000000	-2,147,483,658	-9,223,372,036,854,775,808
-1		-1	FF FF	11111111 11111111		
0		0	00 00	00000000 00000000		

Figure 4: Integer Ranges

In C we can use `#include <limits.h>` to get declared constants with those values specific for our platform. Those constants would then be `ULONG_MAX, LONG_MAX, LONG_MIN , ...`

Integers are signed by default. If we want an unsigned value we need to specify it by appending a U as in: `0U`. We already discussed how casting (not) changes the bit representation. But another question is when casting occurs. One case is explicit casing. But when mixing different integer types, we also have implicit casting. Then, signed values are interpreted as unsigned values.

3.2 Number Operations

3.2.1 Bit-wise Operations

Notice that numbers in C are not numbers as in mathematics. They are `int`s, i.e., they are a sequence of bits. On those bits, we can perform bit-level operations. Such operations can be used on integer-type data types, i.e., everything not a float. We have `&` (AND), `|` (OR), `~` (NOT), and `^` (XOR).

3.2.2 Logical Operations

C has the logical operators `&&` (logic AND), `||` (logic OR), and `!` (logic NOT). They consider 0 to be false and anything non-zero as true and always evaluate to 0 or 1. Evaluation uses short-circuit evaluation.

Listing 8: Logical Operation in C

```
!0x41 -> 0x00
!0x00 -> 0x01
!!0x41 -> 0x01
0x60 && 0x55 -> 0x01
0x69 || 0x55 -> 0x01
```

3.2.3 Shift Operations

A left-shift moves all bits one to the left and adds 0s to the right. Bits pushed out on the left are discarded.

Right shifts can be logical or arithmetic. Independent of the variant, the bits are shifted to the right by the given number of positions. Bits pushed out on the right are discarded. With a logical shift, we fill the void placed on the left with 0s. With an arithmetic shift, we fill the void places with the most significant bit of the original int.

In C, we do logical shifts on unsigned `int`s and arithmetic shifts on signed `int`s.

Listing 9: Shifting in C

```
01100010U << 3 -> 00010000
01100010 << 3 -> 00010000
01100010U >> 2 -> 00011000
01100010 >> 2 -> 00011000

10100010U << 3 -> 00010000
10100010 << 3 -> 00010000
10100010U >> 2 -> 00101000
10100010 >> 2 -> 11101000
```

Shifting by < 0 or $\geq$ word size is undefined behavior.

3.3 Integer Addition & Subtraction

The one's complement of an integer `i` is defined to be `~i`, i.e., all bits flipped. Then see that `i+~i=0xFF...=-1` so that `-x = ~x + 1` is the two's complement of an integer and corresponds to its negation.

3.3.1 Unsigned Addition

The true sum of two unsigned integers may require one additional bit to store. However, we discard of that bit on the left to get an int of the same size. So, the standard addition function ignores the carry output. Instead, the C standard defines that the number 'wraps around', i.e., is just the result without the carry. Mathematically:

$$\text{unsignedAdd}_w(u, v) = u + v \mod 2^w$$

$$\text{unsignedAdd}_w(u, v) = \begin{cases} u + v, & u + v < 2^w \\ u + v - 2^w, & u + v \geq 2^w \end{cases}$$

This has several mathematical properties so that integer addition in C/computer arithmetics is an Abelian group.

- closed under addition: $0 \leq UAdd_w(u, v) \leq 2^w - 1$

- commutative: $UAdd_w(u, v) = UAdd_w(v, u)$
- associative: $UAdd_w(t, UAdd_w(u, v)) = UAdd_w(UAdd_w(t, u), v)$
- 0 is the additive identity: $UAdd_w(u, 0) = u$
- Every element has an additive inverse:
  - $UComp_w(u) = 2^w - u$
  - $UAdd_w(u, UComp_w(u)) = 0$

3.3.2 Signed Addition

On a bit level, this works just as unsigned addition: We do standard addition and discard of the carry bit. This this is possible is even the reason why signed integers use two's complement format. In contrast to unsigned addition, overflow is not defined by the standard. But all sensible implementations do this just as unsigned addition in hardware, so the behavior is usually the same.

$$\text{signedAdd}_w(u, v) = \begin{cases} u + v + 2^w, & u + v < TMin_w \\ u + v, & TMin_w \leq u + v \leq TMax_w \\ u + v - 2^w, & TMax_w < u + v \end{cases}$$

Mathematically, this is isomorphic to unsigned addition with unsignedAdd. 2's complement under signedAdd forms a group just as we have for unsigned addition.

An interesting difference is the inverse, which is $TComp_w(u) = \begin{cases} -u, & u \neq TMin_w \\ TMin_w, & u = TMin_w \end{cases}$.

3.4 Integer Multiplication

One can quickly see that adding two arbitrary integers may yield a new integer which is outside the range of representable integers.

$$\text{range for unsigned } \texttt{int}\text{s: } 0 \leq x \cdot y \leq (2^w - 1)^2 = 2^{2w} - 2^{w+1} + 1$$

$$\text{range for signed } \texttt{int}\text{s:}$$
$$-2^{2w-2} + 2^{w-1} =\geq (-2^{w-1}) \cdot (2^{w-1} - 1) \leq x \cdot y$$
$$x \cdot y \leq (-2^{w-1})^2 = 2^{2w-2}$$

To get a precise result, we would (to cover the worst case) have to double the word size with each multiplication. If one wants such precision, it is done using 'arbitrary' precision libraries. But in practice we want to the result to be of the same word size as the inputs.

3.4.1 Unsigned Multiplication

As with addition, we just discard any additional bits and just keep the lower bits that fit our word size.

$$UMult_w(u, v) = u \cdot v \mod 2^w$$

The mathematical properties of this correspond to a commutative ring. We don't have a field because the inverse generally doesn't exist.

- closed under multiplication
- commutative
- associative
- 1 is the multiplicative identity
- multiplication distributes over addition

3.4.2 Signed Multiplication

This is again just as for unsigned multiplication: We simply ignore/discard of the higher order w bits and retain the word size. Accordingly, this is also isomorphic to unsigned multiplication and addition.

3.5 Ordering Properties of Numbers

This is just a brief remark that common ordering properties of integers don't translate to `int`s. The following are NOT ebeyed by machine arithmetic:

- $u > 0 \Rightarrow u + v > v$
- $u > 0, v > 0 \Rightarrow u \cdot v > 0$

3.6 Integer Multiplication and Division using Shifts

Integer addition and subtraction typically work in one cycle. Meanwhile, multiplication takes significantly longer. Historically, about 20 cycles. Modern machines may manage in about 4 cycles. Division is even worse. But even if it can be done in a few cycles, the power consumption and required chip area is still noticeably higher. Therefore, programmers have sought alternative approaches to multiply and divide for special cases. One such special case is multiplication and division with powers of two.

3.6.1 Left Shift / Multiplication by Powers of Two

With left-shifts, we can multiply by powers of 2. We just discard of bits which are shifted out on the left and add zeros on the right. Accordingly, we have modular arithmetic for unsigned integers. For signed integers, the behavior may be wired.

This can be used to do certain operations faster. For instance, `u * 8` can be written as `u << 3`, or `u * 24` as `(u<<5) - (u<<3)` (may even be done in 2 cycles on superscalar machines). As machines generally execute shift and add faster, these alternatives are chosen. Even the compiler can detect such simplifications and generate assembly, which implements such optimizations.

3.6.2 Right Shift / Division by Powers of Two

Unsigned Integers Here, with logical shift (fill with zeros on the left), `u >> k` and $\lfloor$`u/2^k`$\rfloor$ are equivalent expressions. We discard of all bits which are shifted out on the right side. This has the same semantics as $u/2^k$ if we write it directly in C.

Signed Integers If we do right-shifts with signed integers, we do an arithmetic shift (fill with the sign bit on the left) and `u >> k` and $\lfloor$`s/2^k`$\rfloor$ are equivalent. But this does not correspond to what we usually want. If we divide -15213 by two, a mathematical division results in -7606.5. Normally, we round toward 0, but with shifting we get -7607 instead, i.e., we round toward $-\infty$. Actually, we want to compute $\lceil$`s/2^k`$\rceil$ for negative numbers. We can do so by computing $\lfloor(s + 2^k - 1)/2^k\rfloor$. This can be done in C as we take the floor with `(s+(1<<k)-1)>>k`.

When one writes a regular division in C and the dividend is known, C compiles the division to an assembly expression of the above form.

3.7 Puzzle

4 Pointers

4.1 Memory Basics

The OS provides each program with its own virtual address space. This address space is private to a program. In modern byte-addressable systems, each address corresponds to a byte. On a 32 bit host, we have 2^{32} bytes of virtual memory. On a 64 bits host, we have 2^{64} bytes of virtual memory. This memory is not actually available, as we do not have sufficiently large storage/memory units. But this is the potentially usable address space.

When a program is loaded by the OS, it lazily copies regions of the executable file into the right place in the address space while performing final linking, relocation, and other preparations.

Some top addresses are reserved by the OS, some bottom addresses contain the program itself, global variables, ..., and somewhere in the middle we can find dynamically linked libraries.

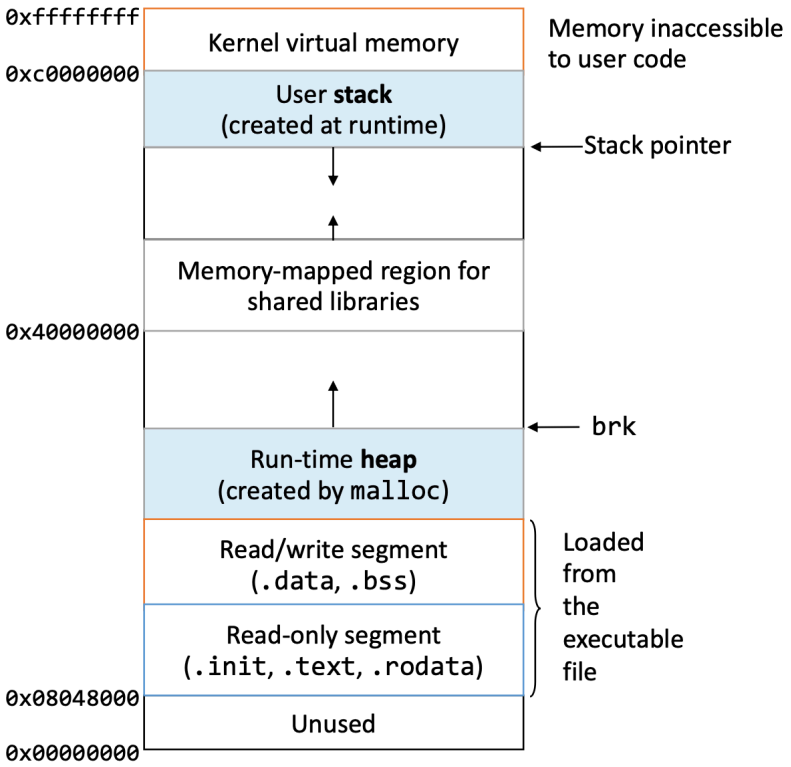


Figure 5: Program Memory Regions overview

In that order from low to high addresses:

- `.text`: executable code, i.e., the program
- `.rodata`: read-only data like string literals and constant values.
- `.data`: initialized global and static variables.
- `.bss`: uninitialized global and static variables (zeroed at startup)
- `.init`: initialization code for the program

Furthermore, we have the heap and stack. Those are common concepts used in many languages. In C, the stack is automatically managed (throught the compiler & OS), while we manually

need to put and remove elements on/from the heap. In assembly, the stack pointer is just increased to allocate on the stack and the OS then must ensure that those virtual addresses are properly mapped. On the other hand, the heap requires more programmer attention, because memory needs to be allocated and freed as disucssed later.

Stack Many languages such as C, C#, Java, Python, Rust, ... use a stack. It is used to store the state of each instantiation of functions/procedures (i.e., whatever is 'running'). This is used to support 'reentrant' code.

Memory on the stack is allocated by the program in frames. Each procedure/function uses a stack frame. They allocate memory but only need it for a limited amount of time: From when being called to returning. Stack discipline dictates how the stack is to be used by functions. This includes:

- where to put function parameters not fitting in registers
- alignment of the stack (usually 16 bytes ?)
- where the return address is stored (return instruction pointer)

The stack grows downwards. The lower end of the stack is called the top and identified by the stack pointer. The frame pointer points to the end of the current frame (i.e., the highest address of the current frame).

The stack pointer is initialized by the OS and then used by the program to grow the stack (by incrementing it). The OS randomly initializes the stack pointer for a program. This is a security feature to prevent unauthorized access and prevent overflow attacks by being able to predict where things will reside in memory. (We will look at those attacks later.) A consequence of this is: When printing memory locations of variables/pointers, those will vary between executions of the program, even if it did the same thing. Just because the base address of the stack pointer has been varied by the OS. Unfortunately, this also makes debugging more difficult. Such random initialization/address assignments also happen for shared library locations.

4.2 Pointers in C

A pointer is a type of variable in C, which stores the memory address of another variable. Given a variable, we can use the `&` operator to get the (virtual) address of that variable, i.e., the memory location of where the data of that variable is stored. In `printf()`, a pointer can be printed with `%p`. We can use `&` not only on variables, but also on functions and get the location of the function code in memory.

Listing 10: Pointers in C

```
int foo() {}
int x;
int a[2];
printf("x is at %p\n", &x);
printf("a[0] is at %p\n", &a[0]);
printf("foo is at %p\n", &foo);
```

Pointers are stored in special variables. We add an `*` to the type to indicate that we want to store a pointer to such a type. We may declare a pointer with `type *name;` and can also initialize it at the same time with `type *name = address;`.

The pointer type specifies what kind of data is stored at the memory location the pointer references. This is important for pointer arithmetic. If we write `void` for the type, we store a

pointer to an element of unknown type. But generally, we should always use typed pointers to have as much support from the compiler as possible to detect mistakes and have pointer arithmetic function properly. As the type, we may also user pointer types so that we specify pointers to pointers of values. We may nest arbitrarily.

Listing 11: Tricky C Pointer Declarations

```
int arr[3] = {2, 3, 4};
int *p = &arr[1];
int **dp = &p;

int *p // p is pointer to int
int *p[13] // p is array[13] of pointers to int
int *(p[13]) // p is array[13] of pointers to int
int **p // p is pointer to pointer to int
int (*p)[13] // p is pointer to array[13] of int
int *f() // f is function returning a pointer to int
int (*f)() // f is pointer to function returning int
int (*(*f())[13])() // f is function returning pointer to array
    [13] of pointers to functions returning int
int (*(*x[3])())[5] // x is array[3] of pointers to functions
    returning pointers to array[5] of ints
```

One may use (not in the exam, of course) https://cdecl.org to get a translation between English and C gibberish. The general scheme of understanding a declaration is to start at the name/innermost part and then always alternate between considering the next specification on the right and left.

When having a pointer (variable), we often need to get the value, which is located at the memory address, which is stored in the pointer. Doing so is called dereferencing and is done by putting a `*` in front of the variable name. Dereferencing a double/triple/... pointer works by putting multiple `*`.

Listing 12: Dereferencing Pointers in C

```
v = *pointer; // dereference a pointer
*pointer = value; // dereference and assign a pointer
```

Technically, a pointer just stores an 8 byte address (on a 64 bit system). So we can assign anything we want and try to dereference the contents of any variable (once casted to a pointer). Notice that when we try to access a memory location (by dereferencing a pointer with some random value/address), we usually get a (page) segmentation fault as the program may only access memory, which has been allocated. There are no checks where a pointer points do. We have to make sure it is a valid address or accept that our program will crash.

In many cases it is helpful to have a pointer value which is definitely invalid to indicate that some pointer is not set/known or similar. For that we may use the macro `NULL`. During preprocessing it is substituted with all zeros and any attempt to dereference `NULL` will result in a page segmentation fault. `typeof(NULL)` is `void **`.

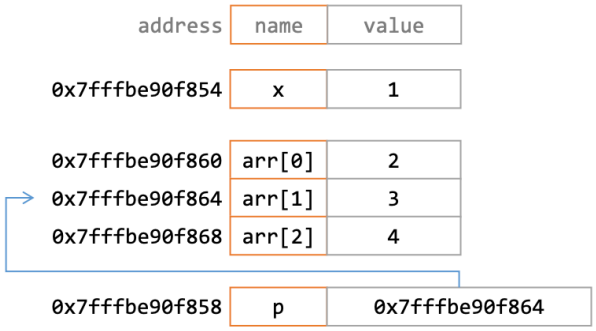


Figure 6: Box and Arrow Diagram to Visualize a Memory Layout

4.3 Pointer Arithmetic

Pointer arithmetic refers to doing addition etc. on pointers. When we do `*p += 1;`, we work on the dereference pointer, i.e., the value stored at the memory address contained in the pointer. But if we do `p += 1;`, we work on the pointer itself.

We already know that pointers are typed. When doing pointer arithmetic, the basic unit corresponds to the size of the type the pointer references. So, if we do `p += 1;` for `int *p`, we increase the address by 4 bytes as an integer is stored in 4 bytes. But if `p` were to reference a `char`, we would only increase by one byte as a char is stored in one byte.

So, pointer arithmetic internally works knowing the (bit-/byte-)size of different types. We can also manually get this size in C using `sizeof(...)`. As a parameter, we pass a type or a value/variable. This evaluates at compile time to the size of the parameter in bytes.

4.4 Arrays & Pointers

An array is a collection of homogeneous data elements stored at continuous memory addresses. Generally, an array is NOT a pointer - but we will see that it is mostly treated as one.

In expressions, an array is usually treated as a pointer to the first element of the array. But there are some exceptions: `sizeof(array)` provides the length of the array and `&array` returns the address of the array.

In fact, `A[i]` is always interpreted as `*(A+i)` by the compiler. The squared brackets `[]` don't do anything besides addition and dereferencing. So, instead of `a[5]` we may write `5[a]`. But because they are not truly pointers, assignments such as `array1 = array2` do not work, because `array1` is not an pointer and thus can't be assigned a pointer (what the `array2` in the expression is considered to be).

A special case is if we take an array as a function parameter. Then it is just special notation for taking a pointer. If 'array' is the parameter to a function, we can write 'array = array2;'. Getting 'array' as a parameter can be done in various ways.

Listing 13: Array as Parameter in C

```
1 int arrfun(int *array) {}
2 int arrfun(int array[]) {}
3 int arrfun(int array[43]) {}
```

But notice that `int arrfun(int (*array)[]){}` is different. Here we consider a pointer to an array. Thus, one must pass the array's pointer and do some more things adequately. Only then one can also assign. In the end, this is still a pointer and not a 'true' array.

Finally, pay attention to initialization. Depending on how an array is initialized (as an array or pointer) the content may be stored on the stack or in the `.data` section of memory. This is particularly relevant for strings.

Listing 14: String Initialization on Stack vs. in .data Section

```
char a[] = "Hello!"; // allocated on the stack
char *b = "Hello!"; // pointer allocated, points to .data
    segment (read-only)
```

4.5 Pass-by-Value/-Reference

In general, function arguments are passed by value in C, which means that the callee gets a copy of the argument. If the callee edits the parameters, it only edits values in its stack frame. But this does not have an impact on the caller's stack frame. Therefore, the callers variables remain unchanged.

When using pointers, we can enable pass-by-reference. The callee still receives a copy of the argument/variable. But now that copy is a pointer/memory address. And when dereferencing that address/pointer, one works on the original value in memory. Then, the callee can modify a variable in the scope of the caller (or even another scope or dynamic memory).

Listing 15: Pass-by-Value vs. Pass-by-Reference in C

```
// Pass-by-Value - this doesn't work as intended
void swapValue(int a, int b) { // we need to pass values when
    calling
  int tmp = a;
  a = b;
  b = tmp;
}
// Pass-by-Reference - this works as intended
void swapReference(int *a, int *b) { // we need to pass pointers
     when calling
  int tmp = *a;
  *a = *b;
  *b = tmp;
}
```

A real-world example of pass by reference is `strcpy`:

Listing 16: `strcpy` in C

```
char *strcpy(char *dest, char *src)
{
  char *r = dest;
  while(*dest++ = *src++);
  return r;
}
```

5 Dynamic Memory

When dealing with memory so far, we have considered statically and automatically allocated memory. The former are global variables, and static function member variables. They are allocated when the program is loaded in the `.data` section, and deallocated when the program exists. The latter are variables inside functions, which only exist in the scope of that function. They are allocated when the function is called and deallocated when the function returns. But this does not cover all use cases:

- We may want some variable/memory location to outlive the lifetime of a function but not live for the entire program duration (i.e., be global).
- Some complex data structure may be too large to fit on a stack. The stack is pre-allocated and its size of often determined at program startup.
- A function might want to return something of which the size is unknown during compilation. So it can't simply return the value.

The solution is to explicitly request memory locations, which can then be used to store large data, can be used until not longer needed/freed accross multiple functions, threads, etc., and can be passed around by means of pointers.

The program explicity requests a new block of memory, which is then allocated by the language runtime (with support by the OS). Dynamically allocated memory persists until it is explicitly deallocated by the program in C. In other languages a garbage collector might automate this task, but in C we have much more manual control (and need to exercise it).

The difficult thing is to allocate and mange (i.e. deallocate correctly) memory explicitly and manually. One needs to allocate the right amount of memory and then fill it with structured types. This involves tracking the allocated addresses so that one doesn't fill up memory with allocated blocks that the program forgot exist. More complex data structures can be and need to be built manually using pointers to allocated memory.

5.1 The C Memory API

The C memory API is declared in `stdlib.h`, which needs to be imported to be able to use the dynamic memory system explained in the following. In that header file, we also have the type definition of `size_t`. We will use `size_t` whenever referring to pointer indices or similar. It is an unsigned integer of some size, commonly an `unsigned long`. It is large enough to hold the size of the largest possible array in memory. We also have `ptrdiff_t`, which is less common, and used to store signed integers. It is common to store the result of subtracting two pointers in a `ptrdiff_t`.

5.1.1 malloc

`void *malloc(size_t sz)` is the function signature of the function to be used to allocate a block of memory on the heap of the given size, where `sz` refers to the number of bytes, i.e., the number of addresses to be allocated.

The function returns a pointer to the first byte of that memory, i.e., the lowest address of the allocated memory locations. If allocation failed, we get `NULL`. Before using a pointer from `malloc`, we should always make sure that it is not `NULL` and then cast it to the proper pointer type we intend to use the memory for. Also, there is no guarantee regarding the content of the allocated memory. We should assume there are garbage values.

When allocation memory, we need to specify how much memory we require. As already stated, the parameter specifies the number of bytes. A useful function to compute the number of required bytes is `sizeof(...)`, which is evaluated during compilation to the implementation defined byte size of passed variable/type.

Listing 17: Malloc Allocation

```
long *arr = (long *)malloc(10*sizeof(long));
if (arr == NULL) {
  return ERRCODE;
}
arr[0] = 5L;
// ...
```

5.1.2 calloc

`void *calloc(size_t m, size_t sz)` is the function signature of the function to be used to allocate blocks of memory of size $(\text{nm} \times \text{sz})$. The return behavior etc. is just as with malloc with one important difference: The memory is filled with zeros. Hence, this is also slightly slower than `malloc`.

Listing 18: Calloc Example

```
long *arr = (long *)calloc(10, sizeof(long));
if (arr == NULL) {
  return ERRCODE;
}
arr[0] = 5L;
// ...
```

5.1.3 free

Once we finished using memory we allocated with `malloc` or `calloc`, we should release it so that it can be used again. Otherwise, the OS and language runtime assume that it is still required and may fill the entire memory.

To free memory locations that have been allocated, we need a pointer to the first byte of the malloced/calloced memory, and then call `free(pointer)`. Some future malloc/calloc then might reuse that memory address. It is good practice to `NULL` the pointer afterwards so that we don't accidentally use the freed memory again.

Listing 19: Free Example

```
long *arr = (long *)calloc(10, sizeof(long));
if (arr == NULL)
{
  return ERRORCODE;
}
// Do something ...
free(arr);
arr = NULL;
```

5.1.4 realloc

Above, we allocated memory of a fixed size. But in some cases, we might want to extend our memory region (i.e., if we want to grow an array, for instance). For this purpose, we can use `void *realloc(void *ptr, size_t size)`. We must pass a pointer to the first byte in our memory block and our newly desired memory region size as the number of bytes.

Either, we get a pointer to some memory location, which has our newly requested size (and the content of the old location). Then, the original pointer is invalid. Or we get 'NULL' and couldn't get a larger memory region. Then, our original pointer is still invalid.

Listing 20: Realloc in C

```
long *arr;
if (!(arr = (long *)malloc(10*sizeof(long)))) {
  return ERRCODE;
}
// Do something ...
if (!(arr = (long *)realloc(arr, 20*sizeof(long)))) {
  return ERRCODE;
}
```

5.1.5 Example

Listing 21: Dynamic Memory Usage Example in C

```
#include <stdio.h>
#include <stdlib.h>
#define INIT_SIZE 8

int main(int argc, char *argv[]) {
  int num; // Num. of integers
  int *arr; // Array of ints.
  size_t sz; // Array size
  int m, in; // Index & input num

  // Allocate the initial space.
  sz = INIT_SIZE;
  arr = (int *)calloc(sz, sizeof(int));
  if (arr == NULL) {
    fprintf(stderr, "calloc failed.\n");
    exit(1);
  }

  // Read in the numbers.
  num = 0;
  while(scanf("%d", &in) == 1) {
    // See if there's room.
    if(num >= sz) {
      // There's not.  Get more.
      sz *= 2;
      arr = (int *)realloc(arr, sz*sizeof(int));
```

```
27        if(arr == NULL) {
28          fprintf(stderr, "realloc failed.\n");
29          exit(1);
30        }
31      }
32      // Store the number.
33      arr[num++] = in;
34    }
35    // Print out the numbers
36    for(m = 0; m < num; ++m) {
37      printf("%d\n", arr[m]);
38    }
39    free(arr);
40    return 0;
41  }
```

5.2 Managing the Heap

The heap, a large pool of memory/area of the virtual memory space, is where all the memory addresses acquired through dynamic memory allocation reside.

