accu conference 2025

Dynamic Memory Allocation Challenges in Safety Critical Systems

Xavier Bonaventura

DYNAMIC MEMORY ALLOCATION CHALLENGES IN SAFETY CRITICAL SYSTEMS

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ABOUT ME

- Where to find me:
  - @limdor
  - @xbonaventurab
- Working in C++
  - since 2011
  - in safety critical systems since 2018

- I represent BMW at the MISRA C++ working group and at the ISO C++ committee meetings

ABOUT YOU

- How many of you are not allowed to use dynamic memory allocation?
- How many of you do not know what are the issues with dynamic memory allocation?

DEFINITION OF A SAFETY CRITICAL SYSTEM

- A system whose failure could lead to:
  - Loss of life or serious injuries
  - Significant property damage
  - Significant environmental damage

FUNCTIONAL SAFETY IS KEY IN SAFETY CRITICAL SYSTEMS

- What is functional safety?
  - “Protecting a user from technology”

  - “Systems that lead to the freedom from unacceptable risk of injury or damage to the health of people by the proper implementation of one or more automatic protection functions (often called safety functions). A safety system consists of one or more safety functions.”

    TÜV SÜD

FUNCTIONAL SAFETY IS KEY IN SAFETY CRITICAL SYSTEMS

- Safety in a kettle
  - Automatic switch off
    - Burning risk
  - Boil dry protection
    - Fire hazard due to catch fire
  - Pouring without splashing
    - Burning risk

THERE ARE MULTIPLE STANDARDS TO ENSURE FUNCTIONAL SAFETY

- One standard to rule them all

IEC 61508 – General

- One standard for each industry

IEC 61511 – Industrial processes

IEC 62061 – Machinery

IEC 60880 – Nuclear power plants

ISO 26262 – Automotive

IEC 62304 – Medical devices

EN 50128 – Railway

NOT EVERYTHING IS EQUALLY CRITICAL (ISO 26262 – AUTOMOTIVE)

- Multiple categories to define criticality (Hazard and Risk Analysis)
  - Severity
    - If something happens, how bad is it?
  - Exposure
    - How frequently are you exposed to that situation?
  - Controllability
    - If something bad happens, how hard is for the user to control the situation?

ASIL LEVELS IN ISO 26262

Severity	Probability	Controllability		
		Simple	Normal	Difficult
Light and moderate injuries	Very low	QM	QM	QM
	Low	QM	QM	QM
	Medium	QM	QM	A
	High	QM	A	B
Severe and life threatening injuries	Very low	QM	QM	QM
	Low	QM	QM	A
	Medium	QM	A	B
	High	A	B	C
Life threatening injuries and fatal injuries	Very low	QM	QM	A or QM
	Low	QM	A	B
	Medium	A	B	C
	High	B	C	D

REQUIREMENTS PROVIDED BY THE STANDARD

- ISO 26262-6:2018 - Road vehicles — Functional safety — Part 6: Product development at the software level

	ASIL			
	A	B	C	D
Entry 1	o	+	+	++
Entry 2	+	+	++	++
Entry 3	++	+	o	o

++	Method is highly recommended
+	Method is recommended
o	No recommendation for or against

REQUIREMENTS PROVIDED BY THE STANDARD

- ISO 26262-6:2018 - Road vehicles — Functional safety — Part 6: Product development at the software level

  - General topics for the product development at the software level (Clause 5)
    - Requires use of coding guidelines that covers (5.4.3)
      - Use of language subsets with the goal of excluding language constructs that
        - can be interpreted different by different developers
        - experience tell us that they can lead to mistakes
        - can lead to unhandled run-time errors

REQUIREMENTS PROVIDED BY THE STANDARD

- ISO 26262-6:2018 - Road vehicles — Functional safety — Part 6: Product development at the software level

  - Software architectural design (Clause 7)
    - To avoid systematic faults should consider (7.4.3)
      - Appropriate management of shared resources

REQUIREMENTS PROVIDED BY THE STANDARD

- ISO 26262-6:2018 - Road vehicles — Functional safety — Part 6: Product development at the software level

  - Software unit design and implementation (Clause 8)
    - To achieve (8.4.5)
      - Correct order of execution of subprograms and functions
      - Correctness of data and control flow
    - The following principles should be applied
      - No dynamic objects or variables, or else online test during their creation
      - Avoid global variables or else justify their usage
      - No hidden data flow or control flow

REQUIREMENTS PROVIDED BY THE STANDARD

- ISO 26262-6:2018 - Road vehicles — Functional safety — Part 6: Product development at the software level

  - Software unit verification (Clause 9)
    - To provide evidence for (9.4.2)
      - Confidence in the absence of unintended functionality
      - Sufficient resources to support functionality
    - The following combination of methods shall be applied
      - Semi formal verification
      - Formal verification
      - Control flow analysis
      - Data flow analysis
      - Static code analysis
      - Resource usage evaluation

DYNAMIC MEMORY ALLOCATION IN CODING GUIDELINES

- JSF++ Joint Strike Fighter Air Vehicle C++ coding standards for the system development and demonstration program
- AUTOSAR Guidelines for the use of the C++14 language in critical and safety-related systems
- MISRA C++:2023 Guidelines for the use of C++17 in critical systems

Do not use dynamic memory allocation

Do not use dynamic memory allocation after initialization phase

If you have to, they provide guidelines

DYNAMIC MEMORY ALLOCATION HAS POTENTIAL PROBLEMS

Memory leaks

Out of memory

Allocation/deallocation mismatch