`malloc()` allocates chunks of memory in the heap, `free()` returns them. `malloc()` (must) maintain bookkeeping data in the heap to track allocated blocks so that (a) addresses are not allocated multiple times, (b) the size of an allocated region is known, ... We will consider the details of the implementation and bookkeeping data in the section on implementing dynamic memory allocation and management.

But already on the level using the specified memory API provided by C, we need to know what we are doing. Otherwise we may corrupt memory and cause our program to crash.

5.2.1 Memory Corruption

- assign past the end of an integer
- mess up pointer arithmetic by assigning unallocated pointers
- work with `void *` points (cast to a specific type whenever possible)
- assume `malloc` puts zeroes in memory
- pass pointer to `free` that wasn't malloced
- free memory address twice
- use a pointer on which we called `free`

Listing 22: How to Corrupt Memory in C

```
1  #include <stdio.h>
2  #include <stdlib.h>
3  int main(int argc, char **argv) {
4    int a[2];
5    int *b = malloc(2*sizeof(int)), *c;
6    a[2] = 5; // assign past the end of an array
7    b[0] += 2; // assume malloc zeroes out memory
```

```
  c = b+3; // mess up your pointer arithmetic
  free(&(a[0])); // pass pointer to free() that wasn't malloc'ed
  free(b);
  free(b); // double-free the same block
  b[0] = 5; // use a free()'d pointer
  return 0;
}
```

5.2.2 Memory Leaks

Memory leaks happen when our code doesn't deallocate allocated memory that is not used anymore. This does not impact correctness, but performance. The program's memory footprint will keep growing. This might:

- slow down the program over time due to virtual memory trashing (discussed later)
- use up all available memory and crash (need to allocate A LOT)
- might starve other programs of memory

5.3 Structures and Unions

5.3.1 struct

In C, a `struct` is a type that contains a set of fields. `struct`s don't have member functions but only contain fields, which are put contiguously in memory. Instances may be allocated on the stack or heap - depending on where they are used.

Listing 23: Structs in C

```
struct structNAme {
  type name;
  type2 name2;
  type3 anem3;
  ...
}
struct Point {
  int x;
  int y;
}
```

To access a field of a struct we use `.` after the variable name followed by the field name. When working with a pointer to a struct, we would write `(*pointer).fieldName`. A shorter notation for that is `pointer->fieldName`.

Listing 24: Accessing Structs

```
int main(int argc, char **argv) {
  struct Point origin = { 0, 0 };
  struct Point *origin_ptr = &origin;
  origin.x = 1;
  origin_ptr->y = 2;
  return 0;
}
```

When assigning one struct to another struct, we assign by copying every field from one to the other struct. When passing as parameters, structs are also passed by value (as everything in C). When we want to pass a reference, we need to pass a pointer to the struct.

A struct is aligned in memory by the size of its largest element. And inside the struct, each element is aligned according to its size. Because the elements are in memory in the specified order, the compiler may add padding in between values and at the end.

5.3.2 union

A `union` is similar to a `struct` by defining a set of fields. But other than a `struct`, it only holds one of those values at a time. The memory allocated (and memory alignment) for a `union` corresponds to its largest field and we can access any of a `union`'s fields without checks for what is currently stored in the memory location.

Access to the fields of a `union` works just as for a `struct`.

Listing 25: Unions in C

```
union unionName {
  type name;
  type2 name2;
  type3 name3;
  ...
}
union u {
  int ival;
  float fval;
  char *sval;
}
union u my_uval;
```

5.4 Type Definitions

With `typedef` we can define a new type. Specifically, we create a new name for a type (which may be a combination of various other types, pointers, arrays, functions). After declaring a new type, we can use the new name interchangeably with the original expression. We use typedef like this: `typedef actualType newNameForThatType`.

This is particularly often used with `struct`s and `union`s.

Listing 26: `typedef` in C

```
typedef unsigned uint32_t;
uint32_t ui;
typedef int **myptr;
int *p;
myptr mp = &p;
typedef struct skbuf skbuf_t;
skbuf_t *sptr;

// instead of:
int (*(*x[3])())[5];
// we may do:
typedef int fiveints[5];
```

```
typedef fiveints* p5i;
typedef p5i (*f_of_p5is)();
f_of_p5is x[3];
```

Listing 27: `typedef` with `struct`s and `union`s

```
// option 1
struct list_el {
  unsigned long val;
  struct list_el *next;
};
typedef struct list_el el_t;
struct list_el my_list;
el_t my_other_list;

// option 2
typedef struct list_el {
  unsigned long val;
  struct list_el *next;
} el_t;
struct list_el my_list;
el_t my_other_list;
```

5.5 Dynamic Data Structures

Using pointers and dynamically allocated memory, we can manually build data structures, which are often provided in other languages. We will consider a singly linked list as an example here.

5.5.1 Fixed Data Types

Listing 28: `int` Linked List in C - only pushable

```
#include <stdio.h>
#include <stdlib.h>
#include <assert.h>
struct node {
  int element;
  struct node *next;
};
struct node *Push(struct node *head, int e) {
  struct node *n = (struct node *)malloc(sizeof(struct node));
  assert(n != NULL);  // crashes if false
  n->element = e;
  n->next = head;
  return n;
}
int basicMain(int argc, char **argv) {
  struct node n1, n2;
  n1.element = 1;
  n1.next = &n2;
```

```
  n2.element = 2;
  n2.next = NULL;
  return 0;
}
int pushMain(int argc, char **argv) {
  struct node *list = NULL;
  list = Push(list, 1);
  list = Push(list, 2);
  return 0;
}
```

5.5.2 Generics

Listing 29: Generic Linked List in C - only pushable

```
#include <stdio.h>
#include <stdlib.h>
#include <assert.h>
struct node {
  void *element;
  struct node *next;
};
struct node *Push(struct node *head, void *e) {
  struct node *n = (struct node *)malloc(sizeof(struct node));
  assert(n != NULL); // crashes if false
  n->element = e;
  n->next = head;
  return n;
}
int main(int argc, char **argv) {
  char *hello = "Hi there!";
  char *goodbye = "Bye bye.";
  struct node *list = NULL;
  list = Push(list, (void *) hello);
  list = Push(list, (void *) goodbye);
  return 0;
}
```

6 Implementing Dynamic Memory Allocation

We have used `malloc`, `calloc`, and `free` to allocate and free memory. But how do we end up to get a pointer to a memory address? What processes happen to assign memory, make sure that it isn't used otherwise, we free exactly the right amount of memory when calling `free`, ...?

Memory allocation is a process that happens jointly between the virtual memory hardware and kernel software. On the abstraction level of the OS, one deals with pages, which can be multiple KB large. But application objects (structs, arrays, ...) are typically smaller. Hence, one needs to manage to allocate pages and then assign and distribute memory blocks in pages upon calls to `malloc`. (A block is here understood as a continuous range of bytes in memory.)

The program/application requests some number of bytes of memory. The dynamic memory allocator manages and allocates pages if necessary. In other words, this makes the abstraction between the actual heap memory and us calling 'malloc' etc.

In C, memory management means that we allocate memory from some page explicitly when `malloc` is called and only free that memory when `free` is called. In other languages that is different. If languages have garbage collection, the garbage collector can free memory as soon as some memory location/object becomes unreachable. And in languages such as Rust, the compiler generates the free automatically by analyzing the program and requiring the programmer to specify some additional information for variables/use specific programming paradigms.

6.1 The Challenge

Consider the heap, from which `malloc` etc. take addresses, as just one large chunk of memory. We have several properties that implementations of the Memory API should meet for calls in arbitrary order to `malloc`, `calloc`, `realloc`, and `free` (only when freeable):

- must respond immediately to `malloc` requests
- can't control the number or size of allocated blocks
- must allocate memory blocks from free memory
- must align blocks so that they satisfy all alignment requirements (commonly, 8 byte alignment – may require to add padding)
- an only manipulate and modify free memory
- can't move allocated blocks

Besides those properties that are relevant to the user, there are also some apparent challenges that must be solved as problems internal to the implementation:

- How does the dynamic memory allocator know how much memory to free when given only a pointer to the first byte of the block?
- How do we keep track of free blocks to distribute them to `malloc` requests?
- How do we handle space that is not needed, i.e., when allocating a block that does not cover the entire free block is placed in?
- How to we pick a free block for allocation? There may be multiple that fit?
- How to we technically free a block?

The Goal Any implementation (that must adhere to the before mentioned properties) aspires to provide high performance and peak memory utilization. Lets consider a sequence of n memory requests $R_0, R_1, \ldots, R_k, \ldots, R_{n-1}$. Performance can clearly be understood as the number of completed memory requests per unit time. Peak memory utilization is more difficult to understand and we must introduce some definitions for it. When calling `malloc(p)`, a block with a payload of p bytes is allocated. the *aggregate payload* P_k is the sum of currently allocated payloads after request R_k has been completed. And as stated earlier, all those blocks are put on the heap. The heap grows by the implementation requesting additional pages from the OS with `sbrk()`. The *current heap size* H_k is the current and nondecreasing size of the heap as the size of all pages requested from the OS. Then: Peak memory utilization after k requests is $U_k = \frac{\max_{i<k} P_i}{H_k}$.

Ideally, we would have U_k but that is not possible in practice, because we need to add meta data and have fragmentation.

Meta-data is necessary to store where the blocks are located, which memory addresses are currently allocated and which are free, what is the size of the allocated blocks, ... The meta-data (including the length of the allocated word) is usually put in memory right before the data. That is called the header/header file. It takes up memory but does not count towards the payload data. Furthermore, we often also store similar information after the payload in a footer. We will see later why that is done.

Fragmentation describes that some memory also remains unused. For instance, we might have to add padding to guarantee alignment. Or we have free regions of memory but the to be allocated block is too large to fit and we must request a new page despite having free regions.

6.1.1 Internal Fragmentation

The request `malloc(p)` actually allocates more than p bytes of memory. It allocates some memory for a header, some memory for a footer, and in-between there are the p‘ bytes for the payload. This has already been stated before. The header/footer are necessary (and useful) to maintain the heap data structure.

However, additionally, we might add padding if the head, footer, and payload do not cover the entire addresses, which are connected by the alignment requirements. So, internal fragmentation is caused by the dynamic memory allocator - specifically, when it allocates more memory than requested.

We say that the internal fragmentation only depends on the pattern of previous requests. Thus it is comparatively easy to measure.

6.1.2 External Fragmentation

External fragmentation occurs when there is enough aggregated heap memory but no single free block is large enough to cover our `malloc` request. Then, we (may) have to request a new page and leave memory free in the existing pages. Because we can’t modify pointers we returned earlier, we can’t move the allocated blocks to a different location to reduce external fragmentation.

6.2 Keeping Track of Free Blocks

There are 4 common methods to keep track of free blocks. We will consider those below. But first, we need to discuss a technique used in multiple of those methods to reduce external fragmentation. It iss called coalescing.

Coalescing It may be helpful to read the part on implicit free list until coalescing is mentioned to best understand how this is relevant.

The idea of coalescing is that if we free a block and there is/are free blocks before/after, that we join (coalesce) them instead of introducing false fragmentation.

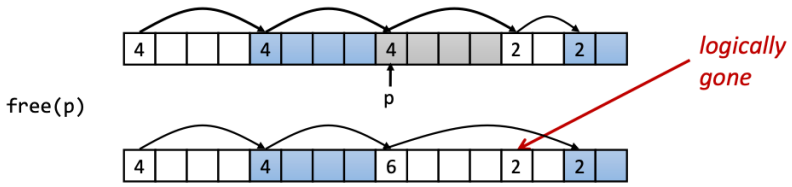


Figure 7: Coalescing

Listing 30: Coalesce with the next Block

```
1 void free_block_after(ptr p) {
2   *p = *p & -2; // clear allocated flag
3   next = p + *p; // find next block
4   if ((*next & 1) == 0) {
5     *p = *p + *next; // add to this block if not allocated
6   }
7 }
```

To enable bidirectional coalescing we utilize the footer, which we already mentioned earlier. In case of the implicit free list it also stores the size and is-allocated flag and comes at the end of the memory block. This allows us to traverse the list backwards but also requires extra space.

Coalescing takes constant time. This becomes apparent when considering the four possible cases:

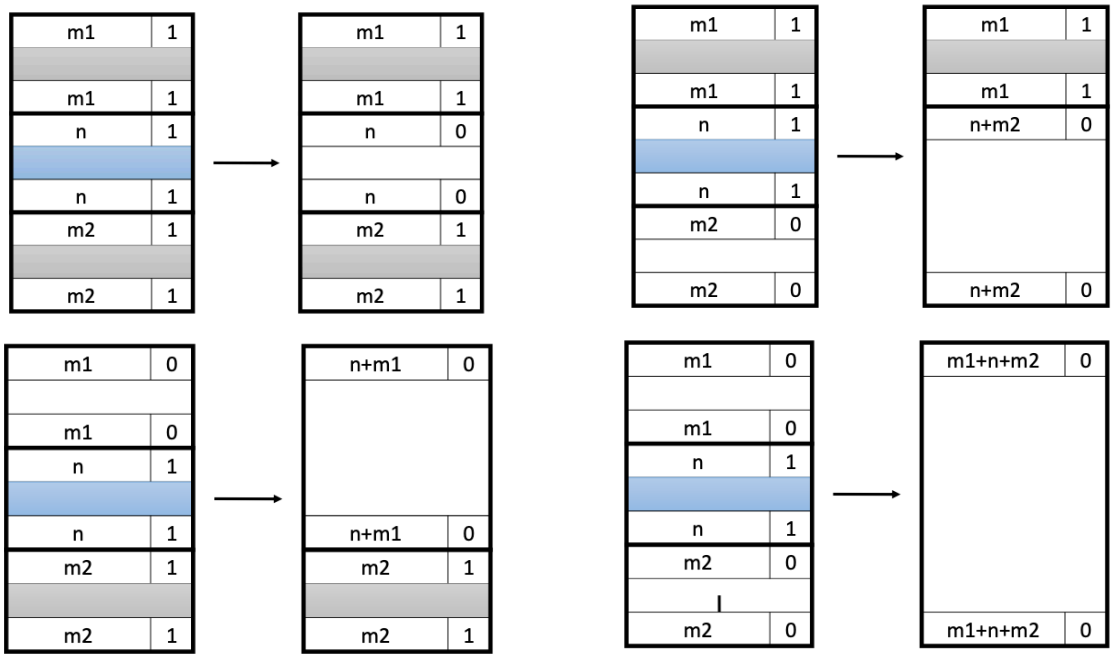


Figure 8: Four Cases of Coalescing

Another interesting question is to decide when to coalesce. This is referred to as the coalescing policy. Immediate coalescing: Coalesces each time ‘free‘ is called. Deferred coalescing: This improves the performance of ‘free‘ by deferring coalescing until needed (possibly when ‘malloc‘ is called, or when external fragmentation reaches some threshold).

6.2.1 Implicit Free List

For each block we store its length (including the header, footer, etc.) and whether it is currently allocated or not. Usually, memory blocks are aligned, so some lower-order address bits are always 0. Hence, we can just use the least significant bit to store the is-allocated flag.

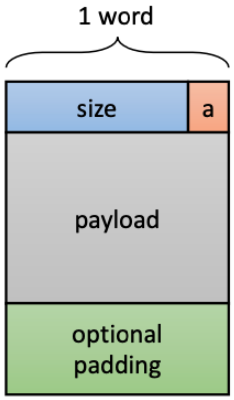


Figure 9: Implicit Free List Memory Block (Header only)

When the payload is required to adhere to some alignment, we must make sure that the header is put before the alignment requirement so that the payload and not the entire used memory region starts at the aligned address.

Summary:

- simple implementation
- linear time worst case allocate coast
- constant time worst case free cost (event with coalescing)
- memory usage depends on the placement policy

Because of the linear time complexity, this is only used in special purpose applications.

Finding a Free Block / Placement Policies There are multiple approaches to finding a free block in such a list. Fundamentally, we must iterate over the list and can access subsequent blocks by jumping size bits to the next block. We must always mask out the is-allocated flag bit.

With first fit, we search the list from the beginning and choose the first free block that fits. This can take linear time in the total number of blocks (allocated and free). The following code snippet does not take care of requesting a new page from the OS if space is not sufficient.

Listing 31: Implicit Free List - Frist Fit

```
1 p = start;
2 while ((p < end) && \\ not passed end
3   ((*p & 1) ||\\ already allocated
```

```
4   (*p <= len))) { \\ too small
5     p = p + (*p & -2);
6     \\ goto next block (word addressed)
7 }
```

With next fit, we start where the previous search finished. This should be faster than first fit, because we avoid re-scanning unhelpful blocks. But research suggests that fragmentation is worse (as we tend to allocate new pages quicker).

With best fit, we iterate over the entire list and choose he best free block, i.e., the block that fits with the fewest bytes left over. This reduces fragmentation but runs slower as we iterate the entire list instead of likely stopping early.

Allocating in a Free Block / Splitting When having found a suitable block, it might very well be that the block is larger than the actually required and to be allocated space. In such a case, we may want to split the block so that the unused parts can be allocated by another `malloc` call. The decision of how much internal fragmentation we intend to allow as the result of splitting is referred to as the splitting policy.

Listing 32: Example Splitting / Adding Implementation

```
1 void addblock(ptr p, int len) {
2   int newsize=((len+1)>>1)<<1; // round up to even - assumes len
        covers payload and header
3   int oldsize = *p & -2; // mask out low bit
4   *p = newsize | 1; // set new length
5   if (newsize < oldsize) {
6     *(p+newsize) = oldsize - newsize; // set length in remaining
          part of block
7   }
8 }
```

Freeing a Block In the simplest implementation we only need to clear the is-allocated flag with `void free_block(ptr p){ *p = *p & -2 }`. But this can lead to what we call false fragmentation. Instead, we do coalescing as explained at the beginning of this subsection.

6.2.2 Explicit Free List

Here, we introduce an explicit list of only all free blocks and not all free and allocated blocks. Because the next free block could be anywhere in memory, we have to store forward/backward pointer for a doubly-linked list. We still need the boundary tags (header and footer) for coalescing. So the question rises where we store the next and prev pointers. Remember that the block is free, so there is no payload. But there are bytes available for a payload due to alignment.

Summary:

- Allocation is in linear time in the number of free blocks (in comparison to all blocks a before). This is much faster when the memory is (almost) full.
- More complicated allocate and free (need to edit the list).
- Additional memory/space needed for the links (does not increase fragmentation if alignment already coarse enough).

Figure 10: Explicit Free List - Allocated

Figure 11: Explicit Free List - Free

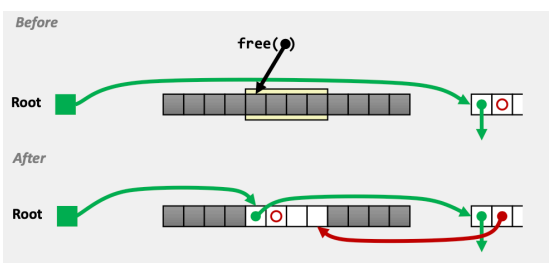
Allocating Memory & Placement Policy Allocating memory includes finding a large enough-free block through the explicit free list and then redirecting the list pointers. This means either removing one element or redirecting the pointers to some late part of the current block if we do splitting.

Insertion Policy An insertion policy defines where we insert a free block into the explicit free list.

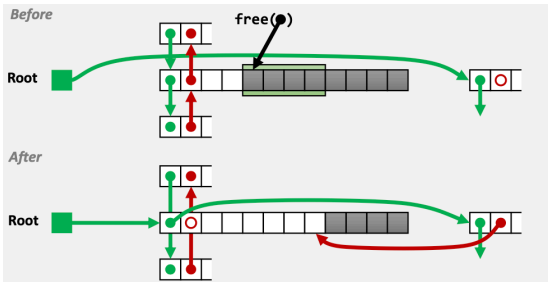
With the last-in-first-out (LIFO) policy we insert a freed block at the beginning of the free list. This is simple to implement and works in constant time. But studies suggests that this has worse external fragmentation.

With the address-ordered policy we insert freed blocks so that the free list's blocks are always in address order. Studies suggests that this has lower fragmentation. But it comes at the cost of having to search for the corresponding place in the free list.

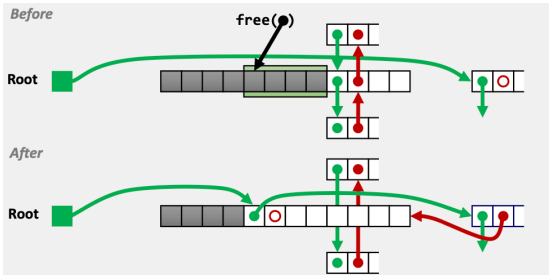
The following demonstrates how the LIFO policy looks with coalescing.



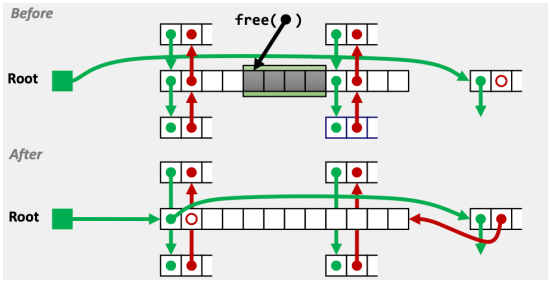
Case 1



Case 2



Case 3



Case 4

Figure 12: Explicit Free List coalescing

6.2.3 Segregated Free List

This is an extension of the explicit free list. Instead of maintaining one list, we now maintain separate lists for different sizes of blocks. Thus, we can spend less time searching for a block. The asymptotic runtime is still unchanged, but the real-world constants are much lower as we can skip all small free blocks caused by excessive external fragmentation.

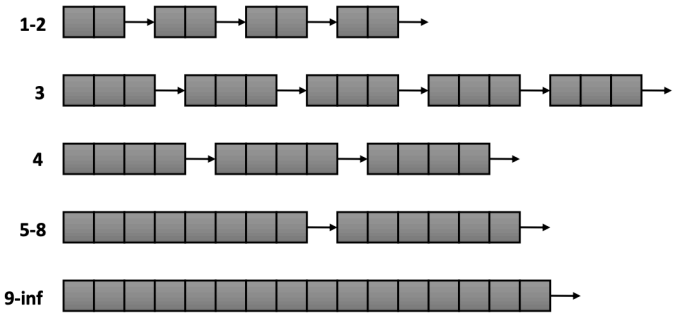


Figure 13: Segregated Free Lists

The advantage of seglists is higher throughput and better memory utilization. It can be understood as a more efficient approximation of best-fit placement.

Segregated Free List Allocator To allocate a block of size n, we search the appropriate (i.e. first one with available blocks) free list for block of size $m \geq n$. If no block is available across all lists, one has to request additional heap memory from the OS using the system call `sbrk()`.

Freeing a Block To free a block one can coalesce and then integrate the new free block into the suitable list.

6.3 Garbage Collection

So far we considered explicit memory collection. Garbage collection is available in many modern object oriented programming languages such as Java, Perl, Mathematica etc. In C and C++ only some conservative garbage collectors exist. But they are not part of the standard language and we don't use them. With garbage collection, instead of manually calling `free(...)`, the system should automatically detect that the memory is unreferenced and free it.

Garbage Collectors need to know which memory can be freed. But in general what is used or not depends on conditionals, which we don't know yet. Still, an implicit memory management system can be sure that some memory location isn't needed anymore as soon as there is not pointer referencing it, because the program can't work with that location afterwards.

For this to work we need to make some assumptions regarding pointers. Those are not guaranteed in C, hence, garbage collection is not part of C.

- memory manager can distinguish pointers from non-pointers (only possible in C when sticking to good-practices)
- cannot hide pointers (can store pointers in 'int'/'long' in C, for example)
- all pointers point to the start of a block (not-guaranteed in C)

Classical GC algorithms are: mark-and-sweep collection (1960), reference counting (1960), copying collection (1963), and generational collectors (1983).

6.3.1 Garbage Collection Algorithms

6.3.2 Memory as a Graph

Most GC algorithms consider memory (locations) as a graph. Blocks in memory are nodes. We have a pool of nodes on the stack (root nodes). Directed edges correspond to references to some location. All unreachable nodes, which are not on the stack (or .data segment) can be freed.

6.3.3 Mark and Sweep Collection

This always allocates new memory when ‘malloc‘ is called. Only when the program runs out of memory, the program is halted and the GC runs. The GC uses an extra mark bit in the head of each block. It starts at each root node in the graph and sets the mark bit on it and each reachable block. Afterwards, the GC sweeps all blocks and frees all those which are not marked.

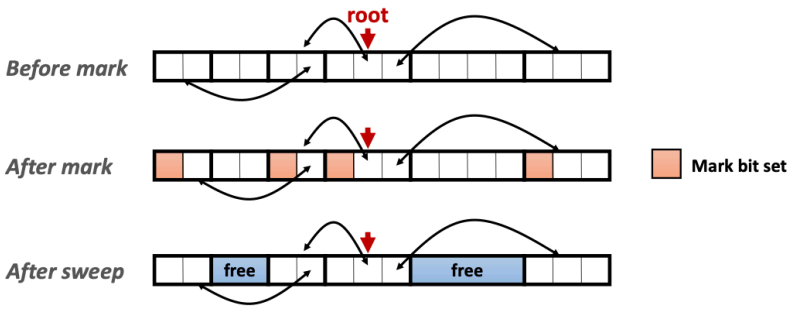


Figure 14: Mark and Sweep Collection

Listing 33: Mark and Sweep Code Idea

```
ptr mark(ptr p) {
  if (!is_ptr(p)) return; // do nothing if not pointer
  if (markBitSet(p)) return; // check if already marked
   setMarkBit(p); // set the mark bit
  for (i=0; i < length(p); i++) { // call mark on all words
    mark(p[i]); //   in the block
  }
  return;
}
ptr sweep(ptr p, ptr end) {
  while (p < end) {
    if markBitSet(p) {
      clearMarkBit();
    } else if (allocateBitSet(p)) {
      free(p);
    }
    p += length(p);
  }
}
```

Here it is specifically important that the assumptions regarding pointers stated earlier are made, including that pointers always point to the beginning of a block. This is not guaranteed in C. So

instead of 'conservative garbage collection' we can maintain a balanced-tree of pointers, ordered by their size. Then, we can easily find the beginning of the allocated block for some pointer.

6.4 Memory Pitfalls

This repeats some common pitfalls with memory. We already outlined some/many of those in the preceding sections.

Dereferencing bad Pointers Now we understand why this is troublesome. We just don't know if the location has been allocated at all. If it hasn't been we likely get a page segmentation fault as we don't have access to that address. And if it has been allocated by chance the next pitfall applies.

Reading uninitialized Memory In many high-level languages any data will be initialized to zero for us. Not in C. This has the consequence that we would ready whatever has been in that location last. And that likely seems as complete nonsense.

Overwriting Memory If we allocate memory we must make sure that we allocate enough memory. Otherwise it may happen that we exceed the allocated memory with an access or write. That could result in corrupting the heap data structure and other data. This pitfall commonly occurs when...

- allocating memory for a single element and then treating the pointer as an array.
- working with off-by one errors
- writing to string pointers and exceeding their allocated memory
- forgetting that pointer arithmetics behaves differently depending on the pointer type

Referencing nonexistent Variables This commonly occurs when returning a pointer to a variable which has been allocated on the stack. This memory location won't be available later and and accessing it may be an error, corrupt other data, etc.

Freeing Blocks multiple Times The `free` function does the procedure considered above (and may include coalescing). This is troublesome if the meaning of the data in the location of the specified pointer does not correspond to what the `free` function excepts. Its behavior is unpredictable then.

Referencing Freed Blocks Referencing freed block corresponds basically to Dereferencing bad pointers and/or Reading uninitialized memory.

Failing to free Blocks Well, this results in memory leaks. In the long run those will render our program and system overwhelmed and irresponsive. In any case, we will encounter virtual memory trashing and very bad performance.

6.5 Finding Memory Bugs

Because the memory systems is so intricate and there are little to no guarantees/help from the OS/compiler to avoid mistakes, even minor mistakes can be destructive. Finding those small mistakes is surprisingly hard. But there are some tools that can help us.

- **gdb**: This is the conventional C debugger. It can be used to find bad pointer dereferences but helps little with finding other memory bug.
- **UToronto CSRI malloc**: This is a wrapper for ‘malloc‘. It detects memory bugs at ‘malloc‘ and ‘free‘ boundaries such as heap structure corrupting writes, memory writes, and maybe freeing blocks multiple times. But it cannot detect overwriting data in the middle of allocated blocks.
- **valgrind**: This is a powerful debugging and analysis technique. It works by rewriting the text section (i.e., the actual code) of executable object files. By doing so it can help to detect:
  - all errors already mentioned with before mentioned techniques
  - bad pointers (at runtime)
  - overwriting (at runtime)
  - referencing outside of allocated blocks (at runtime)

  Valgrind manages a separate memory area to keep track of our memory usage by adding code to our program. Thus, it enables some sort of runtime environment to track errors and problems.

7 Some More C

7.1 Function Pointers

As their name suggests, function pointers are pointer who point to the location of where some function resides in memory. Hence, one can call a function pointer to change the program counter to that address to execute said function. A function pointer is a pointer just as any pointer and, hence, needs to have a type: `returnType (*name)(param1Type, param2Type);`. We can use this with `typedef` just as any other type.

When adding function pointers as variables to a `struct`, we can achieve something similar to the concept of member variables in OO programming languages. However, we have no protection, visibility, or other convenience features. Also, we still need to define the function somewhere.

7.2 The C Preprocessor

Now, we talk about a specific part of the C toolchain again: The preprocessor. Its executable is called `cpp`. We can execute the preprocessor either with that executable or by adding the `-E` flag to `gcc`: `gcc -E foo.c`.

The C processor goes over a C file before compilation and does basic text modifications/substitutions to it. A command for the preprocessor starts with `#`.

7.2.1 #include

An include statements can have two forms:

- `#include <file1.h>`: This includes system headers. The preprocessor looks in predefined system folders.
- `#include "file1.h"`: This includes custom/one's own headers. The preprocessor looks in the current folder.

What happens is that the preprocessor takes the content of the to be included file and replaces the `#include ...` with the contents of that file. So one may also include the same file twice via nested includes, which will most likely cause a compilation error. Avoiding double includes can be done with macros.

7.2.2 Macros

This enables token-based text substitution. We define a macro with `#define NAME SUBSTITUTION`. After a `#define ...`, every occurrence of `NAME` will be replaced with `SUBSTITUTION`. With `#undef NAME` we can stop the effect.

Also, we can do more complex and parameterized replacements: `#define BAR(x)(x+3)`. When writing `BAR(y)` somewhere after the `define`, it will substituted with `(y+3)`. Notice that NO evaluation happens. This is simply text substitution.

When wanting to insert a full statement, consider the use of `;`. Macros are no statements, so they don't need a `;`. If one adds one, there might end up being two. To be able to write a `;` after a macro one has to omit the `;` in the substitution. Furthermore, macros can be written across multiple lines for convenience and readability. To do so, one has to add a backslash `\` at the end a line to continue with the next line. By using those features, one can build large macros.

Listing 34: Macros Examples

```
1 // without ;
```

```
#define SKIP_SPACES(p, limit)     \
  { char *lim = (limit);         \
    while (p < lim) {           \
      if (*p++ != ' ') {       \
      p--; break; }}}
SKIP_SPACES(p, limit)
// with ;
#define SKIP_SPACES(p, limit)      \
  do { char *lim = (limit);       \
    while (p < lim) {           \
      if (*p++ != ' ') {       \
      p--; break; }}}    \
  while (0)
SKIP_SPACES(p, limit);
```

Stringizing, Concatenation When considering macros with parameters, we may either want to paste the parameters directly, be attached in other expressions without spaces or be represented as strings. To paste them directly, we just use them separated from other text and get substitution. But if they are not separated, i.e., the parameter `c` appears in `c_command` in the substitution, the `c_command` will not be modified. Similarly, the `c` in `"c"` won't be substituted.

We use `#c` to get the string of the text of `c`, i.e., `"c"` and `##` to concatenate after substitution, i.e., remove the spaces on both sides of the `##`.

Listing 35: Stringizing and Concatenation with Macros

```
#define COMMAND(c) { #c, c ## _command }
COMMAND(quit) // is equivalent to:
{ "quit", quit_command }
#undef COMMAND
#define COMMAND(c) { "c", c_command }
COMMAND(quit) // is equivalent to:
{ "c", c_command }
```

Predefined Macros The preprocessor has many predefined macros. Among those are:

- `__FILE__`: the name of the file being processed
- `__LINE__`: the line number of this usage of the macro
- `__DATE__`: the date when the preprocessor is running
- `__TIME__`: the time at which the preprocessor is being run
- `__STDC__`: defined if this is an ANSI standard C compiler
- `__STDC_VERSION__`: the version of the standard C being compiled
- ...

7.2.3 Conditionals

We can also use `#if`, `#else`, `#endif`, `#ifdef`, `#ifndef`, ... to conditionally (not) remove sections from our file. The conditions need to use only things defined for the preprocessor with `#define ...` as this happens even before compile-time and we don't know about program values yet. `#ifdef FOO` und `#ifndef BAR` are shorthand notations for `#if defined(FOO)` and `#if !defined(BAR)`.

Listing 36: C Preprocessor Conditionals

```
#if expression
... (text1)
#else
... (text2)
#endif

#ifdef FOO
... (text1)
#else
... (text2)
#endif

#ifndef BAR
... (text1)
#else
... (text2)
#endif
```

7.3 Assertions

A statement 'assert(¡scalar expression¿);' evaluates the expression at run time. If it is true the statement does nothing. If it is false, it prints the file, line, and expression, which failed and aborts execution. We need to include `#include <assert.h>` to use `assert(...);`.

`assert` statements are basically macros, because they are turned into code which actually achieves the just mentioned behavior at compile-time. But they are still evaluated at run-time. We can also add the compiler flag `-DNDEBUG` to remove all `asserts` during compilation. We would do so because they have no benefit for the user but slightly decrease runtime. The primary purpose is to support debugging for the developer.

Listing 37: Assertions Example

```
void array_copy(int a[], int b[], size_t count) {
  int i;
    assert(a != NULL);
    assert(b != NULL);
    for(i=0; i<count; i++) {
    a[i] = b[i];
  }
}
```

7.4 Modularity

In C, we achieve modularity with header `.h` files. But first, we need to distinguish declaration and definition. We already know about forward declaration. Thus, we basically understood what a declaration is: It states that something exists somewhere, and declares how it looks, i.e., specifies its signature. But only the definition says what it actually is/does.

Listing 38: Declaration vs. Definition in C

```
// declaration
char *strncpy(char *dest, const char *src, size_t n);
// definition
char *strncpy(char *dest, const char *src, size_t n)
{
  size_t i;
  for (i = 0; i < n && src[i] != '\0'; i++)
  {
    dest[i] = src[i];
    }
  for ( ; i < n; i++)
  {
    dest[i] = '\0';
  }
    return dest;
}
```

During compilation, C deals with compilation units. A compilation unit is a `.c` file and everything it includes, i.e., the file after preprocessing. For declarations we have two annotation options:

- `extern`: the definition is either in this compilation unit or somewhere else (default)
- `static`: the definition is in this compilation unit and can't be seen outside

So, how does this help us with modularity in C? A module is a self-contained piece of a larger program. It consists of...

- externally visible stuff: functions, typedefs, global variables, cpp macros, ... (the client should/can use this)
- internal stuff: functions, types, variables, ... (the client should not look at this)

The externally visible stuff is called the module's interface. In C, we specify such interfaces with header files.

Some module `foo` has its interface defined in `foo.h` via declarations for the externally visible stuff. Clients in foo then `#include "foo.h"` to know about what `foo` can do. But `foo.h` does not provide and definitions. The definitions and only internally visible declarations are defined in the `foo.c` file.

Listing 39: Avoiding Including `.h` Files Multiple Times

```
#ifndef __FILE_H_ // __FILE_H_ if chosen uniquely for each
   header file
#define __FILE_H_
...
#endif
```

7.5 goto

The `goto` statement was dominant in very early programming. However, today it is almost never a good idea to use it. On the one hand, there is little/no performance gain to other programming constructs. On the other hand, it makes code very confusing and difficult to understand. Still, there certain cases where `goto` is helpful.

7.5.1 Early Termination of Nested Loops

When having nested loops, other languages offer labels to break some outer loop. We don't have this option in C. Instead, we would have to set some flag variable and then also break the outer loop if that flag is set. But this is cumbersome. Instead we can jump out directly with a `goto` statement.

```
// cumbersome version without goto
int a[MAXROW][MAXCOL]
int i,j;
bool found=false;
for(i=0; i< MAXROW; i++) {
  for(j=0; j < MAXCOL; j++) {
    if (a[i][j] == 0) {
      found=true;
      break;
    }
  }
  if (found)
    break;
}
if (found) {
  <do processing on i and j>
} else {
  <do processing when not found>
}

// improved with goto
int a[MAXROW][MAXCOL]
int i,j;
for(i=0; i< MAXROW; i++) {
  for(j=0; j < MAXCOL; j++) {
    if (a[i][j] == 0) {
      goto found;
    }
  }
}
<do some processing when not found>
found:
<do some processing on i and j>
```

7.5.2 Nested Cleanup Code

Consider the case where we have a sequence of operations. And if any one of them fails, we need to undo al the previous steps. This might happen if some operation on a data structure fails and we don't want to corrupt it. Or if we allocate memory in multiple steps and want to free what we allocated in earlier steps if one allocation fails.

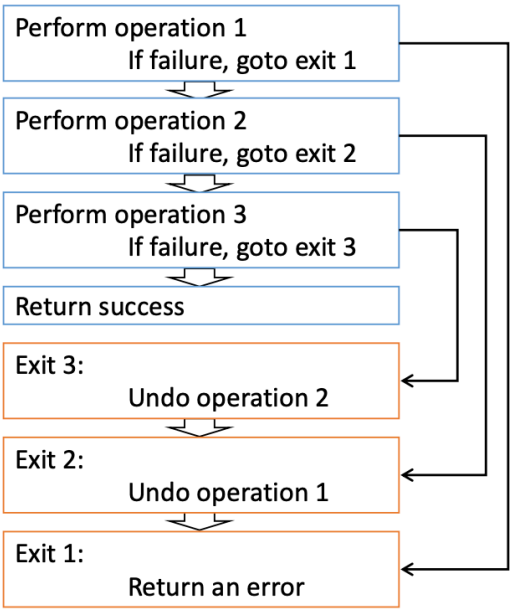


Figure 15: Nested Cleanup with goto

8 Basic x86 Architecture

8.1 Instruction Set Architectures (ISAs)

When talking about architecture, we mostly refer to the Instruction Set Architecture (ISA). It is the part of the processor design that one needs to understand to write assembly code for the processor. It is the 'contract' between the processor manufacturer and the programmer/compiler. ISAs specify the set of instructions, available register, addressing modes, data formats for processing units, etc. Some ISAs are: x86, RISC-V, MIPS, ia64, VAX, Alpha, ARM, ...

A microarchitecture, on the other hand, is a specific implementation of the ISA. The uarch then defines some aspects, which the developer/compiler doesn't need to know to create correct programs. Such as the cache size, core frequency, etc.

There have been various ISAs in the past. IBM S/360 has been the first to adapt the just described separation between ISA and uarch. When writing C programs, knowing the ISA is sufficient to write correct code. However, considering the uarch unlocks additional opportunity for performance optimizations.

ISA is a form of abstraction for the programmer. It specifies the instructions and assembly language to create programs for uarchs that implement this ISA. How the computer works looks different, depending on the abstraction layer.

- Above the ISA: This is about how to program the machine.

  We see a processor state as registers, memory, ... We can use instructions (`addl`, `movq`, `leal`, ...), which are presented in bytes to the processor to modify the state. Instructions appear to execute in-order.

- Below the ISA: This consider what needs to be built to execute programs.

  Doesn't need to conform to sequential instruction execution or any other requirement of the ISA as long as it appears it does. Code may be executed out-of-order. There may be more/different registers than the ISA specifies, which are, however, not modifiable by the program.

8.1.1 Complex Instruction Set Computer (CISC)

This was dominant throughout the mid-80s. The basic philosophy was: Add instructions to perform 'typical' programming tasks. So if some complex operation was common, one would usually introduce an instruction to cover this complex task with one instruction. Some characteristics:

- stack-oriented instruction set (pass arguments and return pointer via stack, explicit push/pop instructions)
- arithmetic instructions can access memory (complex address calculation)
- condition codes ('memorize' side effects of arithmetic and logical instructions)

8.1.2 Reduced Instruction Set computer (RISC)

This was popularized at Stanford and Berkeley as folks started to challenge the idea of adding instructions for everything and having very complex systems. Instead, they opted for fewer, simpler instructions. One usually needs more instructions to get things done, but instructions can also be executed faster and with simpler hardware. Some characteristics:

- register-oriented instruction set (more registers, used for arguments/return pointers/temporaries/...)
- load-store architecture (memory access separated with specific instructions)
- no condition codes
- conditional instructions (less branches, higher code density)
- explicit delay slots (e.g. MIPS) - quickly abandoned

8.1.3 CISC vs. RISC

RISCs usually have highly uniform operations (all instructions have same length, take similar time to execute, operations between registers, operate on 64 or 32 bit quantities, ...). Note that the variable instruction length of CISCs has little impact on execution performance today.

CISC proponents say they are easy for the compiler and provide smaller code sizes. RISC proponents say they are better for compiler optimizations and run fast with simple chip design. But today the choice of not a technical issue as basically anything can run fast. Still, for embedded processors RISC still makes sense for size, cost, and power constraints.

8.2 x86 History

The x86 architecture was born with the 8086 processor (1978), which was the first 16-bit processor. (x86-16 architecutre) Later came the 80386 (1985), which extended the capabilities to 32 bits. This was capable of running Unix. Modern linux for 32-bit uses no instructions introduced after this. (x86-32/ia32 architecture) The Pentium 4F (2005) introduced 64-bit processors for Intel. (x86-64/em64t architecture) Throughout those advancements, clock speeds increased noticeably just as the transistor count did.

Some features which were added to the x86 ISA over time are:

- instructions for multimedia operations (parallel operations on 1, 2, 4-byte data)
- more efficient conditional operations
- virtualization extensions
- multiprocessor synchronization

8.3 Basics on Machine Code

When looking as x86 assembly, we will consider the AT&T syntax, which is most commonly used for Unix. The Intel syntax is more present when using windows and just switches the order of the operands. A processor is very complicated but for writing assembly a simplified understanding is sufficient. We have the CPU, which consists of:

- The Program Counter (PC) that contains the address of the next instruction. This ist the `rip` register on x86-64.
- The register file contains the registers accessible and heavily used by programs.
- condition codes store status information/side effects from arithmetic and logic operations for conditional branching.
- Then we have the memory which provides the instructions to the processor. Also, we can provide addresses to get the data stored at the specified location. Through memory we have access to code, user data, (some) OS data, etc. The stack and heap are locate in memory.

8.3.1 Asembling

After having written a program, it is first compiled into assembly. To compile a `.c` file into assembly (an `.s` file), we can use the `-S` flag: `gcc -S code.c`. When also adding `-O0` we turn of optimizations and get a raw translation of our program. What we will see after this can be understood after reading further about instructions/operations, ... below.

Afterwards, the assembly is translated into an `.o` object file in which every instruction is binary encoded. This is a nearly-complete image of the executable code.

Notice that these steps can also (somewhat) be reserved. Disassembling turns an object file intro the corresponding instructions. However, some part of the assembly `.s` file gets removed during conversion to an `.o` file. Thus, the disassembled `.s` file usually misses some stuff from the original `.s` file. We can disassemble with `objdump -d p`. This works on objects file but also executables, which are created after linking.

One can get a similar result by using the gdb debugger. We do so by writing `disassemble name` in a gdb session to disassemble the function `name`. With gdb we can also examine bytes at some memory location. We can write `x/30bx sum` to examine (`x/`) 30 bytes (`30b`) in hex (`x`) at sum (`sum`).

Finally, the linker resolves references between `.o` files and combines the `.o` file with static run-time libraries. Some libraries are also dynamically linked when the program begins execution.

8.3.2 Assembly Data Types

In x86 assembly we can work with integer data of 1, 2, 4 or 8 bytes. This stores whatever we just want to represent as bits in memory. Then we also have floating point data of 4, 8, or 10 bytes. This is for floating point numbers and will be considered later. We do not have aggregated types (arrays, ...). Those are all build on top of the basic integer types etc. from the compiler.

8.3.3 Assembly Code Operations/Machine Instructions

With instructions we perform operations to alter the state of the system. Using those, we can:

- perform arithmetic/logic functions on registers or memory data
- transfer data between memory and register
- transfer control (unconditional jumps to/from procedures, conditional branches)

With x86 assembly, instructions have the format `op operand1, operand2`, where not all operands may be used with all instructions. Registers are identified by a unique name. With AT&T syntax, the result of an operaiton on `operand1` and `operand2` is put in `operand2`.

8.4 x86 Architecture

8.4.1 Registers

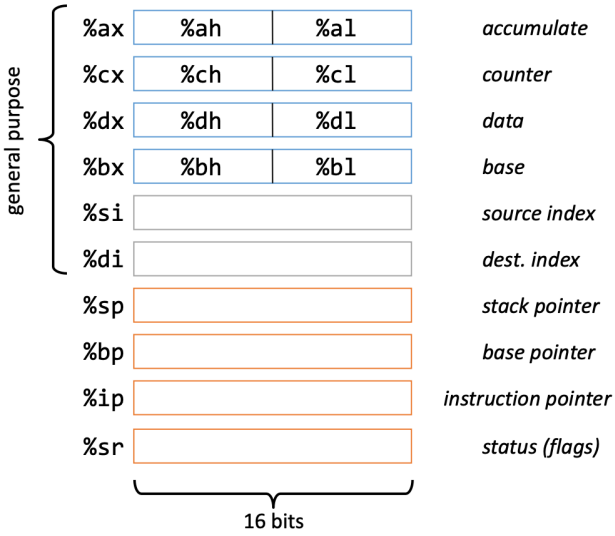


Figure 16: Registers of Intel 8086 / x86-16 Architecture

With `%ah`, `%al`, etc. we can access the 8 high or low bits of a 16 bit unit. Here we have 6 general purpose registers. The six registers had some special meaning in earlier versions. That's the reason for the strange naming. They are acronyms for their original meaning.

All other register cannot be freely used. The `%ip`, `%bp`, `%sp`, and `%sr` are special-purpose and must be used according to their definition/meaning.

The `x` in addresses stands for extended, because originally, we couldn't access the the four top 16 bit registers on the preceding 8-bit machine.

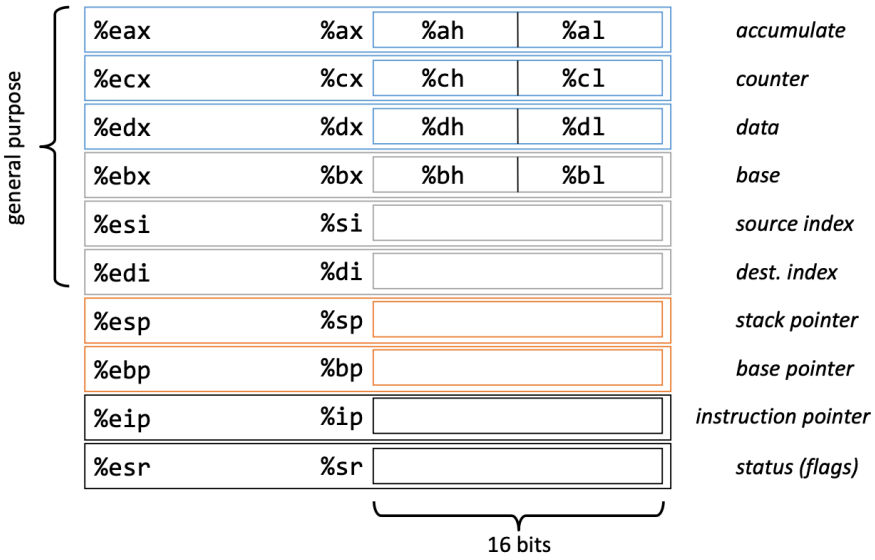


Figure 17: Registers of Intel 80386 / x86-32 Architecture

With the step to 32 bits with the 80386, the register size was increased. An `e` is preceding

when wanting to access the 32 bit version and not just work on the lower 16 bits with the same names as before. The `e` stands again for extended.

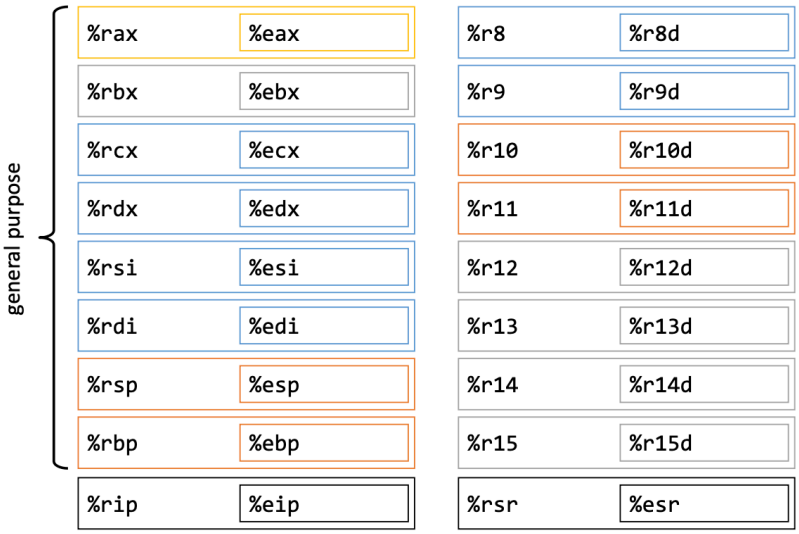


Figure 18: Registers of x86-64 Architecture

With the step to x86-64 the registers were extended again by adding an `r` in front of each naming. Another change was that the ordering of the first four registers now is alphabetically. Furthermore, the `%rsp` and `%rbp` (stack pointer and base pointer) have become general-purpose registers too. Anyway, they are still used for their original purposes almost always. Finally, an additional 8 general purpose registers have been added. Conveniently those are numbered in chronological order.

If we set the lower 8 or 16 bits, the upper bits remain unchanged.
But if we set the lower 32 bits, the upper 32 bits will be zeroed out.

8.4.2 Move Instructions

We use the `movx source, dest` instruction to move data (where `x` is replaced with an element from $\{b, w, l, q\}$).

- `b` is 1-byte.
- `w` is a word / 2-bytes.
- `l` is a long-word / 4-bytes.
- `q` is a quad-word / 8-bytes.

We also have `movABx`, where `x` is as above. `A` is either s for sign extending the remaining-bits of the register (if only writing to lower bits) or `z` for zeroing out. The `B` identifeis what we choose as input, i.e., what size our source has.

We have different types of data we can choose as operands:

- immediate: constant integer data

example: `$0x400, $-533` (we have to write the prefix `$`).

Those values are encoded with 1, 2, 4, or 8 bytes

- register values (we can choose one of the 16 general purpose registers)

  example: `%eax, %r14d`

- values from memory (the number of bytes from memory depends on the instruction type)

  example: `(%rax)`

We can combine those data types mostly arbitrarily. But we can't specify an immediate as a destination or have to memory accesses in the same operation.

Memory addressing is more capable than just staed. It follows the general scheme of `D(Rb,Ri,S)`, where `D` is a constant displacement (offset), `Rb` is the base register address (any of the general purpose integer registers), `Ri` is the index register, and `S` specifies a scale as one of the values 1, 2, 4, or 8. The memory access corresponds to this: `Mem[Reg[Rb] + S*Reg[Ri] + D]`. We may leave out some of those 'parameters'.

In addition to memory accesses, we also have the `lea operand1, operand2` operation. Ir computes the address according to the same scheme but instead of accessing that location, the address is saved to the second operand. So this corresponds to `Reg[Rb] + S*Reg[Ri] + D`.

8.5 x86 Integer Arithmetic

Integer arithmetics in x86 assembly generally uses two-operand instructions. As with move instructions, the suffix determines the size we operate on. I.e., if there is an `l` in the end, we operate on long-words (32 bits) etc.

instruction	format	computation
`addl`	`src, dest`	`dest <- dest + src`
`subl`	`src, dest`	`dest <- dest - src`
`imull`	`src, dest`	`dest <- dest * src`
`sall`	`src, dest`	`dest <- dest << src`
`sarl` (arithmetic shift)	`src, dest`	`dest <- dest >> src`
`shrl` (logical shift)	`src, dest`	`dest <- dest >> src`
`xorl`	`src, dest`	`dest <- dest ^ src`
`andl`	`src, dest`	`dest <- dest & src`
`orl`	`src, dest`	`dest <- dest | src`

instruction	format	computation
`incl`	`dest`	`dest <- dest + 1`
`decl`	`dest`	`dest <- dest - 1`
`negl`	`dest`	`dest <- -dest`
`notl`	`dest`	`dest <- ~dest`

We can also use `leal` for (basic) arithmetic instructions. Because `leal` is usually very optimized in hardware because it uses the same frequently used unit as for memory accesses, this is rather fast.

The compiler is also quite smart. So when writing C code it might rearrange and change stuff so that the observed behavior is identical while the specific computation is different.

Listing 40: Compiler Evaluation

```
int logical(int x, int y) {
  int t1 = x^y;
  int t2 = t1 >> 17;
  int mask = (1<<13) - 7;
  int rval = t2 & mask;
  return rval;
}
// is assembled into
logical:
  movl %edi, %eax
  xorl %esi, %eax
  sarl $17, %eax
  andl $8185, %eax
  ret
```

8.6 Condition Codes

The x86 architecture specifies some additional special-purpose one-bit registers, which can't be set explicitly. They are set implicitly/as a side effect by arithmetic operations performed in the ALU. So 'leal' doesn't set those bits. But a regular add or multiply does. They are always set to indicate whether their respective condition holds on the produced output. The condition codes are then used for branching etc.

- CF: Carry Flag (overflow for unsigned)

  set if carry out from the most significant bit (unsigned overflow)

- ZF: Zero Flag

  set if $t == 0$ (t is the operation result)

- SF: Sign Flag (for signed)

  set if $t < 0$ (t is the operation result)

- OF: Overflow Flag (for signed)

  set if 2's complement (signed) overflow, `(a>0 && b>0 && t<0)|| (a<0 && b<0 && t>=0)` (t is the operation result)

There are also instructions, which compute some value, i.e., do some arithmetic operation (at least as long as necessary to compute the condition codes) without actually saving the result.

- `cmpl src2, src1` computes `src1-src2` and sets the condition codes without storing the result.

- `testl src2, src1` computes `src1 & src2` and sets the condition codes without storing the result

Conditions codes are mostly used for conditional branching. But we can also extract the bit values and put them into general purpose registers with special instructions.

instruction	condition	description
sete	ZF	equal / zero
setne	~ZE	no equal / not zero
sets	SF	negative
setns	~SF	non-negative
setg	~(SF^OF)&~ZF	greater (signed)
setge	~(SF^OF)	greater or equal (signed)
setl	(SF^OF)	less (signed)
setle	(SF^OF)|ZF	less or equal (signed)
seta	~CF&~ZF	above (unsigned)
setb	CF	below (unsigned)

We use the same syntax for doing conditional jumps.

instruction	condition	description
jmp	1	unconditional
je	ZF	equal / zero
jne	~ZE	no equal / not zero
js	SF	negative
jns	~SF	non-negative
jg	~(SF^OF)&~ZF	greater (signed)
jge	~(SF^OF)	greater or equal (signed)
jl	(SF^OF)	less (signed)
jle	(SF^OF)|ZF	less or equal (signed)
ja	~CF&~ZF	above (unsigned)
jb	CF	below (unsigned)

9 Compiling C Control Flow

In this section we consider how control flow structures from the C language are translated to (x86) assembly.

9.1 if-then-else statements

If conditions work by testing the opposite conditions and if the opposite is true, we do a conditional jump to the section after the loop content. If we have an else condition, then the assembly for that comes after the if code and when the if-code finishes, it jumps after the else section. The ternary operator is compiled to an if statement as just described.

Listing 41: If Statement in C

```c
#include <stdio.h>
int putmax(int x, int y) {
  int result;
  if (x> y) {
    result = printf("%d\n", x
       );
  } else {
    result = printf("%d\n", y
       );
  }
  return result;
}
```

Listing 42: Compiled If Statement

```
putmax:
  subq $8, %rsp
  cmpl %esi, %edi
  jle .L2
  movl %edi, %edx
  movl $.LCO, %esi
  movl $1, %edi
  movl $0, %eax
  call __printf_chk
  jmp .L3
.L2:
  movl %esi, %edx
  movl .LC0, %esi
  movl $1, %edi
  movl $0, %eax
  call __printf_chk
.L3:
  addq $8, %rsp
  ret
```

However, in certain cases the assembly can be optimized. Specifically if the code blocks of the if/else block don't call functions or have other side effects. Then it is often faster to compute both cases and then use a conditional move to keep the right result in the end. This is used for many very short if/else conditionals. This is more efficient because we don't have the overhead from branching.

Listing 43: If Statement in C Optimized

```c
int absdiff(int x, int y) {
  int result;
  if(x>y) {
    result = x-y;
  } else {
    result = y-x;
  }
  return result;
}
```

Listing 44: Compiled If Statement Optimized

```
absdiff:
  movl %edi, %eax
  subl %esi, %eax
  movl %esi, %edx
  subl %edi, %edx
  cmpl %esi, %edi
  cmovle %edx, %eax
  ret
```

9.2 do-while loops

Here we use a backward branch to continue looping. I.e., we execute our code once and if the condition then holds, we again jump to the beginning of the loop content.

Listing 45: Do-While Loop in C

```
int fact_do(int x) {
  int result = 1;
  do {
    result *= x;
    x = x-1;
  } while (x > 1);
  return result;
}
```

Listing 46: Compiled Do-While Loop

```
fact_do:
  movl $1, %eax
.L3:
  imull %edi, %eax
  subl $1, %edi
  cmpl $1, %edi
  cmpl $1, %edi
  jg .L3
  rep ret
```

9.3 while loops

`while` loops can be implemented in various ways (just as other control flow structures can be too). `gcc`'s approach is to test the condition initially. If it doesn't hold we jump to the section after the loop. If it does, a do while basically follows.

Listing 47: While Loop in C

```
int fact_while(int x) {
  int result = 1;
  while (x>1) {
    result *= x;
    x = x - 1;
  };
  return result;
}
```

Listing 48: First Compiled While Loop

```
int fact_while_goto1(int x) {
  int result = 1;
  if (!(x>1))
    goto done;
Loop:
  result *= x;
  x = x - 1;
  if (x>1$
    goto Loop;
done:
  return result;
}
```

A newer style for `while` loops (jump-to-middle while) is to not have separate code for the initial condition test. Instead we do an unconditional jump to the beginning of the test of the do-while. So, we have basically a do while with one additional jump. This approach is chosen today, because unconditional jumps/'goto's don't incur any noticeable performance penalty these days.

Listing 49: Second Compiled While Loop

```
int fact_while_goto2(int x) {
  int result = 1;
  goto middle;
Loop:
  result *= x;
  x = x - 1$;
middle:
  if (x>1)
    goto Loop;
```

```
  return result;
}
```

9.4 for loops

A for loop is basically a while loop with some initial variable setup and some variable update and test at the end of each iteration to check whether to execute the next iteration.

Listing 50: p-th power of x

```
for (result = 1; p != 0; p = p>>1) {
  if (p & 0x1)
    result *= x;
  x = x*x;
}
```

Listing 51: Compiled For Loop

```
  result = 1;
  if (p == 0)
    goto done;
loop:
  if (p & 0x1)
    result *= x;
  x = x*x;
  p = p >> 1;
  if (p != 0)
    goto loop;
done:
```

Listing 52: Compiled For Loop - Modern

```
  result = 1;
  goto middle;
loop:
  if (p & 0x1)
    result *= x;
  x = x*x;
  p = p >> 1;
middle:
  if (p != 0)
    goto loop;
dome:
```

9.5 switch

9.5.1 jump tables

This is efficient if we only have a small range of values as cases to check. We then add a static jump table with target addresses for each case and index this table with the variable on which to do the switch after doing a sanity check that we don't definitely have the default case in which we jump to it directly.

Listing 53: Jump Table Setup

```
  .section .rodata
  .align 8
  .align 4
.L4:
  .quad .L8 # x=0
  .quad .L3 # x=1
  .quad .L5 # x=2
  .quad .L9 # x=3
  .quad .L8 # x=4
  .quad .L7 # x=5
  .quad .L7 # x=6
```

Listing 54: Switch Statement Compiled

```
switch_eg:
  movq %rdx, %rcx
  cmpq $6, %rdi
  ja .L8
  jmp *.L4(,%rdi,8)
```

9.5.2 sparse switch statements via binary search tree

But if we have many cases or large values for our cases the previous approach is undesirable, because it consumes a lot of memory and we might run into cache issues. The following example would generate a 1000 entry jump table, for instance.

Listing 55: Switch Statement

```
int div111(int x) {
  switch(x) {
    case 0: return 0;
    case 111: return 1;
    case 222: return 2;
    case 333: return 3;
    case 444: return 4;
    case 555: return 5;
    case 666: return 6;
    case 777: return 7;
    case 888: return 8;
    case 999: return 9;
    default: return -1;
  }
}
```

Listing 56: Compiled Switch Statement as Binary Search Tree

```
div111:
  cmpl $444, %edi
  je .L3
  jle .L28
  cmpl $777, %edi
  je .L10
  jg .L11
  cmpl $555, %edi
  movl $5, %eax
  je .L5
  cmpl $666, %edi
  movb $6, %al
  jne .L2
.L5: // done
  rep ret
.L2: // default case
.L3: // case 444
.L28: // cases 0-333
.L10: // case 777
.L11: // cases 888-999
// ...
```

9.6 procedure calls and returns

We already discussed the stack as the area of memory where local variables etc. are managed. We say that it is managed with stack discipline, i.e., by respecting conventions on how to use the stack. Historically, the stack pointer had to be located in `%rsp` (or their lower-bit equivalents) because the concept of a stack is baked in to x86. Today we could use a different register but still stick to the convention.

There exist some basic instructions to interact with the stack through the stack pointer. In practice we only use those instructions in a limited setting. If we want to allocate a larger region on the stack, we usually work on the stack pointer directly. However, for single values this still is used.

- `pushl src`: Fetches the operand at `src`, decrements `%rsp` by 4 and then write the operand to that address. Equivalently, we could use `pushw`, etc.
- `popl dest`: Reads the operand at address `%rsp` and increments `%rsp` by 4, and write the operand to `dest`.

The stack is used to support procedure calls and returns. When calling a function, we write `call addr`, where `addr` is the location of the function in memory to which the instruction pointer is changed. We can also use a label in assembly language. That adds the address of the

next instruction to the stack and jumps to the target address. So, the return address for a function is stored on the stack. Returning can be done with `ret`, which reads the return address, removes it from the stack and jumps to that address.

This is a variation from the original wheeler jump. It stored the return address in a special register. On other ISAs we have that with 'jump and link' instructions. Then, this register is callee saved, or at least it must make sure to return to that address. x86 is different, because we don't store the return address in a special register (i.e., link to it for returning later) but simply put it on the stack instead.

Furthermore, when passing arguments to a function and their size/number exceeds what we can store in the designated registers by the calling conventions, we put them on the stack before the return address.

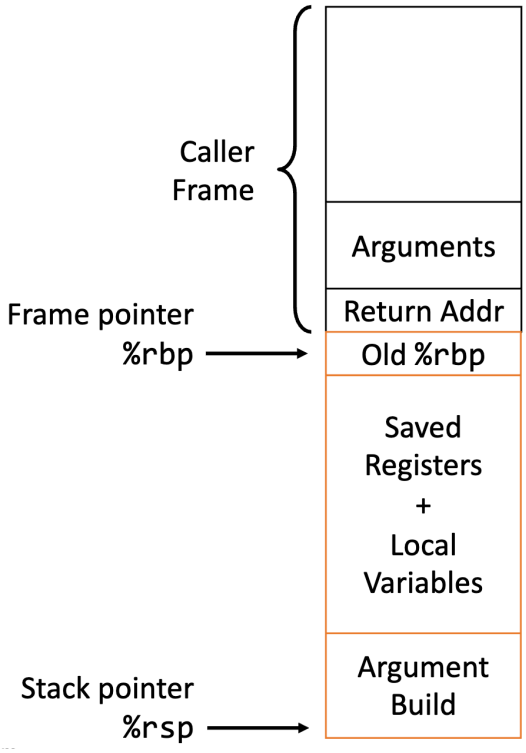


Figure 19: x86-64 Full Stack Frame

Usually, the stack is aligned. Mostly to 16 bits/2 bytes (?). Thus, a function can assume that this holds when it is called and must make sure that it holds again once it calls a function itself.

9.7 calling conventions

In x86 and especially other ISAs we have plenty registers and the ISA does not define how to use them. But the calling conventions specify a common schema to pass arguments to a method, provide a return value etc. This is helpful to be able to link binaries/assembly from different compilers etc. The calling conventions specify a common interface between the caller and the callee.

The calling conventions boil down to the special meaning of some registers and rules on who (caller or callee) saves which registers. The procedure executing 'call' is the caller and the procedure which we jump to is the callee. Caller saved registers are those registers saved and restored by the caller (by using the stack) before calling another procedure. Callee saved registers are those

registers saved and restored by the callee (by using the stack) before using them itself.

name	meaning	who saves?
`%rax`	return value, #args	caller
`%rbx`	base pointer	callee
`%rcx`	4th argument	caller
`%rdx`	3rd argument	caller
`%rsi`	2nd argument, 2nd return value	caller
`%rdi`	1st argument	caller
`%rsp`	stack pointer	
`%rbp`	frame ptr	callee
`%r8`	5th argument	caller
`%f9`	6th argument	
`%r10`	static chain ptr	
`%r11`	used for linking	
`%r12`		callee
`%r13`		callee
`%r14`		callee
`%r15`		callee

This table specifies six registers for arguments. If we need to pass more than 6 parameters, the rest is passed on the stack as specified in the previous subsection. These registers (if not used for parameters) can be used as caller saved registers. All references to the stack frame are done via the stack pointer `%rsp`. Thus, we don't need to update the `%rbp` (base pointer).

If we need to (re)store some registers or otherwise need to handle more data than fits in the available registers, we need to work on the stack. If we are a leaf procedure, we can access a few bytes beyond the stack pointer in the red zone without risking a page fault or stack overflow. The red

However, if we call another procedure ourselves or want to be sure, we should allocate a stack frame. This is done by decrementing the stack pointer once according to our memory requirements & stack alignment requirements. Once we want to return from the function, we can deallocate memory from the stack by increasing the stack pointer by the same amount we decrement it earlier.

9.7.1 Examples

Factorial Here, the register `%rax` is used within the function without worrying about existing data. The register `%rbx` is used too, but we save the contents before and put it back afterwards.

Listing 57: Factorial in C

```c
int rfact(int x) {
  int rval;
  if (x<=1)
    return 1;
  rval = rfact(x-1);
  return rval * x;
}
```

Listing 58: Factorial Compiled

```
rfact:
  pushq %rbx
  movl %edi, %ebx
  movl $1, %eax
  cmpl $1, %edi
  jle .L2
  leal -1(%rdi), %edi
  call rfact
  imull %ebx, %eax
.L2:
  popq %rbx
  ret
```

Locals in the Red Zone .

Listing 59: Swap Using Local Array

```c
void swap_a(long *xp, long *
    yp) {
  volatile long loc[2];
  loc[0] = *xp;
  loc[1] = *yp;
  *xp = loc[1];
  *yp = loc[0];
}
```

Listing 60: Swap Compiled

```
swap_a:
  movl (%rdi), $rax
  movq %rax, -24(%rsp)
  movq (%rsi), %rax
  movq %rax, -16(%rsp)
  movq -16(%rsp), %rax
  movq %rax, (%rdi)
  movq -24(%rsp), %rax
  movq %rax, (%rsi)
  ret
```

Non-Leaf Function Without Stack Frame .

Listing 61: Swap Without Stack Frame

```c
long scount = 0;

void swap_ele_se(long a[],
    int i) {
  swap(&a[i], &a[i+1]);
  scount++;
}
```

Listing 62: Swap Compiled

```
swap_ele_se:
  movslq %esi, %rsi
  leaq (%rdi, %rsi, 8), %rdi
  leaq 8(%rdi), %rsi
  call swap
  incq scount(%rip)
```

Call Using a Jump This optimizes a function call if it does not require a stack frame itself and does not need to result execution after calling another function. Then that function can just return the original caller.

Listing 63: Swap Using Local Array

```
long scount = 0;

void swap_ele(long a[], int i
    ) {
  swap(&a[i], &a[i+1]);
}
```

Listing 64: Swap Compiled

```
swap_ele:
  movslq %esi, %rsi
  leaq (%rdi, %rsi, 8), %rdi
  leaq 8(%rdi), %rsi
  jmp swap
```

9.8 variadic functions

We have used `printf(...)` at various occasions before. Now that we have seen the calling conventions and how to pass arbitrarily many arguments, we can understand how this function processes its parameters.

In C, `printf` is declared like this: `int printf(const char *format, ...);`, which is C's syntax for variadic functions. Let's consider `void print_integers(unsigned num_ints, char *msg, ...);` to make it easier to understand what's going one. We may invoke the following calls, which returns the expected values.

- `print_integers(0, "Hello");`
- `print_integers(1, "The answer...", 42);`
- `print_integers(2, "A couple", 2, 4);`
- `print_integers(10, "Quite a few", 10, 8, 7, 6, 5, 4, 3, 2, 1);`

Listing 65: Implementation of `print_integers`

```
#include <stdio.h>
#include <stdarg.h> // library to use work with variable amounts
    of arguments

void print_integers(unsigned num_ints, char *msg, ...)
{
  printf("%s\n", msg);
  printf("About to print %u ints:\n", num_ints);
  va_list ap; // variable which tracks the currently considered
     argument (similar to an iterator)

  va_start(ap, msg); // initialization of ap based on the last
     fixed argument
  for(int i = 0; i<num_ints; i++)
  {
    int j = va_arg(ap, int); // return the next argument cast to
        an int
    printf("int %d = %d\n", i, j);
  }
  va_end(ap); // free up the iterator
}
```

`va_arg` clearly can't be a function as it accepts a type as a parameter. It may be a macro. On modern machines, `gcc` turns this into compiler intrinsic. So it is replaced with code provided by the compiler. We can see this when looking at the definitions in `stdarg`: `#define va_arg(v,l)__buildin_va_arg(v,l)`.

10 Compiling C Data Structures

10.1 One-Dimensional Arrays

If we allocate for `T A[L]` (type `T`, length `L`), we allocate a continuous region of `L * sizeof(T)` in memory.

Listing 66: Array Access in C

```
int get_digit(zip_dig z, int dig) {
  return z[dig];
}
```

Listing 67: Array Access Compiled

```
get_digit:
  movsql %esi, %rsi
  movl (%rdi,%rsi,4), %eax
  ret
```

Figure 20: Looping over an Array in C

```
int zd2int(zip_dig z)
{
  int i;
  int zi = 0;
  for (i = 0; i < 5; i++) {
    zi = 10 * zi + z[i];
  }
  return zi;
}
```

```
int zd2int(zip_dig z)
{
  int zi = 0;
  int *zend = z + 4;
  do {
    zi = 10 * zi + *z;
    z++;
  } while (z <= zend);
  return zi;
}
```

```
zd2int:
.LFB0:
  endbr64
  leaq 20(%rdi), %rcx
  xorl %eax, %eax
.L2:
  leal (%rax,%rax,4), %edx
  movl (%rdi), %eaxaddq $4, %rdi
  leal (%rax,%rdx,2), %eax
  cmpq %rcx, %rdi
  jne .L2
  ret
```

10.2 Nested Arrays

If we have `T A[R][C]`, we have a 2D array of data type `T` with `R` rows and `C` columns. If type `T` requires `K` bytes, this has size `R*C*K` bytes in memory. It is arranged in row-major order.

```c
typedef int[][] zip_dig;
zip_dig pgh[4] =
  {{1, 5, 2, 0, 6},
   {1, 5, 2, 1, 3 },
   {1, 5, 2, 1, 7 },
   {1, 5, 2, 2, 1 }};
```

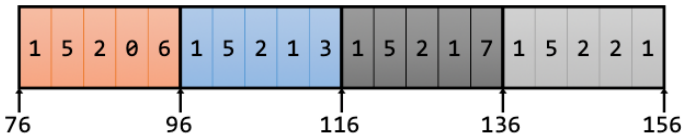


Figure 21: 2D Array in Memory

To access some element in a row, we add `j*K` for the j-th element in that row to the base address for that row. In total, to access `A[i][j]` (of elements of type `T` with `K` bytes each), we get `A + i*(C*K)+ j*K = A + (i*C+j)*K`.

Listing 68: 2D Array Access in C

```c
int get_pgh_digit(int index,
    int dig)
{
  return pgh[index][dig];
}
```

Listing 69: 2D Array Access in Assembly

```
get_pgh_digit:
  endbr64
  movslq %edi, %rdi
  movslq %esi, %rax
  leaq (%rdi,%rdi,4), %rsi # 5
     * index
  addq %rax, %rsi # dig + 5 *
     index
  leaq pgh(%rip), %rax
  movl (%rax,%rsi,4), %eax # *(
     pgh + 4*(dig + 5*index))
  ret
```

When accessing arrays and interpreting `a[i][j]` as just described, it would be reasonable that in our `pgh` example `pgh[0][19]` and `pgh[4][-1]` correspond to the same element. In practice this holds for most compilers but is not guaranteed by the C standard. The C standard (C99) only guarantees the expected behavior for access at most 1 beyond the bound of the array. I.e., `a[2][5]` is guaranteed while `a[2][6]` is not in our example.

10.3 Multi-Level Arrays

Variable multi-level arrays can contain the same data as nested arrays. However, multi-level arrays require more memory. With this cost, we 'buy' additional flexibility.

Listing 70: Multi-Level Array in C

```c
zip_dig cmu = { 1, 5, 2, 1, 3 };
zip_dig mit = { 0, 2, 1, 3, 9 };
zip_dig ucb = { 9, 4, 7, 2, 0 };
int *univ[3] = {mit, cmu, ucb};
```

This has the benefit of being more flexible. The subarrays may have different length, for instance. But it also requires more memory as we now need to store the pointers to the subarrays in the main arrays. Also, we require multiple memory accesses to get to the actual value so that the access latency is increased.

Despite this being different than nested arrays, we can still use the same indexing syntax in C. But it will be compiled to different assembly. An access `array[a][b]` to an array like

`int array[20][30]` would be compiled to something implementing `Mem[Mem[array+8*a]+4*b]`.

Listing 71: Multi-Level Array Indexing in C

```
int get_univ_digit(
  int index,
  int dig
) {
  return univ[index][dig];
}
```

Listing 72: Compiled Listing 71

```
get_univ_digit:
  endbr64
  movslq %edi, %rdi
  leaq univ(%rip), %rax
  movslq %esi, %rsi
  movq (%rax,%rdi,8), %rax
    # Mem[univ+8*index]
  movl (%rax,%rsi,4), %eax
    # Mem[... +4*dig]
  ret
```

Notice that with nested arrays, we were able to go beyond the borders of one array to access the last/first element of another array. But this does not hold here, because we are not guaranteed that the subarrays are put continuously in memory. The pointers may lead to arbitrary locations.

10.4 Dynamic Arrays

Above we have considered array with static sizes. But though explicit memory management, we can also work with dynamic array sizes. But we then must do the index computation explicitly. Also accessing elements is costly, because we must do a multiplication.

Listing 73: Dynamic Array Allocation

```
int * new_var_matrix(int n) {
  return (int *)
    calloc(sizeof(int), n*n);
}
```

Listing 74: Dynamic Array Indexing

```
int var_ele(int *a, int i,
  int j, int n) {
  return a[i*n+j];
}
```

Notice that the function `int var_prod_ele(int *a, int *b, int i, int k, int n);`, which computes an entry of the matrix-matrix produce, may perform very different, depending on its implementation.

Listing 75: Inefficient Multiply

```
  // per iteration:
  // - 3 multiplications
  // - 4 additions
{
  int j;
  int result = 0;
  for (j = 0; j < n; j++)
    result += a[i*n+j] * b[j*n+k
        ];
  return result;
}
```

Listing 76: Efficient Multiply

```
  // per iteration:
  // - 4 multiplications
  // - 1 addition
{
  int j;
  int result = 0;
  int iTn = i*n;
  int jTnPk = k;
  for (j = 0; j < n; j++) {
    result += a[iTn+j] * b[jTnPk
        ];
    jTnPk += n;
  }
  return result;
}
```

10.5 Structures

For structures we allocate a contiguous region of memory for the members (of different types).

```
1 struct rec {
2   int i;
3   int a[3];
4   int *p;
5 }
```

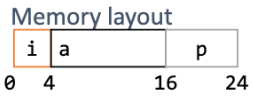


Figure 22: `struct` layout in memory

The memory layout of structures must validate alignment. Consider that section to see why this memory layout it valid and how other structures would be put in memory.

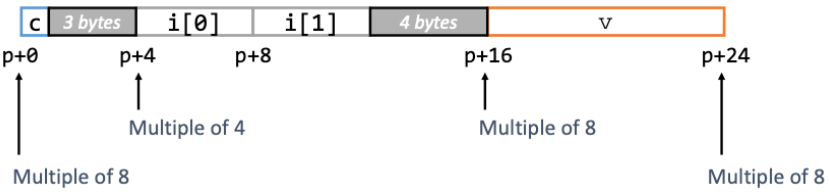
10.6 Alignment

Alignment describes the memory locations at which some data may reside in memory. In general it describes that a data type which requires `K` bytes must have an address, which is a multiple of `K` i.e., be `K` aligned. On early ARM, Alpha, ... this is required. On x86 this is treated depending on the platform but generally advised.

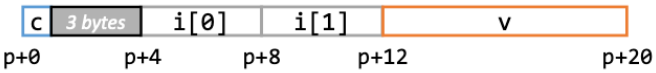
The concept of alignment helps performance, because memory is accessed by aligned chunks of 4 or 8 bytes. Alignment then simplifies providing data to the ALU and moving it within the system. The compiler usually inserts gaps in structures to ensure correct alignment of fields.

For structures, each element's alignment requirement must be satisfied. And the overall structure has alignment requirement `K`, where `K` is the largest alignment of any element. To guarantee this for the fields to be in memory in the specified order, padding is added in memory.

```
1 struct S1 {
2   char c;
3   int i[2];
4   double v;
5 } *p;
```



x86-64 Layout (doubles have 8 byte alignment)



ia32 Layout (doubles have 4 byte alignment)

Figure 23: `struct` Alignment

A good C programmer knows about this and writes the structs in such an order that padding is minimized. With structs, one may also specify bitfields. In those, one provides the size of each field in bits. But do not use these for explicit memory layout! The compiler can pack multiple fields into a single char/short/int/... We have no guarantee on the memory format! Padding, byte-ordering, event-bit ordering, ... may be unexpected.

Listing 77: Bitfields in C

```
struct BitFieldExample {
    unsigned int field1 : 3; // 3 bits
    unsigned int field2 : 4; // 4 bits
};
```

10.7 Unions

We have already discussed unions and know that we can only use one field at a time. Thus, it is intuitive to understand that memory is allocated only according to the largest element.

```
union U1 {
  char c;
  int i[2];
  double v;
} *up;
```

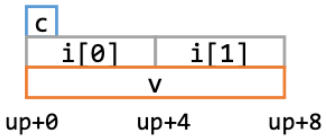


Figure 24: `union` memory layout

A common use case for unions is to access the bit pattern of some types. When casting floats/doubles to ints, the C compiler/machine tries approximate conversion by rounding. But if we want to access the bit pattern, we can store the data in a union and then read the int values.

Listing 78: Accessing Bit Pattern of Types through `union`s

```
union bit_float {
  float f;
  unsigned u;
};

float bit2float(unsigned u) {
  union bit_float arg;
  arg.u = u;
  return arg.f;
}

unsigned float2bit(float f) {
  union bit_float arg;
  arg.f = f;
  return arg.u;
}
```

11 Unorthodox Control Flow

In high-level languages we are familiar with many common programming techniques/structures. We work with OOP, threads, synchronization techniques, etc. While those are helpful in many situations, C unlocks many more possibilities and techniques. However, we have to implement them mostly manually. Here we will consider unhinging normal control flow to unlock possibilities not feasible in higher-level languages. Learning about such optimizations and learning such low-level concepts is essential to reach even better optimizations.

11.1 setjmp() and longjmp()

`setjmp` and `longjmp` allow us to leave regular control flow. With `setjmp` we can set a position in code and, later, go to that specific position with `setjmp` in a way that resets all registers etc. to the state that has been once we have been at that location in code the first time.

The way we save the information with `setjmp` about the location we jump to later mandates, that we can only jump there in a way that the stack has not yet been deallocated. I.e., we can only jump there from the function itself or subroutines.

11.1.1 setjmp

Calling `setjmp(jmp_buf env)` saves the current stack state (i.e., the position of the stack) and the environment (register values) in the buffer `env` and returns 0.

Listing 79: `setjmp` in C

```
#include <setjmp.h>
int setjmp(jmp_buf env);
```

11.1.2 longjmp

`setjmp(val)` changes to control flow to jump to the point in code saved earlier with `setjmp(..)`.. However, once we resume execution at the `setjump`, it does not return 0 but instead it returns `val` (if `val` is 0, it is turned into 1 - so one can't return 0). For each `setjmp(..)`. we can call `longjmp(..)`. only once.

As already mentioned in the introduction: By how this works under the hood, it is invalid to call `longjmp(..)`. if the function that called `setjmp(..)`. already returned!

Listing 80: `setjmp` and `longjmp` Toy Example

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

static jmp_buf buf;

void second(void) {
  printf("second\n");
  longjmp(buf,1);
}

void first(void) {
  second();
  printf("first\n");        // does not print
```

```
14 }
15
16 int main() {
17   if ( ! setjmp(buf) ) {
18     first();              // when executed, setjmp returns 0
19   } else {                  // when longjmp jumps back, setjmp
       returns 1
20     printf("main\n");     // prints
21   }
22   return 0;
23 }
```

11.2 implementing setjmp() and longjmp()

11.2.1 setjmp

When calling `setjmp(env)`, we store (a) all callee saved registers, (b) the current state of the stack (i.e., the stack pointer), and (c) the return address in the `env` buffer.

Listing 81: `setjmp` in Assembly

```
1 /* Copyright 2011-2012 Nicholas J. Kain, licensed under standard
     MIT license */
2 setjmp:
3   mov %rbx,(%rdi).  /* rdi is jmp_buf, move registers onto it */
4   mov %rbp,8(%rdi)
5   mov %r12,16(%rdi)
6   mov %r13,24(%rdi)
7   mov %r14,32(%rdi)
8   mov %r15,40(%rdi)
9   lea 8(%rsp),%rdx  /* this is our rsp WITHOUT current ret addr
       */
10  mov %rdx,48(%rdi)
11  mov (%rsp),%rdx   /* save return addr ptr for new rip */
12  mov %rdx,56(%rdi)
13  xor %eax,%eax   /* always return 0 */
14  ret
```

11.2.2 longjmp

When `longjmp` is called, (a) all the previously stored registers are restored and (b) the stack pointer is set to its value as it was in the function calling `setjmp` and, thus, deleting all stack frames allocated after `setjmp` (assuming it did not return). Afterwards, `longjmp` returns to the return address of the `setjmp` call, i.e., the next instruction after `setjmp`. Before that is done, however, the return value is set according to the parameter to `longjmp` - assuming it is not 0.

Listing 82: `longjmp` in Assembly

```
1 /* Copyright 2011-2012 Nicholas J. Kain, licensed under standard
     MIT license */
2 longjmp:
3   xor %eax,%eax
```

```
4   cmp $1,%esi          /* CF = val ? 0 : 1 */
5   adc %esi,%eax        /* eax = val + !val */
6   mov (%rdi),%rbx      /* rdi is the jmp_buf, restore regs from it
        */
7   mov 8(%rdi),%rbp
8   mov 16(%rdi),%r12
9   mov 24(%rdi),%r13
10  mov 32(%rdi),%r14
11  mov 40(%rdi),%r15
12  mov 48(%rdi),%rsp
13  jmp *56(%rdi)        /* goto saved address without altering rsp
       */
```

The `adc` instructions sets the output to the sum of the destination operand, the source operand, and the carry flat (set by the previous `cmp` instruction if `%esi` is 0).

11.3 Why Coroutines?

Now we begin to elaborate on the use of all of this. For what reason do we consider coroutines? We will discuss this based on an example. But coroutines are the foundation of almost all concurrent programming. We intend to read a file, which as been compressed and then run a parser/lexer on the decoded text to tokenize it.

The first stage to processing the compressed file is the **decompressor**, which is rather simple. If a character is repeated in the text, the compressed version stores the number of repetitions and the character.

Listing 83: Decompressor Code

```
while (1) {
  c = getchar();
  if (c == EOF)
    break;
  if (c == 0xFF) {
    len = getchar();
    c = getchar();
    while (len--)
      emit(c);
  } else
    emit(c);
}
emit(EOF);
```

This reads a character from the file through `getchar()` and then produces output for this using `emit(...)`.

The **lexer** distinguishes between alphabetic characters and everything else. It outputs words as tokens and each other symbol as a separate punctuation token. It reads characters from the decoded text using `getchar()` and then outputs tokens using `got_token(...)` after having constructed them using `add_to_token(...)`.

Listing 84: Parser/Lexer Code

```
while (1) {
  c = getchar();
  if (c == EOF)
    break;
  if (isalpha(c)) {
    do {
      add_to_token(c);
      c = getchar();
    } while (isalpha(c));
    got_token(WORD);
  }
  add_to_token(c);
  got_token(PUNCT);
}
```

Notice that we can't simply stick those simple two methods together. The decoder calls a method to provide a new symbol. Similarly, the lexer calls a method to get a new token. We see two immediate solutions:

- We first decode the entire file and then run the lexer on the complete text. This is undesirable, because we want to process the file in real time. But this approach would only yield tokenized output once the entire file had been processed by the decoder (which might take a while).
- We make one of the two methods callable. This involves rewriting at least one of the two methods - work we don't want to do. Such implementations would use `static` variables. But that limits us to processing one file unless we have multiple instanciations.

Listing 85: Rewritten Compressor

```
int decompressor(void) {
  static int repchar;
  static int replen;
  if (replen > 0) {
    replen--;
    return repchar;
  }
  c = getchar();
  if (c == EOF)
    return EOF;
  if (c == 0xFF) {
    replen = getchar();
    repchar = getchar();
    replen--;
    return repchar;
  } else
    return c;
}
```

Listing 86: Rewritten Lexer

```
void lexer(int c) {
  static enum {
    START, IN_WORD
  } state;
  switch (state) {
    case IN_WORD:
    if (isalpha(c)) {
      add_to_token(c);
      return;
    }
    got_token(WORD);
    state = START;
    /* fall through */
    case START:
    add_to_token(c);
    if (isalpha(c))
      state = IN_WORD;
    else
      got_token(PUNCT);
    break;
  }
}
```

What we would like instead is that the parser calls the lexer when it has a new character and then the lexer hands execution back to the parser when it requires new characters. This concept is implemented by continuations.

The decompressor runs until it has a character to emit. It then saves its state (stack, variables, etc.) and calls into the parser. The parser continues where it previously left off. It processes the new character and runs until it needs a new character. Once that is the case, it calls back to the decompressor. This then goes back and forward until the entire file is processed properly.

11.4 Implementing Coroutines

This is a very minimal implementation for illustratory purposes. It has to be used like this:

1. Call `co_init();`
2. Create the coroutines, which should switch between each other with `co_new(...);`
3. Switch to the first coroutine with `co_switchto(...);`
4. Once one of the coroutines terminates, we will continue execution here.

```
typedef void (co_start_fn)(void *);
static struct coroutine *cur_co;
static struct coroutine *main_co;

struct coroutine
{
  void *stack;         // call stack of coroutine
  jmp_buf env;         // the saved context
  co_start_fn *start; // function to call
  void *arg;           // argument to the function
};

struct coroutine *co_new(co_start_fn *start, void *ctxt)
{
  struct coroutine *co = (struct coroutine *)calloc(1, sizeof(
     struct coroutine));
  co->stack = calloc(1, CORO_STACK_SIZE + 16);
  co->start = start;
  co->arg = ctxt;

  setjmp(co->env);
  // Those two lines are a machine-depenent hack to set the %rsp
      and %rip.
  // We do this so that we jump to the desired location and not
     back here.
  co->env[0].__jmpbuf[6] = ((uint64_t)(co->stack) +
     CORO_STACK_SIZE);
  co->env[0].__jmpbuf[7] = ((uint64_t)(start_cl));

  return co;
}
```

```
28
29 static void start_cl(void)
30 {
31   (cur_co->start)(cur_co->arg);
32   co_switchto(main_co);
33   printf("Error: returned from coroutine start closure.\n");
34   exit(-1);
35 }
36
37 extern void co_free(struct coroutine *self);
38
39 // switching coroutines
40 void co_switchto(struct coroutine *next)
41 {
42   if (setjmp(cur_co->env) == 0) {
43     cur_co = next;
44     longjmp(cur_co->env, 1);
45   }
46 }
47
48 void co_init()
49 {
50   main_co = (struct coroutine *)calloc(1, sizeof(struct
       coroutine));
51   cur_co = main_co;
52   co_switchto(main_co);
53 }
```

11.4.1 Coroutines in Decoder, Lexer Example

```
1 static char param;
2 struct coroutine *lx_co;
3 struct coroutine *dc_co;
4
5 #define DEC_PUTCHAR(c) do { param = c; co_switchto(lx_co); }
     while(0)
6 void decompress(void *ctxt)
7 {
8   int c;
9   int len;
10  printf("Started decompressor\n");
11  while ((c=getchar()) != EOF) {
12    if (c == ESCAPE) {
13      len = getchar();
14      c = getchar();
15      while (len--) {
16        DEC_PUTCHAR(c);
17      }
18    } else {
```

```
      DEC_PUTCHAR(c);
    }
  }
}

#define LEX_GETCHAR() ( co_switchto(dc_co), param )
void lexer(void *ctxt)
{
  int c;
  while ( (c = LEX_GETCHAR() ) != EOF) {
    if (isalpha(c)) {
      do {
        add_to_token(c);
        c = LEX_GETCHAR();
      } while (isalpha(c));
      got_token(WORD);
    } else {
      add_to_token(c);
      got_token(PUNCT);
    }
  }
}

int main(int argc, char *argv[])
{
  co_init();

  // Create the decompressor and lexer coroutines
  dc_co = co_new( decompress, NULL );
  lx_co = co_new( lexer, NULL );

  // Start by switching to the lexer
  co_switchto( lx_co );

  // When one of them returns or switches back to main, we're
     done.
  return 0;
}
```

To avoid passing the `char` with a global variable, one could modify `co_switchto()` to enable argument passing between coroutines:

```
void *co_switchto(struct coroutine *next, void *arg) {
  if (setjmp(cur_co->env) == 0) {
    cur_co = next;
    cur_co->arg = arg;
    longjmp(cur_co->env, 1);
  }
  return cur_co->arg;
}
```

11.5 Adding a Scheduler: "Not Quite Threads"

Coroutines enable a generalized control flow passing. It is known under many different names: Lightweight threads, Protothreads, Fibers, Cooperative multitasking, Goroutines, ...

So far, however, we are missing:

- true concurrency or parallelism as everything is executed on a single thread
- this is a directed context switch, so we have no scheduling
- no blocking/sleep+wakeup functionality
- no preemption (cannot pause a coroutines unless it hands of execution itself)

To create some approximation of threads, we now add a scheduler. This is used like:

1. Implement your threads as functions `void *threadName(void *arg)`.
2. Call `nathread_init()`.
3. Call `nathread_create(&nathreads[i], threadName, (void *)param)` for each thread with a unique i.
4. Call `nathread_schedule()`.

```
1  // Maximum number of nathreads we can create
2  #define MAX_NATHREADS 20
3
4  // State of each nathread - extend this for blocking/asleep/etc.
5  enum status { NAT_FREE = 0, NAT_RUNNABLE, NAT_EXITED };
6
7  // The nathread table itself
8  struct nat {
9    struct coroutine *co;
10   void *(*start)(void *);
11   void *arg;
12   enum status state;
13 } nathreads[MAX_NATHREADS] = {};
14
15 // What's currently running?
16 static nathread_t cur_nathread = NULL;
17
18 typedef struct nat *nathread_t;
19
20 // create a not-a-thread
21 int nathread_create(nathread_t *nt, void *(*start)(void *), void
       *arg) {
22   // Look for a free nathread in the array
23   for(int i=0; i < MAX_NATHREADS; i++) {
24     *nt = &nathreads[i];
25     if ((*nt)->state == NAT_FREE) {
26       // Initialize the nathread
27       (*nt)->start = start;
```

```
28        (*nt)->arg = arg;
29        (*nt)->co = co_new(wrapper, NULL);
30        (*nt)->state = NAT_RUNNABLE;
31        return 0;
32      }
33    }
34    return EAGAIN;
35  }
36
37  static void wrapper(void *arg) {
38    nathread_t nt = cur_nathread;
39    (nt->start)(nt->arg);
40    nathread_exit(nt->co->arg);
41  }
42
43  // terminate this thread with a return value
44  void nathread_exit(void *retval) {
45    cur_nathread->state = NAT_EXITED;
46    nathread_yield();
47  }
48
49  // switch to another nathread (not preemtion!)
50  void nathread_yield(void) {
51    co_switchto( main_co, NULL );
52  }
53
54  // initialize the package
55  void nathread_init(void) {
56    co_init();
57  }
58
59  // scheduler, run until nothing is runnable any more
60  void nathread_schedule(void) {
61    int t = 0;
62    do {
63      // Look for a runnable nathread
64      cur_nathread = NULL;
65      for(int i=0; i < MAX_NATHREADS; i++) {
66        t = (t + 1) % MAX_NATHREADS;
67        if ( nathreads[t].state == NAT_RUNNABLE) {
68          // Switch to this runnable nathread.
69          cur_nathread = &nathreads[t];
70          co_switchto( cur_nathread->co, NULL );
71          break;
72        }
73      }
74    } while (cur_nathread != NULL);
75  }
```

```c
#include <stdio.h>
#include "nt.h"

/*
* Very simple not-a-thread demo: just count to 3!
*/

static void *my_thread(void *arg)
{
  long index = (long)arg;
  for(int count=0; count < 3; count++) {
    printf("Not-a-thread %ld: count %d\n", index, count);
    nathread_yield();
  }
  return NULL;
}

#define NUM_NATHREADS 3

int main(int argc, char *argv[])
{
  nathread_t nathreads[ NUM_NATHREADS ];

  // Create our not-a-threads
  nathread_init();

  for( int i=0; i<NUM_NATHREADS; i++) {
    nathread_create( &nathreads[i], my_thread, (void *)(long)i )
       ;
  }

  // Enter the scheduler
  nathread_schedule();

  // Back here when nothing left to run
  return 0;
}
```

11.5.1 What is still Missing for Threads?

Although this is a pretty complete setup, it is still missing a few key aspects to be considered to implement the concept of threads.

- Join: Waiting for a `nathread` to terminate and get its return value.
- Blocking/sleep and wakeup: We would need to add a new sate `NAT_WAITING`. A signal would then handle to change the state back to `NAT_RUNNABLE`.
- Locks, condition variables: This is a trivial extension to sleep/wakeup.

- Parallelism (multiple cores): This is a bit tricky. We would need to synchronize the scheduler queue. For instance with a spinlock or atomics? Also, we would have to make changes to sleep/wakeup and store the state of thread per-core. For each core we would need to know the current thread.
- Preemption: So far, each coroutines/not-a-thread has to call `yield(...)`, which is called cooperative multitasking. Instead, we want a mechanism to asynchronously switch coroutines. That may be done with processor exception, which we will consider later.

All in all, the details of everything discussed in this section of unorthodox control flow proably isn' very relevant. Well, `setjmp` and `longjmp` should be understand. But the rest probably only is to illustrate what those (rather simple but still complex) functions enable.

12 Linking

We have already learned about the C toolchain/workflow. When we typically just say compiling, in reality multiple steps happen: preprocessing, compilation, assembling, and linking. We have already discussed preprocessing (`#` instructions/macros) and compilation of C functions and data structures. Assembling simply corresponds to converting the assembly into its binary equivalent. After assembling, we have an .o object file, but that is not executable yet. We will look at this .o file in depth here and what we have to do to make it executable.

At its core, (static) linking combines different compiled compilation units into one executable. This has to be done, because the different compilation units may depend on each other. For instance, one specifies an interface, which the other library knows exists (as it includes the header files), but the actual implementation is somewhere else.

Consider this example: We have two .c files, where `main.c` references a function in `swap.c` . Pre-processing, compilation, and assembling happens independently for each .c file/compilation unit. Thus, the assembled .o file of `main.c` can not contain a proper reference for the call to `swap()` as the compiler did not have any information about its location in memory.

Thus, we call those .o files relocatable object files. Only by using a linker, we can resolve those references and create an executable object file, which contains all necessary code and references.

Dynamic linking is still different. But the intuition for that is better built after static linking has been fully understood.

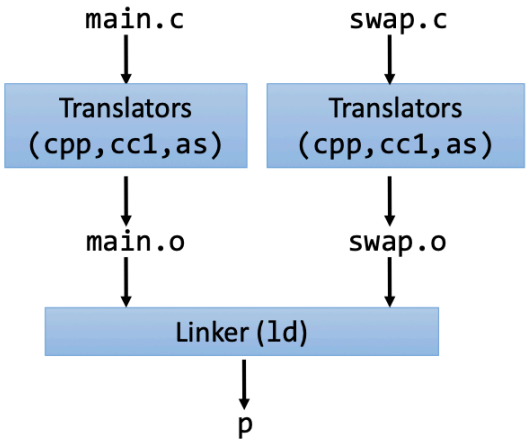


Figure 25: Static Linking Conceptually

Linking has many practical advantages:

- Without linking, we would be required to have everything in one compilation unit from the beginning.
- Separating compilation like this enables us to build libraries of common functionality which must not be built every time but only included through linking. But even without libraries, this increases efficiency, because when changing the content of one file, we only need to recompile that file and relink instead of recompiling the entire source code.
- Linking saves a lot of space. This will become apparent when we understand dynamic linking later on. We only include code for the functions which are actually unique to our program.

Notice that each .c file is considered separately for compilation. This means that we don't have any cross-file compilation optimizations. We accept this because we can rarely increase the performance by compiling across multiple files.

However, one thing that is sometimes done is called inlining. Inlining a function means to insert its code directly into the caller to avoid the calling overhead. But there are engineering concerns: Changes to the source but not modify the inlined function. This is prevented by including the inlined code in a header file which we include so that recompilation automatically happens. Generally, inlining is only helpful in certain cases (usually often called from one position such as loops), where the inlined function is small.

12.1 Linking in 2 Steps

12.1.1 Symbol Resolution

Every program defines and references symbols, which correspond to variables and functions.

Examples:

- `void swap(){...}` defines the symbol `swap`
- `swap();` references the symbol `swap`
- `int *xp = &x;` defines the symbol `xp` and references the symbol `x`

The compiler worked with the user-defined names for variables and functions but the assembler then works out the different symbols and puts all symbols into a symbol table. There is one entry for each symbol that is declared and/or referenced. The symbol table is an array of structs. Each entry/struct contains:

- symbol name
- symbol type
- symbol size
- symbol location (if known)
- (meta-information whether the symbol is static/its visibility etc.)

So this symbol table is created during assembling, i.e., even before the linker is involved. During its first step, the linker then looks at the symbol tables of multiple relocatable object files and resolves dependencies. It associates each symbol (reference) with exactly one symbol definition.

12.1.2 Relocation

After having figured out one definition for each referenced symbol, i.e., one large symbol table for each definition, relocation corresponds to merging the separate code and data sections of the different relocatable object file into a single executable file.

This also involves using the definitions figured out during symbol resolution to relocate symbols from their relative locations in the relocatable .o file to their final absolute memory locations in the executables.

Finally, all references to any symbols are updated according to their now defined position in the executable file. The memory layout chosen by the linker for this executable file has an impact on performance. Different layouts may result in different cache performance/misses.

12.2 Object Files

There are three types of object files.

- relocatable object file (.o file)

  Each .o file is created from exactly one .c file/compilation unit through compilation and assembling. It contains code and data in a form that can be combined with other relocatable object files.

- executable object file

  This contains code and data in a form that can be copied directly into memory and then executed. This requires that linking has been performed on the .o/relocatable object file. Also, executing an executable object file may required dynamic linking.

- sharable object file (.so file, DDLs on Windows)

  This is a special type of relocatable object files that can be loaded into memory and linked dynamically, at either load time or run-time. It is not an executable itself but a compiled library instead.

All those different types have had different formats depending on the specific machine. Today, we use ELF (Executable and Linkable Format) as the standard binary format for object files. This format was originally proposed by AT&T System V Unix and later adopted by basically everyone else.

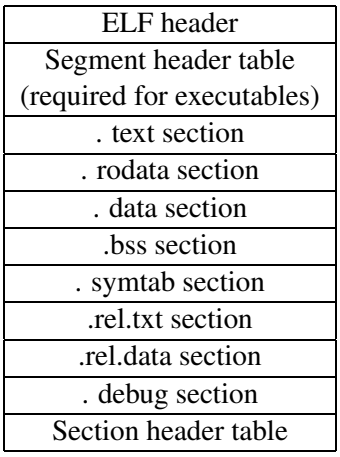


Figure 26: Basic Layout of ELF Binary

- ELF header

  word size, byte ordering (big/little endianess), file type (‘.o‘, ‘.so‘, ‘exec‘), machine type, ...

- segment header table

  page size, virtual address memory segments (sections), segment sizes

- ‘.text‘ sectoin

  code

- ‘.rodata‘ section

  read only data: jump tables, literals, ...

- ‘.data‘ section

  initialized global variables

- ‘.bss‘ section

  uninitialized global variables

  this has a section header but occupies not space in the object file

  still, memory addresses are already designated to the entries of this section

- ‘.symtab‘ section

  this is the symbol table

  it stores the names, locations, etc. of procedures and (static) variables

- ‘.rel.text‘ section

  relocation information for the ‘.text‘ section

  specifically:

  - addresses of instructions that will need to be modified in the executable

  - instructions for modifying those instructions

- ‘.rel.data‘ section

  relocation information for the ‘.data‘ section

  specifically:

  addresses of pointer data that will need to be modified in merged executable

- ‘.debug‘ section

  info for symbolic debugging

  enables getting the line number of the original ‘.c‘ file when sth. goes wrong for example

- section header table

  offsets and sizes of each section

  this comes last, because it was historically easies to compute this table in the end and append it then

12.3 Linker Symbols

The linker distinguishes between three types of linker symbols.

- global symbols: symbols defined by module `m` that can be referenced by other modules (e.g., ‘non-static‘ C functions and ‘non-static‘ global variables)
- external symbols: global symbols that are referenced by module `m` but defined by some other module
- local symbols: symbols that are defined and referenced exclusively by module `m` such as `static` functions and attributes. (local linker symbols are NOT local program variables!)

12.4 Example

Listing 87: `main.c`.

```c
int buf[2] = {1,2};

int main() {
  swap();
  return 0;
}
```

```
Disassembly of section .text:

0000000000000000 <main>:
   0:   48 83 ec 08      sub    $0x8,%rsp
   4:   b8 00 00 00 00   mov    $0x0,%eax
   9:   e8 00 00 00 00   callq  e <main+0xe>
                a: R_X86_64_PC32 swap-0x4
   e:   b8 00 00 00 00   mov    $0x0,%eax
  13:   48 83 c4 08      add    $0x8,%rsp
  17:   c3               retq
Disassembly of section .data:

0000000000000000 <buf>:
   0:   01 00 00 00 02 00 00 00
```

Figure 27: Disassembly of `main.c`

Listing 88: `swap.c`

```c
extern int buf[];

static int *bufp0 = &buf[0];
static int *bufp1;

void swap() {
  int temp;
  bufp1 = &buf[1];
  temp = *bufp0;
  *bufp0 = *bufp1;
  *bufp1 = temp;
}
```

```
Disassembly of section .text:

0000000000000000 <swap>:
   0:    55                       push   %rbp
   1:    48 89 e5                 mov    %rsp,%rbp
   4:    48 c7 05 00 00 00 00     movq   $0x0,0x0(%rip)
   b:    00 00 00 00
                 7: R_X86_64_PC32   .bss-0x8
                 b: R_X86_64_32S    buf+0x4
   f:    48 8b 05 00 00 00 00     mov    0x0(%rip),%rax
                 12: R_X86_64_PC32  .data-0x4
  16:    8b 00                    mov    (%rax),%eax
  18:    89 45 fc                 mov    %eax,-0x4(%rbp)
  1b:    48 8b 05 00 00 00 00     mov    0x0(%rip),%rax
                 1e: R_X86_64_PC32  .data-0x4
  22:    48 8b 15 00 00 00 00     mov    0x0(%rip),%rdx
                 25: R_X86_64_PC32  .bss-0x4
  29:    8b 12                    mov    (%rdx),%edx
  2b:    89 10                    mov    %edx,(%rax)
  2d:    48 8b 05 00 00 00 00     mov    0x0(%rip),%rax
                 30: R_X86_64_PC32  .bss-0x4
  34:    8b 55 fc                 mov    -0x4(%rbp),%edx
  37:    89 10                    mov    %edx,(%rax)
  39:    5d                       pop    %rbp
  3a:    c3                       retq
Disassembly of section .data:

0000000000000000 <bufp0>:
   0:    00 00 00 00 00 00 00 00
                 0: R_X86_64_64   buf

Disassembly of section .bss:

0000000000000000 <bufp1>:
   0:    00 00 00 00 00 00 00 00
```

Figure 28: Disassembly of `swap.c`

```
00000000004004ed <main>:
  4004ed: 48 83 ec 08              sub    $0x8,%rsp
  4004f1: b8 00 00 00 00           mov    $0x0,%eax
  4004f6: e8 0a 00 00 00           callq  400505 <swap>
  4004fb: b8 00 00 00 00           mov    $0x0,%eax
  400500: 48 83 c4 08              add    $0x8,%rsp
  400504: c3                       retq

0000000000400505 <swap>:
  400505: 55                       push   %rbp
  400506: 48 89 e5                 mov    %rsp,%rbp
  400509: 48 c7 05 3c 0b 20 00     movq   $0x60103c,0x200b3c(%rip) # 601050 <bufp1>
  400510: 3c 10 60 00
  400514: 48 8b 05 25 0b 20 00     mov    0x200b25(%rip),%rax      # 601040 <bufp0>
  40051b: 8b 00                    mov    (%rax),%eax
  40051d: 89 45 fc                 mov    %eax,-0x4(%rbp)
  400520: 48 8b 05 19 0b 20 00     mov    0x200b19(%rip),%rax      # 601040 <bufp0>
  400527: 48 8b 15 22 0b 20 00     mov    0x200b22(%rip),%rdx      # 601050 <bufp1>
  40052e: 8b 12                    mov    (%rdx),%edx
  400530: 89 10                    mov    %edx,(%rax)
  400532: 48 8b 05 17 0b 20 00     mov    0x200b17(%rip),%rax      # 601050 <bufp1>
  400539: 8b 55 fc                 mov    -0x4(%rbp),%edx
  40053c: 89 10                    mov    %edx,(%rax)
  40053e: 5d                       pop    %rbp
  40053f: c3                       retq
Disassembly of section .data:

0000000000601038 <buf>:
  601038:    01 00 00 00 02 00 00 00

0000000000601040 <bufp0>:
  601040:    38 10 60 00 00 00 00 00

Disassembly of section .bss:

0000000000601050 <bufp1>:
  601050:    00 00 00 00 00 00 00 00
```

Figure 29: Disassembly of Relocated File

12.5 Strong and Weak Symbols

When considering symbols, the linker behaves differently depending of whether symbols are considered strong or weak. By default, strong symbols are procedures/functions and initialized globals. Weak symbols are uninitialized globals if we set `-fcommon` and strong otherwise.

`-fcommon` has been the default even a few years ago. But today, the default is `-fno-common`, which means that also uninitialized globals are strong symbols.

Then linking, the linker proceeds as follows with those two symbol types:

1. Multiple strong symbols are NOT allowed (each item can be defined only once).
2. Given a strong symbol and multiple weak symbols, the strong symbol is chosen as the definition and references to the weak symbols resolve to the strong symbol.
3. If there are (only) multiple weak symbols, the linker picks an arbitrary one.

One challenge is that the symbols might not even refer to the same type so that writing to the same symbol may lead to writing to 64 bytes (if considered double) even if defined as 32 bit int. This leads to unintended behavior without a guaranteed compiler/linker warning.

Variables/symboles declared with `extern` always rely on a definition in another file. If such a definition is not provided, we get an error. Usually, `extern` symbols have a strong version somewhere.

We rarely make a symbol explicitly weak. By by default everything is strong. However, we can use a pragma to declare a symbol as weak: `__attribute__((weak));`.

Avoid ambiguities and difficulties by never letting such cases arise. Use `static` if possible and either initialize a global variable or use `extern`.

12.6 Static Libraries

Now we consider how to package and include functions commonly used by programmers such as math, I/O, memory management (malloc, ...), string manipulation, ... With the system so far, we have two options: Either put all functions into a single source file which is space and time inefficient (big objects file linked of which only a fraction is needed) or put each function in a separate source file which is efficient but burdensome on the programmer (must explicitly link/include all files).

The solution to this are static libraries. Those are .a archive files, which concatenate related relocatable object files into a single file with an index (called an archive). An enhanced linker now tries to resolve all references by considering the provided files. But if there are still unresolved references in the end, the linker looks for those in specified (or default) libraries. If an archive member file resolves a reference, it links that into the file.

An archive can be created from .o files using an archiver (`ar` on linux). Notice that each function from such as `printf` etc. must still be given through its own .c file so that it gets its own .o file. The archiver allows incremental updates and recompiles functions that changed and replaces their .o file in the archive.

Commonly-used libraries are `libc.a` (the C standard library), which as over 900 object file in 8 MB memory for I/O, memory allocation, signal handling, string allocation, data and time, random numbers, integer math, ... Also, `libm.a` (the C math library) is usually a default library. It has 226 object files and is 1 MB in size. It provides floating point math functionality such as sin, cos, tan, log, exp, sqrt, ...

When resolving dependencies, the linker proceeds like this:

1. Scan .o files and .a files in the command line order.
2. During the scan, keep a list of the current unresolved references.
3. As each new .o or .a file, is encountered, try to resolve each unresolved reference in the list against the symbols defined in that file.
4. If any entries in the unresolved list at end of scan, then error.

This means that the command line order matters. The default libraries should always come later if we want to overwrite them with custom implementations. In practice this means that libraries should be put at the end of the command line. In modern linkers, we may also specify batches for the processing order.

12.7 Shared Libraries

Static libraries have some disadvantages:

- duplication in the stored executables
- duplication in the running executables
- (minor) bug fixes of system libraries require each application to explicitly relink

Shared libraries address those issues. We consider executable object files, which have not all symbols resolved. Instead, at load-/run-time, specific object files (.so on linux, dynamic link libraries (DLLs) in windows) are linked into an application dynamically.

Dynamic linking of shared libraries can happen in two ways:

- load-time linking

  This is the common case for Linux and handled automatically by the dynamic linker (`ld-linux.so`). The standard C library (`libc.so`) is dynamically linked, for instance.

- run-time linking

  In Unix, this is done by calls to the `dlopen()` interface

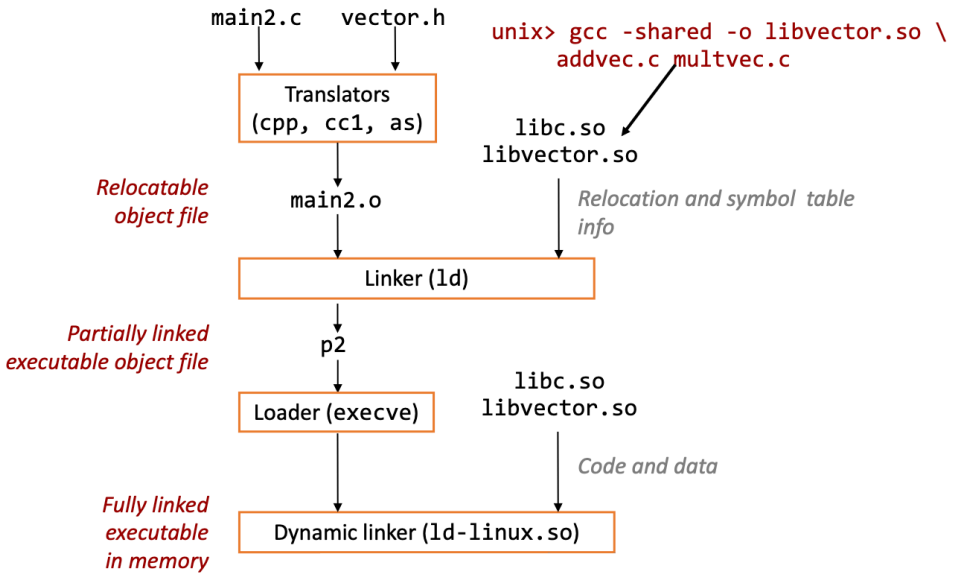


Figure 30: Dynamic Linking at Load Time

Listing 89: Dynamic Linkin gat Run Time

```
#include <stdio.h>
#include <dlfcn.h>
int x[2] = {1,2};
int y[2] = {3,4};
int z[2];

int main(int argc, char *argv[]) {
  void *handle;
  void (*addvec)(int *, int *, int *, int);
  char *error;

  /* dynamically load the shared lib that contains addvec() */
  handle = dlopen("./libvector.so", RTLD_LAZY);
  if (!handle) {
    fprintf(stderr, "%s\n", dlerror());
    exit(1);
```

```
  }
  /* get a pointer to the addvec() function we just loaded */
  addvec = dlsym(handle, "addvec");
  if ((error = dlerror()) != NULL ){
    fprintf(stderr, "%s\n", error);
    exit(1);
  }

  /* Now we can call addvec() it just like any other function */
  addvec(x,y,z,2);
  printf("z = [%d %d] \n", z[0], z[1]);

  /* unload the shared library */
  if (dlclose(handle) < 0 ) {
    fprintf(stderr, "%s\n", dlerror());
    exit(1);
  }
  return 0;
}
```

12.8 Library Inter-Positioning

One technique is called library inter-positioning. It allows programmers to intercept calls to arbitrary functions by providing that function themselves and then linking the library after some processing is done beforehand. Inter-positioning can occur at compile-time, link-time or load-/run-time.

We use inter-positioning for several reasons:

- security: confinement (sandboxing) and behind the scenes encryption
- monitoring and profiling: count number of calls to functions, characterize call sizes and arguments to functions, malloc tracing

Listing 90: Intercepting `malloc` to Count Calls

```
void *malloc(size_t size){
  static void *(*fp)(size_t) = 0;
  void *mp;
  char *errorstr;

  /* Get a pointer to the real malloc() */
  if (!fp) {
    fp = dlsym(RTLD_NEXT, "malloc");
    if ((errorstr = dlerror()) != NULL) {
      fprintf(stderr, "%s(): %s\n", fname, errorstr);
      exit(1);
    }
  }

  /* Call the real malloc function */
  mp = fp(size);
```

```
17
18    mem_used += size;
19
20    return mp;
21  }
```

13 Code Vulnerabilities

13.1 Worms and Viruses

First, we can distinguish between worms and viruses. A worm is a program than can run by itself and can propagate a fully working version fo itself to other computers. A Virus is a program that adds itself to other programs and cannot run independently. Both types can cause wide destruction of data and computer networks.

The term worm was coined by early cyberpunk/sci-fi novels. And initial worms weren't necessarily malicious. They were used to gather status data or meta-information.

Probably the first internet worm was designed by Robert Morris in 1988. While convicted, he is now a distinguished professor at MIT and had not harmfulinternetintentions. His goal was to count the number of hosts connected to the interview. The following subsections are just some of the vulnerabilities his worm exploited.

13.2 Stack Overflow Bugs

Stack Overflow Bugs as considered here are a special type of overflow bugs. Those must not always occur on the stack. If they occur on the heap, we call them heap overflow bugs, for instance.

The `gets()` function is a vulnerable function.

Listing 91: Vulnerable `gets()` Function

```
1  char *gets(char *dest)
2  {
3      int c = getchar();
4      char *p = dest;
5      while (c != EOF && c != '\n') {
6      *p++ = c;
7      c = getchar();
8      }
9    *p = '\0';
10   return dest;
11 }
```

This does not limit the number of characters read and, hence, may write read characters beyond the allocated memory section provided with the pointer 'char *dest'. If this pointer is located on the stack, we can overwrite other's stack frames and also the return address if we are a function ourselves and, thus, redirect to malicious code. Other Unix functions such as `strcpy`, `scanf`, `fscanf`, and `sscanf` (when using `%s`) are analogously vulnerable.

Listing 92: Example Misuse of `gets`

```
int main() {
  printf("Type a string:");
  echo();
  return 0;
}

void echo() {
    char buf[4];  /* Way too
       small! */
    gets(buf);
    puts(buf);
}
```

Listing 93: Compiled Version

```
00000000004005bd <echo>:
  sub    $0x18,%rsp
  mov    %rsp,%rdi
  callq  4004c0 <gets@plt>
  mov    %rsp,%rdi
  callq  400480 <puts@plt>
  add    $0x18,%rsp
  retq

00000000004005d6 <main>:
  sub    $0x8,%rsp
  mov    $0x400684,%edi
  mov    $0x0,%eax
  callq  400490 <printf@plt>
  mov    $0x0,%eax
  callq  4005bd <echo>
  mov    $0x0,%eax
  add    $0x8,%rsp
  retq
```

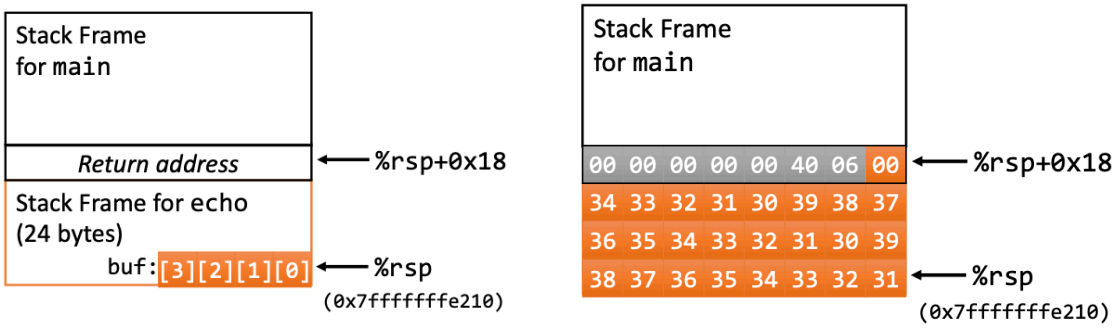


Figure 31: Buffer Overflow Stack & Memory Layout

With `123` as input everything is fine, as with `1234567` as input, although we already write beyond the bounds of the buffer `buf`. That is as the compiler inserted some padding in memory. When we input `12345678901234567890123`4, we get a segmentation fault.

Nevertheless, the compiler wants to help us and may detect some of those vulnerabilities and print warning or may refuse to compile. We use the `gcc` flags as in this command `gcc -D_FORTIFY_SOURCE=0 -fno-stack-protector -0 -S bufdemo` to turn of those protections.

A more sophisticated approach may first write some exploit code, then some padding, and use the return address to jump to the just written exploit code. Notice that this only works if security mechanism, which prevent from executing instructions from the stack, are not active.

Furthermore, one usually wants to know the source code to plan the memory layout, the endianness of the target machine, as well as its architecture. Otherwise, this attack is a shot in the dark and one has to do much try and error.

Generally, such buffer overflow bugs allow remote machines to execute arbitrary code on vic-

tim machines!

But because we only discussed stack overflow bugs, this doesn't mean that heap overflow bugs aren't fatal! They can mess with (segregated) linked list used by malloc to redirect the execution.

13.3 Buffer Overflow Bugs

Here, we consider the `SUN XDR` library as an example to see that overflows on the heap and not only on the stack are destructive. While we don't store return addresses on the heap, we can mess with the dynamic memory allocators meta-information and change the (segregated) linked-list used for memory management.

More specifically: There are function pointers on the heap. We set free bits and prev/next pointers in a memory chunk to hijack control flow, when the memory allocator coalesces 'free' blocks

Listing 94: Vulnerable Function of the XDR Library

```
void* copy_elements(void *ele_src[], int ele_cnt, size_t
    ele_size) {
  void *result = malloc(ele_cnt * ele_size);
  if (result == NULL)
    /* malloc failed */
    return NULL;
  void *next = result;
  int i;
  for (i = 0; i < ele_cnt; i++) {
    /* Copy object i to destination */
    memcpy(next, ele_src[i], ele_size);
    /* Move pointer to next memory region */
        next += ele_size;
    }
    return result;
}
```

The issue arises from the computation `ele_cnt * ele_size` in `malloc`. On a 32-bit machine, we can set $ele\_cnt = 2^{20} + 1$ and $ele\_size = 4096 = 2^{12}$ so that the multiplication is just `ele_size`. Thus, way to little memory is allocated and we can write beyond the allocated memory location when copying the data continuously.

13.4 Stopping Overrung Bugs

13.4.1 Avoiding Overflow Vulnerability

Instead of `gets()` or similar functions, we use library routines that limit the string lengths. Use `fgets` instead of `gets` Use `strncpy` instead of `strcpy` Use `%ns`, where n is a suitable integer in `scanf` or similar.

13.4.2 System-Level Protections

- The compiler can insert checks on functions.

  It may add some arbitrary values in code and check during runtime whether they have been modified, i.e., whether a buffer overflow may have occurred.

- Randomized stack offsets.

  During execution, a random offset can be added to the stack. Then, it is more difficult for attackers to predict memory locations of different segments and successfully redirect control flow. This is done by default in moern machines.

- Nonexecutable code segments

  Besides flags declaring sections as 'read-only' or 'writeable', we may also change the permission 'execute' so that the CPU just won't execute code, which is located on the stack, so that no malicious code can be injected.

13.5 Attack Method: Return Oriented Programming

This is an approach of attackers to deal with limitations on executing dynamically inserted code on the stack. Instead, the addresses are overwritten so that the control flow jumps to and executes cherry-picked machine instruction sequences, which are already present in the application process memory. Those 'useful' instruction sequences are called 'gadgets'.

14 Floating Point Numbers

14.1 Representing Floating-Point Numbers

14.1.1 Fractional Binary Numbers

We start by considering fractional binary numbers in general. They work very similarly to fractional decimal numbers, just using 2 instead of 10 as the base. Bits to the right of the binary point represent fractional powers of 2. Thus: Division by 2 corresponds to shifting right. Multiplication with 2 corresponds to shifting left. And there are fractions, which cannot be exactly represented in this notation. Only numbers of the form $\frac{x}{2^k}$ can be exactly represented. Numbers which can not precisely expressed are for example:

- $\frac{1}{3}$ is $0.0101010101[01]\ldots_2$
- $\frac{1}{5}$ is $0.001100110011[0011]\ldots_2$
- $\frac{1}{10}$ is $0.0001100110011[0011]\ldots_2$

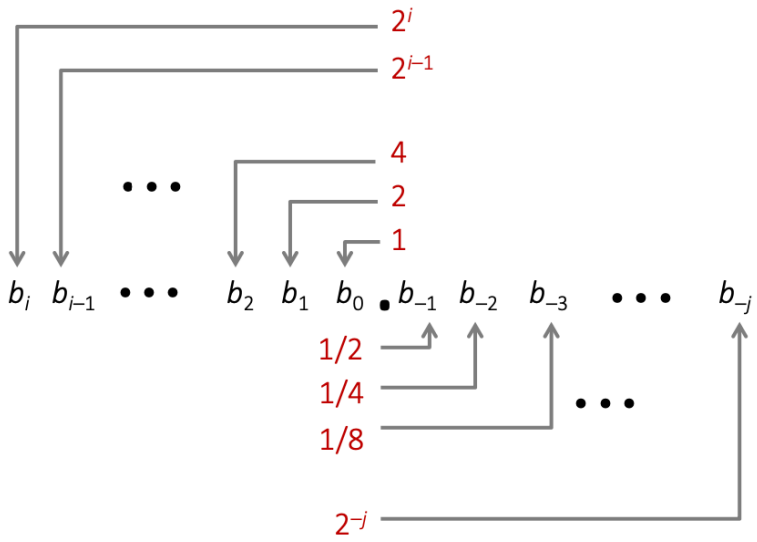


Figure 32: Fractional Binary Numbers

$$\sum_{k=-j}^{i} b_k \cdot 2^k$$

14.1.2 IEEE Floating Point

This is a standard that was established in 1985 to have uniform floating point arithmetics. Before, many custom formats existed. Luckily, all major manufacturers were part of the commission so that the standard is adopted by all major CPUs. The definition was driven by numerical concerns. Numerical scientists wanted a nice standard for rounding, overflow, underflow, ... That came at the tradeoff of being rather difficult to implement in hardware.

The most general form of floating points looks numerically like

$$(-1)^s.M.2^E$$

where s, M, and E are the parameters to define a number.

- s: sign
- M (significant): fractional value, normally in the range $[1.0, 2.0)$ (normalized but in special case also $[0.0, 1.0)$).
- E: exponent, weights value by a power of two

Figure 33: IEEE Floating Point Encoding

- the MSB is the sign bit s
- `exp` encodes E but is not E
- `frac` encodes M but is not M

The details of the encoding scheme will be part of the next subsection.

14.2 Types of IEEE Floating-Point Numbers

If we designate different amounts of bits to ‘exp‘ and ‘frac‘, we get different precision for the representable numbers. Thus, the standard defines two original precisions: IEEE 754 Single Precision (32 bits) and IEEE 754 Double Precision (64 bits).

precision	significant bits	exponent bits	total
half	11	5	16
single	24	8	32
double	53	11	64
quadruple	113	15	128
octuple	237	19	256
Google bfloat16	7	8	16
Nvidia TensorFloat	10	8	19
AMD fp24	17	7	24

Figure 34: Floating Point Precisions

In this table, the sign is counted as part of the significant bits.

In C99, single precision is guaranteed with `float` and double precision is guaranteed with `double`. `long double` etc. usually correspond to what we expect such as quadruple precision but it is implementation defined and not guaranteed by the standard.

Furthermore, we have seen conversion of ‘int‘, ‘char‘, ... as just reinterpreting the bit representation. Here, we instead actually change the bit representation when casting/converting.

- `double`/`float`→`int`

  This truncates the fractional part (like rounding toward zero). When the result is out of range or NaN, this is implementation defined but generally `TMin`.

- `int`→`double`

  This is an exact conversion as an `int` has ≤ 53 bits

- `int`→`float`

  This will round according to rounding mode. We will see (default) rounding later.

14.2.1 Normalized Values

This is the case if `exp`≠`000...0` and `exp`≠`111...1`.

- exponent

  This is encoded as a biased value: `E = exp - bias`, where `exp` is the unsigned value in hardware. `bias`$= 2^{e-1} - 1$, where e is the number of exponent bits. This leads to roughly half of the exponents being above and half below zero.

  single precision: 127 (-126...127)

  double precision: 1023 (-1022...1023)

- significant

  Because values of normalized values are in $[1.0, 2.0)$, we have `1.xxx...x`. Thus, the leading 1 is implied and mustn't be stored.

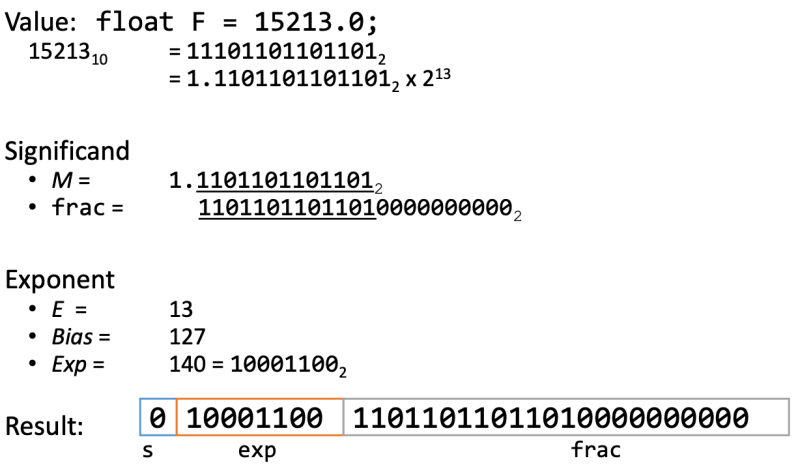


Figure 35: Normalized Encoding Example

14.2.2 Denormalized Values

This is the case if `exp`=`000...0`.

- exponent

  The `bias` is computed as for normalized values. Then, the exponent is `E = -bias + 1`. So we add 1 to get the same exponent as in the case where the exponent is 1.

- significant

  With denormalized values, we have values in `[0.0,1.0)`. So, we implicitly encode with a leading `0`.

Thus, with `frac = 000...0` we encode zero. (One, for each sign.)

14.2.3 Special Values

This is the case if `exp = 111...1`.

- `frac = 000...0`

  This represents ∞ and is assigned of an operation overflows. Notice that we still have the sign bit and, thus, have positive and negative infinity.

- `frac`$\neq$`000...0`

  This corresponds to 'NaN' (Not-a-Number). This is assigned whenever a numeric value can't be assigned, such as `sqrt(-1)`, $\infty - \infty$, $\infty * 0$.

14.2.4 Interesting Numbers & Properties

description	exp	frac	numerical value
Zero	$00\ldots00$	$00\ldots00$	0.0
Smallest pos. denorm. - Single $\approx 1.4 \times 10^{-45}$ - Double $\approx 4.9 \times 10^{-324}$	$00\ldots00$	$00\ldots01$	$2^{-\{23,52\}} \times 2^{-\{126,1022\}}$
Largest denormalized - Single $\approx 1.18 \times 10^{-38}$ - Double $\approx 2.2 \times 10^{-308}$	$00\ldots00$	$11\ldots11$	$(1.0 - \varepsilon) \times 2^{-\{126,1022\}}$
Smallest pos. normalized - Just larger than largest denormalized	$00\ldots01$	$00\ldots00$	$2^{-\{126,1022\}}$
One	$01\ldots11$	$00\ldots00$	1.0
Largest normalized - Single $\approx 3.4 \times 10^{38}$ - Double $\approx 1.8 \times 10^{308}$	$11\ldots10$	11...11	$(2.0 - \varepsilon) \times 2^{\{127,1023\}}$

Figure 36: Interesting Floating Point Numbers

We can almost use unsigned integer comparison to compare floating point numbers. We must only consider to first compare the sign bit, the special values NaN and ∞ and $-\infty$ as well as that $-0 = 0$.

14.3 Floating-Point Spacing

Spacing decreases with distance for normliazed values so that the relative errors stays roughly the same. But there are always blocks according to the size of `frac` which have the same spacing. The denormalized values have the same spacing as the smallest normalized values to fill the entire gap to 0.

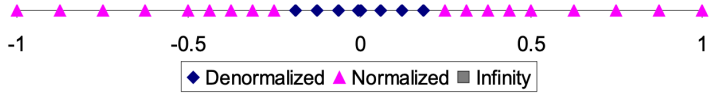


Figure 37: Floating Point Spacing

14.4 Floating-Point Rounding

The basic idea is to define floating point operations is that we would first compute the exact result and then make it fit into the desired precision. If the result is too large, we may get an overflow. And we likely have to round to fit the `frac` into the given number of bits.

So that we can deal with operations, let's understand rounding first. We have four rounding modes of which nearest even is the default one.

	CHF 1.40	CHF 1.60	CHF 1.50	CHF 2.50	CHF -1.50
Towards zero	1	1	1	2	-1
Round down $(-\infty)$	1	1	1	2	-2
Round up $(+\infty)$	2	2	2	3	-1
Nearest Even (default)	1	2	2	2	-2

Figure 38: Rounding Modes Illustration

Nearest Even/"round-to-even" is the default rounding mode for IEEE FP. It means we do 'normal' rounding to the closest number unless we're EXACTLY in between two. Then, we round to the even one. Compared to the other modes, this is the only which is statistically unbiased. All others consistently over-/under-estimate.

Value	Binary	Rounded	Action	Result
$23/32$	10.00011_2	10.00_2	$< 1/2$: down	2
$23/16$	10.00110_2	10.01_2	$> 1/2$: up	$21/4$
$27/8$	10.11100_2	11.00_2	$= 1/2$: up	3
$25/8$	10.10100_2	10.10_2	$= 1/2$: down	$21/2$

Figure 39: Rounding Examples

To consider rounding further, we assume that we are given a real number and want to create a floating pointer from it. We assume that `exp` has 4 bits and that `frac` has 3 bits.

14.4.1 Normalize to Have Leading 1

This will introduce the exponent. Specifically, we start with exponent 0 and decrement the exponent as we shift left/increment as we shift right.

Value	Binary	Fraction	Exponent
128	10000000	1.0000000	7
13	00001101	1.1010000	3
17	00010001	1.0001000	4
19	00010011	1.0011000	4
138	10001010	1.0001010	7
63	00111111	1.1111100	5

Figure 40: Normalization Examples

14.4.2 Round to Fit Within Fraction

Second, we have to round the fraction so that it fits within the designated bits. We denote the bits at the edge of the length of our `frac` with GRS as in the next figure.

Figure 41: Creating Special Rounding Bits

- round $= 0 \Rightarrow$ round down/truncate
- round = 1, sticky = 1 $\Rightarrow$ round up
- round = 1, sticky = 0 $\Rightarrow$ round to even
  - ground $= 1 \Rightarrow$ round up
  - ground $= 0 \Rightarrow$ round down/truncate

Value	Fraction	GRS	Incr?	Rounded
128	1.0000000	000	N	1.000
13	1.1010000	100	N	1.101
17	1.0001000	010	N	1.000
19	1.0011000	110	Y	1.010
138	1.0001010	011	Y	1.001
63	1.1111100	111	Y	10.000

Figure 42: Rounding Fraction Examples

14.4.3 Postnormalize to Deal with Effects of Rounding

Finally, rounding up might have led to an overflow. In that case, we have to shift right and increment the exponent to postnormalize.

Value	Rounded	Exp	Adjusted	Result
128	1.000	7		128
13	1.101	3		13
17	1.000	4		16
19	1.010	4		20
138	1.001	7		134
63	10.000	5	1.000/6	64

Figure 43: Postnormalization Example

14.5 Floating-Point Addition and Multiplication

14.5.1 Floating-Point Multiplication

$$(-1)^s M 2^E = (-1)^{s1} M_1 2^{E1} \times (-1)^{s2} M_2 2^{E2}$$

- new sign $s = s_1 \hat{} s_2$

- new significand $M = M_1 \cdot M_2$
- new exponent $E = E_1 + E_2$

But this theoretical result probably doesn't fit into the floating point representation. If $M \geq 2$, M needs to be shifted right and the exponent must be incremented. If E is out of range, we have an overflow and get ∞. Finally, M must be rounded to fit into `frac` precision.

The most difficult past is multiplying the significands, but that can be done by the already existing integer multiplier.

Mathematical Properties of Comm. Ring	**FP Multiplication ($\neq$ Real Number Mult.)**
closed under multiplication	yes (but may generate infinity or NaN)
commutativity	yes
associativity	no (due to overflow and inexactness of rounding)
1 as multiplicative identity	yes
multiplication distributes over addition	no

Figure 44: Mathematical Properties of Floating Point Multiplication

Monotonicity holds except for infinities and NaNs.

14.5.2 Floating-Point Addition

$$(-1)^s M 2^E = (-1)^{s1} M_1 2^{E1} + (-1)^{s2} M_2 2^{E2}$$

where $E_1 > E_2$ without loss of generality.

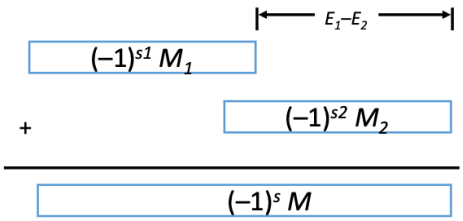


Figure 45: Signed Align and Add

The result of addition is simply signed align and add. Thus, the exponent of the result is just E_1 if we don't have to modify it due to shifting and rounding in the end. Specifically, because the precise result likely won't fit in our floating point representation, we have to modify the result:

- If $M \geq 2$, shift M right and increment E.
- If $M < 1$, shift M left k positions, decrement E by k
- overflow if E out of range
- round M to fit `frac`

Mathematical Properties of Abelian Group	FP Addition ($\neq$ Real Number Add.)
closed under addition	yes (but may generate infinity or NaN)
commutativity	yes
associativity	no (due to overflow and inexactness of rounding)
O as additive identity	yes
every element has additive inverse	almost (except infinities and NaNs)

Figure 46: Mathematical Properties of Floating Point Addition

Additionally, monotonicity holds except for infinities and NaNs.

It follows that the order of adding FP numbers matters. We should always add from small to large numbers after sorting.

14.6 Floating Poin Puzzles

`x == (int)(float)x`

- This does not always hold, because a float may not store all integers.
- Floats have 24 significant bits, so they don't have the precision of 31 bits of a signed int.
- #significantBits ¿ #numberBitsInt

`x == (int)(double)x`

- This always holds, because the significant bits of a double have a enough precision for an int.

`f == (float)(double)f`

- This always holds, because a double may store a float without precision loss.

`d == (float)d`

- This does not always hold, because when comparing, we implicitly cast so that no precision is lost (f loat $\rightarrow$ double). Hence, we may loose precision of d when having it as a float in an intermediate step. This is as with integers, which are also promoted so that accuracy is preserved.

`f == -(-f)`

- This always holds, because floating points numbers are fully symmetric. We have a sign bit.

`2/3 == 2/30.`

- This does not always hold.
- `2/3` becomes 0 in integer arithmetic. After promoted to a floating point number, it does not equal the fraction of `2/30`. (being floating point division as 2 is promoted to a floating point number).

`d<0.0`⇒`((d*2)<0.0)`

- This always holds. Going to infinity would still preserve this equality.

`d>f`⇒`-f>-d`

- This always holds.
- Negation is just flipping the sign bit.

`d*d >= 0.0`

- This only breaks if `d` is `NaN`.

`(d+f)-d == f`

- This does not always hold, because `d+f` may become infinity, which remains infinity even with `-d`. And ∞ may $\neq$`f`.

14.7 SSE Floating Point

This refers to 'Streaming SIMD Extensions', which is an extension to the x86 architecture to support floating point arithmetics. We refer to them as SIMD, because they operate as vector instructions, which allows parallel operation on small vectors of integers or floats.

They are available with Intel's SSE family starting with Pentium 3, which supported 4-way single precision instructions. With SSE2 from Pentium 4, we also had 2-way double precision instructions. An all x86-64 processors have SSE3, which is a superset of SSE2 and SSE. Originally with the 8086 processor, one had to connect a separate unit (8087) to enable IEEE floating point arithmetic.

The floating point SSE instructions work on separate SSE3 registers. Those are 16 128 bit/16 byte register, which each can store 2 double precision or 4 single precision floating point numbers. They are named `%xmm0` to `%xmm15`. All of those are caller saved and we pass arguments in `%xmm0` to `%xmm7`. Further arguments are passed on the stack. The return value is stored in `%xmm0`.

In those `XMM` registers, we can store different data types and have different associated instructions accordingly.

- integer vectors: 16-way bytes, 8-way 2 bytes, 4-way 4 bytes/`int`

Figure 47: Integer Vectors in `XMM` Registers

- floating point vectors: 4-way single precision, 2-way double precision

Figure 48: Floating Point Vectors in `XMM` Registers

- floating point scalars: single precision, double precision

Figure 49: Floating Point Scalars in `XMM` Registers

As one can store integer vectors in those register, there are also integer operations. But we focus on floating point instructions, which look like `operation + single slot/packed + single precision/double precision`.

- `addps %xmm0 %xmm1`

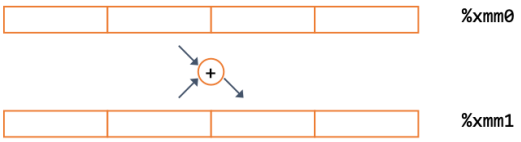


Figure 50: Integer Vectors in `XMM` Registers

- `addss %xmm0 %xmm1`

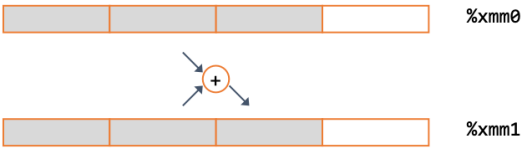


Figure 51: Floating Point Vectors in `XMM` Registers

Some more instructions:

- `movss S D: D <- S`
- `addss S D: D <- D + S`
- `subss S D: D <- D - S`
- `mulss S D: D <- D * S`
- `divss S D: D <- D / S`
- `maxss S D: D <- max(D,S)`
- `minss S D: D <- min(D,S)`
- `sqrtss S D: D <- sqrt(S)`

Furthermore, there are instructions to convert between single and double precision as well as integers and and floating point numbers:

- `cvtss2sd: single -> double`
- `cvtsd2ss: double -> single`

- `cvtsi2ss`: `int -> single` (rounding)
- `cvtsi2sd`: `int -> double` (rounding)
- `cvtsi2ssq`: `quad int -> single` (rounding)
- `cvtsi2sdq`: `quad int -> double` (rounding)
- `cvttss2si`: `single -> int` (truncation)
- `cvttsd2si`: `double -> int` (truncation)
- `cvttss2siq`: `single -> quad int` (truncation)
- `cvttsd2siq`: `double -> quad int` (truncation)

When the `int` can't contain the `double` (being `NaN`, ∞, ...) the `int` gets `T_MIN` in most cases. But this is undefined behavior technically. And when converting with packed and between differently sized types (single and double precision), we convert only as many entries as possible with the larger type and always consider the lowest blocks in the register if we can not fill the entire register.

When using floating point constants in code, the assembly looks unexpected. That is mostly, because assembly doesn't support floating point numbers in a sense, that we can only express bits and show them as integers. Thus, double precision floating point numbers will be stored as two consecutive `.long` (two 32 bit numbers). In the assembly, we see the respective int representation of those 32 bits listed separately.

When writing C code with floating pint numbers, one can instruct the compiler to vectorize the instructions instead of only operating on one floating point value at a time. With `gcc` one can use the flag `-ftree-vectorize` for example. But a speedup is not guaranteed and the optimizations are rather limited. `icc` (Intel compiler) is much better at autovectorizing. To get really high performance one has to do the vectorization oneself. To do so, one uses intrinsics, the C interface to vector instructions.

Intel AVX512 is a more recent extension and support 8-way double and 16-way single precision vectorization.

To get the highest performance, one often resorts to GPUs. Those support very high parallelism with several thousands of threads even on older cards. But programming GPUs is very hard, because one can't use generic C. Programming involves using frameworks/languages such as CUDA or OpenCL. There is also little support for higher-level languages, because compilers struggle to vectorize (complicated) code without a lot of code annotation. Restrictions for vectorization include: data must be aligned, data cannot overlap, loop sizes must be multiple of vector width, ...

15 Optimizations

Here, we consider how the compiler can optimize our code during compilation to increase performance. In the workflow/pipeline required to get an executable from a .c file, this is part of the actual compilation done by `cc1`. We will see what things the compiler can do to help and what may stop the compiler from doing so. Also, we learn about optimizations we can do manually but the compiler can't do by itself for various reasons.

We often consider matrix multiplication as an example of the different concepts here. As already seen in the introduction to the course, we can speed up matrix multiplication noticeably. The main speedup (20x) comes from: blocking/tiling, loop unrolling, array scalarization, instruction scheduling, ... This increases instruction level parallelism (ILP), leads to better register use, and reduces cache misses. That is all possible although all codes use the same fundamental approach of three nested loops with asymptotic complexity $\mathcal{O}(n^3)$.

We already know about asymptotic complexity from other classes. While constants are neglected there, they matter in the real world. Those aspects (among others) impact runtime performance:

- constants
- coding style (unnecessary procedure calls, unrolling, reordering, ...)
- algorithm structure (locality, ILP, ...)
- data representation (complicated structs or simple arrays)

To get very good performance, one must optimize at multiple levels: algorithms, data representation, procedures, loops, ... We try to understand how the compiler optimizes with consideration of execution and memory units to write the best code. This also includes measuring program performance and identifying bottlenecks. We want to do all this while still having maintainable (modular and general) code.

15.1 Optimizing Compilers

For `gcc`, we can use the `-O` flag to specify different optimization levels: `-O0`, `-O1`, `-O2`, `-O3` . But there are also other flags such as `-march=xxx`, with which one can specify the target architecture and `-m64` to state that this will only run on 64 bit machines. One should try different flags, because `-O3` will not always get better performance than `-O2`, for example. Also, other compilers such as `icc` may produce faster binaries than `gcc`.

Compilers are good at mapping a program to a machine. This includes optimizing: register allocation, code selection and ordering, dead code elimination, and eliminating minor (common) inefficiencies. But compilers usually do not increase asymptotic performance. It is up to the programmer to find the best algorithmic solution for a problem. For large inputs, algorithmic improvements may be more important than system-level optimizations.

Also, there are certain 'optimization blocker' (discussed later), which prevent the compiler to optimize for correctness reasons, because of implicit assumptions made by the programmer but not known to the compiler.

Compiler optimizations are conservative to guarantee correctness. Program behavior must not be changed under any circumstances. Most analysis is performed only within procedures as whole-program analysis is too expensive in most cases. Furthermore, analysis is based on static information. The compiler usually does not have information on runtime characteristics such as input values.

As the potential from just working with compiler flags, we may consider the following matrix multiplication. Without optimizations it runs in 820 cycles, with `-O1` in 200 cycles, with `-O2` in 132 cycles, with `-O3` in 32 cycles, and with `-O3 -m64 -march=haswell -fno-tree-vectorize` in 8 cycles.

Listing 95: Matrix Multiplication for Benchmark

```
double a[4][4];
double b[4][4];
double c[4][4];  // set to zero
/* Multiply 4 x 4 matrices a and b */
void mmm(double *a, double *b, double *c, int n) {
  int i, j, k;
  for (i = 0; i < 4; i++)
    for (j = 0; j < 4; j++)
      for (k = 0; k < 4; k++) c[i * 4 + j] += a[i * 4 + k] * b[k
          * 4 + j];
}
```

15.2 Code Motion and Precomputation

Code motion refers to moving some computation so that it is not unnecessarily repeated. This leads to a frequency reduction of said computation. This is also called precomputation, because we precompute a value once to reuse it.

But notice that compilers are not always good at exploiting arithmetic properties.

Listing 96: Unoptimized Code

```
void set_row(double *a, double
    *b, long i, long n) {
  long j;
    for (j = 0; j < n; j++)
        a[n*i+j] = b[j];
}
```

Listing 97: Optimized with Code Motion

```
void set_row(double *a, double
    *b, long i, long n) {
  long j;
  int ni = n*i;
  for (j = 0; j < n; j++)
    a[ni+j] = b[j];
}
```

The compiler will hesitate to do some optimizations. For instance, because floating point operations usually are not associative and, thus, refrain from reordering. We would have to do this manually. So it is worth looking at the assembly to see what's going on.

Listing 98: Unoptimized Code

```
// C
up = val[(i-1)*n + j];
down = val[(i+1)*n + j];
left = val[i*n + j-1];
right = val[i*n + j+1];
sum = up + down + left + right;

// ASSEMBLY
leaq   1(%rsi), %rax  # i+1
leaq   -1(%rsi), %r8  # i-1
imulq  %rcx, %rsi  # i*n
imulq  %rcx, %rax  # (i+1)*n
imulq  %rcx, %r8   # (i-1)*n
addq   %rdx, %rsi  # i*n+j
addq   %rdx, %rax  # (i+1)*n+j
addq   %rdx, %r8   # (i-1)*n+j
```

Listing 99: Optimized by Extracting Common Subexpression

```
// C
int inj = i*n + j;
up = val[inj - n];
down = val[inj + n];
left = val[inj - 1];
right = val[inj + 1];
sum = up + down + left + right;

// ASSEMBLY
imulq %rcx, %rsi # i*n
addq %rdx, %rsi # i*n+j
movq %rsi, %rax # i*n+j
subq %rcx, %rax # i*n+j-n
leaq (%rsi,%rcx), %rcx # i*n+j+n
```

15.3 Strength Reduction

This means replacing a costly operation with a simpler one. This is usually a specialized/"weaker" instruction. For instance, we may replace `*16` with `<<4`. The usefulness of such replacements depends on the target machine as the relative machine latency of the instructions determines the performance gain. Replacing multiplications with shifting is usually worth it. This may also be done automatically by the compiler if optimizations are enabled.

Another common strength reduction is to replace multiplications with additions.

Listing 100: Unoptimized Code

```
for (i = 0; i < n; i++) {
  for (j = 0; j < n; j++) {
    a[n * i + j] = b[j];
  }
}
```

Listing 101: Optimized with Strength Reduction

```
int ni = 0;
for (i = 0; i < n; i++) {
  for (j = 0; j < n; j++) {
    a[ni + j] = b[j];
  }
  ni += n;
}
```

15.4 Optimization Blockers

15.4.1 Procedure Calls

Listing 102: Unoptimized Code

```
void lower(char *s) {
  int i;
  for (i = 0; i < strlen(s); i
     ++) {
    if (s[i] >= 'A' && s[i] <=
       'Z') {
      s[i] -= ('A' - 'a');
    }
  }
}
```

Listing 103: Optimized with Code Motion

```
void lower2(char *s) {
  int i;
  int len = strlen(s);
  for (i = 0; i < len; i++) {
    if (s[i] >= 'A' && s[i] <=
       'Z') {
      s[i] -= ('A' - 'a');
    }
  }
}
```

It may seem surprising, but Listing 102 is actually $\mathcal{O}(n^2)$. This is, because `strlen(s)` is computed during each iteration to check the condition. And being implemented via iteration of the string, that function takes $\mathcal{O}(n)$, leading to $\mathcal{O}(n^2)$ totally. To improve performance, we can do manual code motion/precomputation and, thus, make the assumption that the string length is constant explicit.

The compiler can't do this optimization on its own, because it does not know about potential side effects of `strlen(...)`. And if calls to that function might return different values for the call, it cannot be guaranteed that the behavior is identical if we precompute the value. The compiler does not look inside functions that are called. It treats each as a black box.

Thus, either we have to do the code motion manually as above. Or we have to inline the function so that the compiler optimizes.

15.4.2 Memory Aliasing

In C one can easily have two memory references/pointers refer to a single location. That is a problem, because the compiler generally must assume that this is the case to guarantee correctness in any case. This assumption, however, prohibits the compiler from doing many optimizations. Mostly, because it must assume that when working with two pointers that those might reference to the same/overlapping memory. Hence, simple looking operations cannot be simplified, because they might not be that simple in certain edge cases.

Listing 104: Row Sum Comptutation

```
void sum_rows1(double *a,
    double *b, long n) {
  long i, j;
  for (i = 0; i < n; i++) {
    b[i] = 0;
    for (j = 0; j < n; j++)
      b[i] += a[i*n + j];
  }
}
```

Listing 105: Assembly of Listing 104

```
.L53:
  addsd (%rcx), %xmm0
  addq $8, %rcx
  decq %rax
  movsd %xmm0, (%rsi,%r8,8)
  jne .L53
```

We can not guarantee that `b` and `a` don't overlap in the addresses they reference to. If they don't overlap, this works as our first intuition tells us. But if they overlap, the result will be quite different. Thus, the compiler must make the update to `b[i]` in every iteration of the loop to corre-

spond to the program's semantics. Doing it just once after accumulating all values would be faster but not behave identically in every case.

One way to combat aliasing is scalar replacement. We use a temporary variable for arrays elements that are reused. This only works if there is no memory aliasing (at least with the same behavior) - in many cases we make this assumption.

Listing 106: Scalar Replacement Example

```
void sum_rows2(double *a, double *b, long n) {
  long i, j;
  for (i = 0; i < n; i++) {
    double val = 0;
    for (j = 0; j < n; j++)
      val += a[i*n + j];
    b[i] = val;
  }
}
```

Another option is to use the `restict` keyword, which as introduced with C99 for pointer declarations. This tells the compiler that during the lifetime of the annotated pointer, no other pointer will access the same data structure, which allows the compiler to ignore aliasing for that pointer. If the user violates this guarantee, the behavior is undefined.

15.5 Blocking and Unrolling

This introduces a technique that is relevant when working with matrices or data structured in matrices. Often many or even all array elements are reused but it is a bit tricky to take advantage of that. Blocking and loop unrolling provide techniques to utilize this reuse.

Listing 107: Matrix Multiplication

```
c = (double *) calloc(sizeof(double), n*n);
/* Multiply n x n matrices a and b */
void mmm(double *a, double *b, double *c, int n) {
  int i, j, k;
  for (i = 0; i < n; i++)
    for (j = 0; j < n; j++)
      for (k = 0; k < n; k++)
        c[i*n+j] += a[i*n + k]*b[k*n + j];
}
```

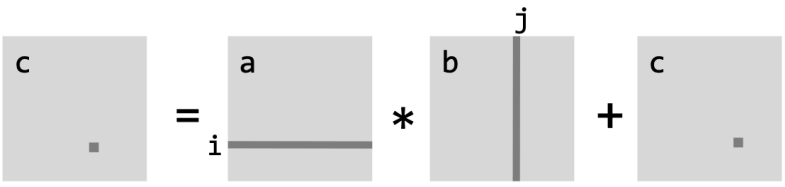


Figure 52: Matrix Multiplication Schematic

The performance of this and why blocking and unrolling works can be attributed cache optimization. When reading the section on caches, this will become more apparent. This example will also

be discussed again in that section. Here, it is important to understand which matrix entries are in cache when the computation is done to understand when and how we want to reuse the elements while they are still in the cache.

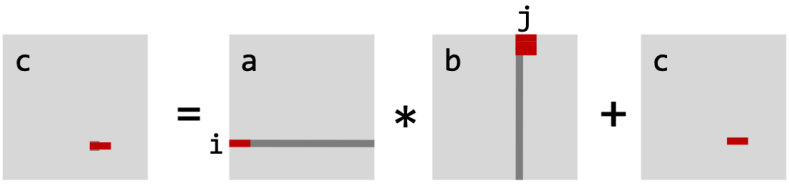


Figure 53: Entries In Cache - Beginning of c Entry Computation

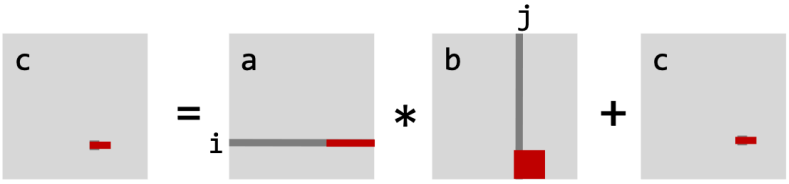


Figure 54: Entries In Cache - End of c Entry Computation

15.5.1 Blocking

Blocking means to do computations in blocks, which we saw to fit into the cache. By doing so, we compute on a set of elements, which can be kept in the cache so that we minimize cache misses and reduce wait time for memory.

Listing 108: Blocking in C

```
c = (double *)calloc(sizeof(double), n *n);
/* Multiply n x n matrices a and b */
void mmm(double *a, double *b, double *c, int n) {
    int i, j, k;
    for (i = 0; i < n; i += 2) // iterating over blocks
        for (j = 0; j < n; j += 2)
            for (k = 0; k < n; k += 2)
                for (i1 = i; i1 < i + 2; i1++) // in block
                    for (j1 = j; j1 < j + 2; j1++)
                        for (k1 = k; k1 < k + 2; k1++)
                            c[i1 * n + j1] +=
                              a[i1 * n + k1] * b[k1 * n + j1];
}
```

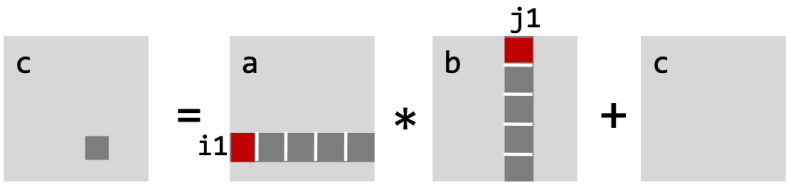


Figure 55: Blocking

15.5.2 Loop Unrolling

Unrolling loops means that we concatenate the different loop iterations directly and thus can also do cross-loop-iteration optimizations. Those optimizations can be very intricate. But in any case we save some jumping at run time.

In this case, we can unroll the computation of the four values in our 2×2 grid. This can be beneficial, because we use each element of our input matrices twice. If we unroll the four computations, we can do scalar replacement for the input values.

Listing 109: Unrolling Matrix Multiplication

```
c = (double *) calloc(sizeof(double), n*n);
/* Multiply n x n matrices a and b */
void mmm(double *a, double *b, double *c, int n) {
  int i, j, k;
  for (i = 0; i < n; i+=2)
    for (j = 0; j < n; j+=2)
      for (k = 0; k < n; k+=2)
        <body>
}

<body>
c[i*n + j] =
a[i*n + k]*b[k*n + j] + a[i*n + k+1]*b[(k+1)*n + j] + c[i*n + j]

c[(i+1)*n + j] =
a[(i+1)*n + k]*b[k*n + j] + a[(i+1)*n + k+1]*b[(k+1)*n + j] + c
    [(i+1)*n + j]

c[i*n + (j+1)] =
a[i*n + k]*b[k*n + (j+1)] + a[i*n + k+1]*b[(k+1)*n + (j+1)] + c[
    i*n + (j+1)]

c[(i+1)*n + (j+1)] =
a[(i+1)*n + k]*b[k*n + (j+1)]
+ a[(i+1)*n + k+1]*b[(k+1)*n + (j+1)] + c[(i+1)*n + (j+1)]
```

16 Architecture and Optimizations

In this chapter, we consider how to optimize our programs beyond what the compiler can do for us by considering the specific characteristics of a processor. To do so, we need some general understanding of modern processor designs and their relation to performance. Much of the architectural foundations here have already been discussed in in the DDCA class and won't be elaborated on much.

Optimizations in general are about exploiting ILP (instruction level parallelism), where the performance is limited by data dependencies. Simple transformations which change the dependencies of subsequent instructions/tasks can yield dramatic performance improvements. Those optimizations often require the use of associativity and distributivity in computations, even if floating point arithmetics technically doesn't guarantee those. We then trade accuracy (floating point numbers are an approximation anyway) for performance.

To analyze and compare the performance of different setups, we need a program, which we optimize to see how those optimizations impact performance. Such a program whose performance we are interested in is called a benchmark. In addition, we need performance metrics. Those are quantitative measurements of the performance of our benchmark. We can look at the latency and throughput of requests.

16.1 Modern Processor Design

Most abstractly, we can compute the program execution time ("performance") from three metrics: IC (instruction count of the program), CPI (cycles per instruction), and CCT (clock cycle time). We have program execution time $= IC \cdot CPI \cdot CCT$. We can reduce the IC by optimizing our program and reducing its complexity in regards to the instruction count. The other two factors will be considered below.

The most simple model of a processor considers a sequential processor design. Those are not used in practice but provide fundamental understanding. Modern processors are pipelined, superscalar, out-of-order, have pipeline registers, pipeline control logic, data/control hazards, stalls, data forwarding, branch prediction, ... (all this was discussed in DDCA). All those enable faster systems by utilizing parallelism.

16.1.1 Sequential Processor Stages

In a sequential processor, each instruction passes through some stages: Fetch, Decode, Execute, Memory, Write Back, and PC Update. In one cycle, the signal must propagate through instruction memory, the register file, the ALU, data memory, ... Thus, the clock needs to run very slowly and h/w units are only active for a fraction of a cycle. This is wasteful in regards to h/w and time. Sequential processing is too slow to be practical.

16.1.2 Pipelined Hardware

With pipelining, we separate the stages and allow executing among those in a pipelined fashion. However, then we must consider data hazards (handled by data forwarding and stalling), control hazards (handled by canceling upon a misprediction and stalling), and control combinations.

By increasing the pipeline depth, we can reduct the CCT. But notice that reducing the CCT by increasing the pipeline depth naturally also slightly increases the latency for each instruction to go through the pipeline. But the throughput on average still get's higher, which also keeps the CPI low. But there are limits to increasing the pipeline depth, because pipeline registers add delay, we can't split the steps completely equally, we have clock skew, ...

Furthermore, we can't pipeline optimally/keep the pipeline full at the entire time. Thus, the CPI does not only increase slightly due to latencies of pipeline registers. But also because of stalls and cancelled instructions when a branch is mispredicted. We write: $CPI = CPI_{base} + CPI_{stalls}$. Stalls may be caused by data hazards (read-after-write, write-after-read, write-after-write), control hazards (resolving jumps, branches), and memory latency.

16.1.3 Superscalar Processors

Modern processors are not only pipelined but also superscalar. This means that they can issue and execute multiple instructions in one cycle. Superscalar is understood as out-of-order execution engines here. The instructions are retrieved from a sequential instruction stream and are usually scheduled dynamically. The benefit is clearly that superscalar processors can take advantage of instruction level parallelism that most programs have without any programming effort.

Superscalar CPUs for x86 are a bit more complicated, because x86 is a CISC (complex instruction set computer). On the one hand, instructions have different sizes when encoded. So the PreDecode separates those instructions, which requries more work that in a RISC machine. On the other hand, the complex instructions of the x86 ISA are split up in hardware into micro instructions, which is done to keep the hardware comparatively simple.

Superscalar Processor Performance .

Instruction	Latency	Cycles/issue
Load/store	4	1
Int Add	1	1
Int Multiply	3	1
Int/Long Divide	$3-30$	$3-30$
Sngl/Dbl FP Multiply	5	1
Sngl/Dbl FP Add	3	1
Sngl/Dbl FP Divide	$3-15$	$3-15$

Figure 56: Intel Superscalar Haswell CPU Latencies

Notice that an execution of several instructions may be latency bound or throughput bound. If we want to do five integer multiplications and those five multiplications are independent, we can just issue them one after another and are done in 7 cycles. We are throughput bound. But if they depend on each other, we must wait for one to complete for the next to start. This takes 15 cycles. We are latency bound.

So the major aspect to reach high performance is to keep pipelines filled and not let any h/w run idle.

16.1.4 Register Renaming

Remember that we discussed data hazards before.

- read after write (RAW): true dependence
- write after write (WAW): output dependence
- write after read (WAR): anti dependence

Notice that only RAW requires us to really wait for the previous computation to complete. The other dependencies only exist due to a limited number of registers. For instance, with write after write we only need to ensure that subsequent instructions read the second write. But nothing is stopping us from computing the second value to be written first. And we can actually do so with register renaming.

This bases on having more registers in hardware than the ISA makes available to the programmer. We map architectural registers to a larger pool of physical registers and give each new value produced its own physical register. That avoids WAW and WAR hazards.

16.1.5 Dataflow Execution

Through what we have now learned about modern processors, we see that they internally function somewhat like a dataflow processor. The traditional imperative execution view considers registers as fixed storage locations and instruction must be executed in the specified sequence to guarantee proper program behavior. But through pipelining, out-of-order execution, register renaming, etc. modern processors can be better understood with a functional view. Each write is understood to create a new instance of a value and operations can be performed as soon as all operands are available. There is no need to execute in the original sequence. Only the retirement/write-back to memory must be done in-order.

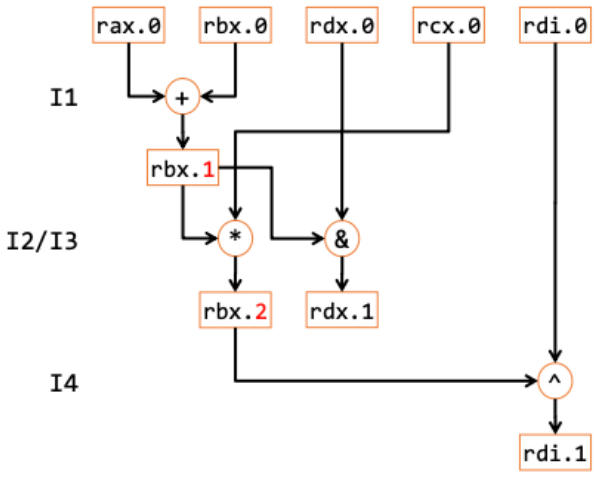


Figure 57: Dataflow Function View

16.2 Architecture-Based Optimization

We will consider this simple benchmark here, where `data_t` may be some data type such as `int`, `long`, `float` or `double`. `OP` and `IDENT` will be replaced by the operation and associated initial value: `+/0`, `*/1`.

Listing 110: Benchmark Program

```
1 struct vec {
2   size_t len;
3   data_t *data;
4 }
5
6 int get_vec_element(struct vec* v, size_t idx, data_t *val) {
7   if (idx >= v->len)
```

```
8       return 0;
9     *val = v->data[idx];
10    return 1;
11  }
12
13  void combine1(struct vec *v, data_t *dest) {
14    long int i;
15    *dest = IDENT;
16    for (i = 0; i<vec_length(v); i++)
17    {
18      data_t val;
19      get_vec_element(v,i,&val);
20      *dest = *dest OP val;
21    }
22  }
```

For this we will consider the Intel Haswell Architecture. Our CPU has 2 load units, 2 store units, 4 integer addition units, 1 integer multiplication unit, 2 floating point multiplication units, 1 floating point addition unit, and 1 floating point division unit. The latencies are as before an as in this figure.

Instruction	**Latency**	**Cycles/issue**
Load/store	4	1
Int Add	1	1
Int Multiply	3	1
Int/Long Divide	$3-30$	$3-30$
Sngl/Dbl FP Multiply	5	1
Sngl/Dbl FP Add	3	1
Sngl/Dbl FP Divide	$3-15$	$3-15$

Figure 58: Intel Superscalar Haswell CPU Latencies

One important metric is Cycles per Element (CPE). It measures how well the procedure would scale with big input vectors. When looking at the total cycles taken for sone amount of elements, it is comprised of an overhead and some amount of CPE. So the CPI is the slope of the execution time graph.

If we take our program as in `combine1` we get a different performance depending on the chosen optimization flags.

Method	**Integer**		**Double FP**	
Operation	**Add**	**Mult**	**Add**	**Mult**
Combine1 unoptimized	22.68	20.02	19.98	20.18
Combine1 -01	10.12	10.12	10.17	11.14

Figure 59

16.2.1 Basic Optimizations

- First, there are some optimizations we have already seen that compilers can not do. For instance, the compiler doesn't know that `vec_length(...)` doesn't have side effects and reevaluates it at each iteration for an overhead.

- Additionally, because of potential memory aliasing between `dest` and `v`, the compiler must mandate a write to `dest` in each iteration, although we semantically care about the accumulation and exclude memory aliasing in general.
- The element access with `get_vec_element(...)` also is quite inefficient, because it's an unnecessary procedure call with an overhead. And we perform some redundant bound checks in that procedure. By inlining it, we can increase performance.

Listing 111: Optimized Benchmark - `combine4`

```
void combine4(struct vec *v, data_t *dest)
{
  long i;
  long length = vec_length(v);
  data_t *d = get_vec_start(v);
  data_t t = IDENT;
  for (i = 0; i<length; i++)
    t = t OP d[i];
  *dest = t;
}
```

Method	**Integer**		**Double FP**	
Operation	**Add**	**Mult**	**Add**	**Mult**
Combine1 unoptimized	22.68	20.02	19.98	20.18
Combine1 -01	10.12	10.12	10.17	11.14
Combine4	1.27	3.01	3.01	5.01

16.2.2 Latency Bound (Superscalar CPU)

When we look at our program, performance after the latest optimizations, we can see that our execution is currently latency bound. This is easy to understand, because we execute the operations one after another and the previous one must complete before the next one can start. The dependencies are sequential and our performance is dictated by the latency of the OP.

Also, we notice that the integer is even worse than latency bound. This comes, because we of course have some overhead with our for loop. But with the longer multiply and FP operations, those instructions can happen in parallel. But the 'quick' int add cannot swallow this overhead.

Method	Integer		Double FP	
Operation	**Add**	**Mult**	**Add**	**Mult**
Combine1 unoptimized	22.68	20.02	19.98	20.18
Combine1 -01	10.12	10.12	10.17	11.14
Combine4	1.27	3.01	3.01	5.01
Latency bound	1.00	3.00	3.00	5.00

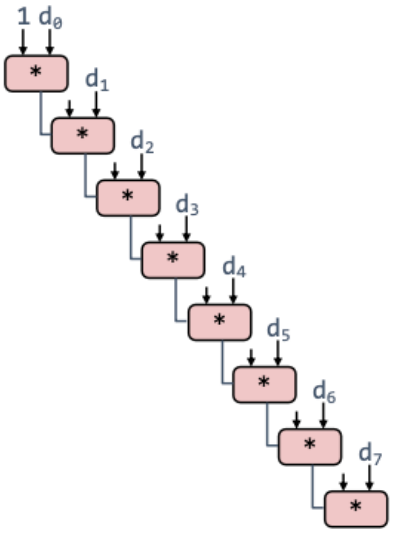


Figure 60: Reason for Latency Boundness

16.2.3 Loop Unrolling

Through loop unrolling, we perform 2x more useful work per iteration. This helps to improve performance for int add, because we now have additional time to execute the loop jumping in parallel through the additional computation.

Listing 112: Optimized Benchmark - `unroll2a_combine`

```
void unroll2a_combine(struct vec *v, data_t *dest) {
  long length = vec_length(v);
  long limit = length-1;
  data_t *d = get_vec_start(v);
  data_t x = IDENT;
  long i;
  /* Combine 2 elements at a time */
  for (i = 0; i < limit; i+=2) {
    x = (x OP d[i]) OP d[i+1];
  }
  /* Finish any remaining elements */
  for (; i < length; i++) {
    x = x OP d[i];
  }
  *dest = x;
}
```

Method	Integer		Double FP	
Operation	**Add**	**Mult**	**Add**	**Mult**
Combine1 unoptimized	22.68	20.02	19.98	20.18
Combine1 -01	10.12	10.12	10.17	11.14
Combine4	1.27	3.01	3.01	5.01
Unroll 2x1	1.01	3.01	3.01	5.01
Latency bound	1.00	3.00	3.00	5.00

16.2.4 Throughput Bound (Superscalar CPU)

Now, we can compare our performance the the theoretical throughput bound. Because we have 4 functional units for integers addition and 2 functional units for load, the integer add is bottlenecked by the 2 loads per iteration. For int multiply and FP add we only have one unit and are limited to one cycle per element. For fp multiply, we have two units and thus can also improve the throughput bound.

Method	Integer		Double FP	
Operation	**Add**	**Mult**	**Add**	**Mult**
Combine1 unoptimized	22.68	20.02	19.98	20.18
Combine1 -01	10.12	10.12	10.17	11.14
Combine4	1.27	3.01	3.01	5.01
Unroll 2x1	1.01	3.01	3.01	5.01
Latency bound	1.00	3.00	3.00	5.00
Throughput bound	0.50	1.00	1.00	0.50

16.2.5 Reassociation

Now we slightly change our program. This is called reassociation, because we change the order in which the operations are performed on the elements in one loop iteration. Notice that for FPs this may change the result of the program, because fp operations are not associative.

With this approach we break sequential dependence. Instead of having to wait for the `x` write of the previous iteration to finish, we can already start performing an operation. We thus need to stall/waste less time to wait for the `x` from the previous iteration to become available.

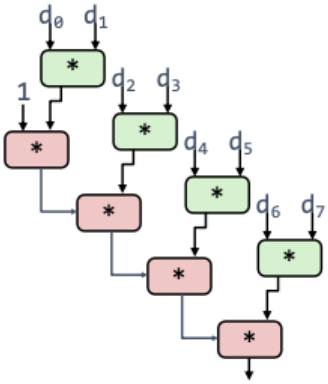
Listing 113: Optimized Benchmark - `unroll2aa_combine`

```
void unroll2aa_combine(struct vec *v, data_t *dest) {
  long length = vec_length(v);
  long limit = length-1;
  data_t *d = get_vec_start(v);
  data_t x = IDENT;
  long i;
  /* Combine 2 elements at a time */
  for (i = 0; i < limit; i+=2) {
    x = x OP (d[i] OP d[i+1]);
  }
  /* Finish any remaining elements */
  for (; i < length; i++) {
    x = x OP d[i];
  }
```

```
15    *dest = x;
16 }
```

As we shorted the linear dependencies by about half, this reduces the required cycles by 50 % generally. Notice that this didn't help for integer add, because integer addition is here limited by the loads as they take comparatively longer - 4 cycles instead of a 1 cycle add.

Method	Integer		Double FP	
Operation	Add	Mult	Add	Mult
Combine1 unoptimized	22.68	20.02	19.98	20.18
Combine1 -01	10.12	10.12	10.17	11.14
Combine4	1.27	3.01	3.01	5.01
Unroll 2x1	1.01	3.01	3.01	5.01
Unroll 2x1a	1.01	1.51	1.51	2.51
Latency bound	1.00	3.00	3.00	5.00
Throughput bound	0.50	1.00	1.00	0.50



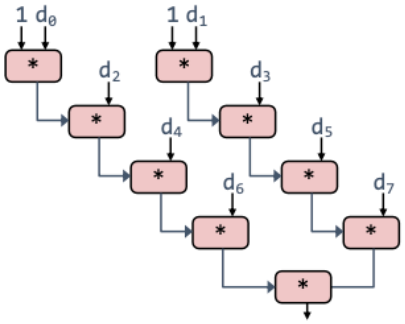
16.2.6 Loop Unrolling with Separate Accumulators

To fix the issue for the integer addition, where the load dominates the actual operation, we can use separate accumulators. This is a similar to reassociation as we still change the order of evaluation for improved performance. But now we don't have to wait for both loads to finish to continue but can wait on the loads and accumulate each independently.

Listing 114: Optimized Benchmark - `unroll2a_combine`

```
1  void unroll2a_combine(struct vec *v, data_t *dest) {
2    long length = vec_length(v);
3    long limit = length-1;
4    data_t *d = get_vec_start(v);
5    data_t x0 = IDENT;
6    data_t x1 = IDENT;
7    long i;
8    /* Combine 2 elements at a time */
9    for (i = 0; i < limit; i+=2) {
10     x0 = x0 OP d[i];
11     x1 = x1 OP d[i+1];
12     }
13   /* Finish any remaining elements */ for (; i < length; i++) {
14     x0 = x0 OP d[i];
15   }
16   *dest = x0 OP x1;
17 }
```

Method	Integer		Double FP	
Operation	**Add**	**Mult**	**Add**	**Mult**
Combine1 unoptimized	22.68	20.02	19.98	20.18
Combine1 -01	10.12	10.12	10.17	11.14
Combine4	1.27	3.01	3.01	5.01
Unroll 2x1	1.01	3.01	3.01	5.01
Unroll 2x1a	1.01	1.51	1.51	2.51
Unroll 2x2	0.81	1.51	1.51	2.51
Latency bound	1.00	3.00	3.00	5.00
Throughput bound	0.50	1.00	1.00	0.50



16.2.7 Combining Multiple Accumulators and Unrolling

Finally, we can unroll further. Specifically, we can unroll to any degree L and accumulate K results in parallel. But L must be a multiple of K for this to make sense. Otherwise, the accumulation would be not evenly distributed and performance doesn't profit. For different operations and data types, the best unrolling factor is different. Through a practical measurement one can best determine how far to unroll and accumulate.

FP *	Unrolling Factor L							
Accumulators K	1	2	3	4	6	8	10	12
1	5.01	5.01	5.01	5.01	5.01	5.01	5.01	
2		2.51		2.51		2.51		
3			1.67					
4				1.25		1.26		
6					0.84			0.88
8						0.63		
10							0.51	
12								0.52

Figure 61: Experiment for Double Mult.

FP *	Unrolling Factor L							
Accumulators K	1	2	3	4	6	8	10	12
1	1.27	1.01	1.01	1.01	1.01	1.01	1.01	
2		0.81		0.69		0.54		
3			0.74					
4				0.69		1.24		
6					0.56			0.56
8						0.54		
10							0.54	
12								0.56

Figure 62: Experiment for Integer Add.

Method	Integer		Double FP	
Operation	**Add**	**Mult**	**Add**	**Mult**
Combine1 unoptimized	22.68	20.02	19.98	20.18
Combine1 -01	10.12	10.12	10.17	11.14
Combine4	1.27	3.01	3.01	5.01
Unroll 2x1	1.01	3.01	3.01	5.01
Unroll 2x1a	1.01	1.51	1.51	2.51
Unroll 2x2	0.81	1.51	1.51	2.51
Best	0.54	1.01	1.01	0.52
Latency bound	1.00	3.00	3.00	5.00
Throughput bound	0.50	1.00	1.00	0.50

16.2.8 SIMD Operations

But there is one trick to get even higher performance. Specifically, to use vector instructions/SIMD instructions. Then, one can truly parallelize the operations on multiple values. One unrolled loop iteration can then be done in one instruction instead of multiple instructions for each accumulator separately.

Method	**Integer**		**Double FP**	
Operation	**Add**	**Mult**	**Add**	**Mult**
Combine1 unoptimized	22.68	20.02	19.98	20.18
Combine1 -01	10.12	10.12	10.17	11.14
Combine4	1.27	3.01	3.01	5.01
Unroll 2x1	1.01	3.01	3.01	5.01
Unroll 2x1a	1.01	1.51	1.51	2.51
Unroll 2x2	0.81	1.51	1.51	2.51
Scalar Best	0.54	1.01	1.01	0.52
Vector Best	0.06	0.24	0.25	0.16
Latency bound	1.00	3.00	3.00	5.00
Throughput bound	0.50	1.00	1.00	0.50
Vector throughput bound	0.06	0.12	0.25	0.12

17 Caches

17.1 Cache Performance

17.2 Cache Miss Types

17.3 Cache Organization

17.4 Cache Reads

17.5 The Memory Hierarchy

17.6 Cache Writes

17.7 Other Cache Features

17.8 Cache Optimization

17.8.1 Example 1

17.8.2 Example 2

17.8.3 Example 3

18 Exception

19 Virtual Memory

20 Multiprocessing & Multicore

21 Devices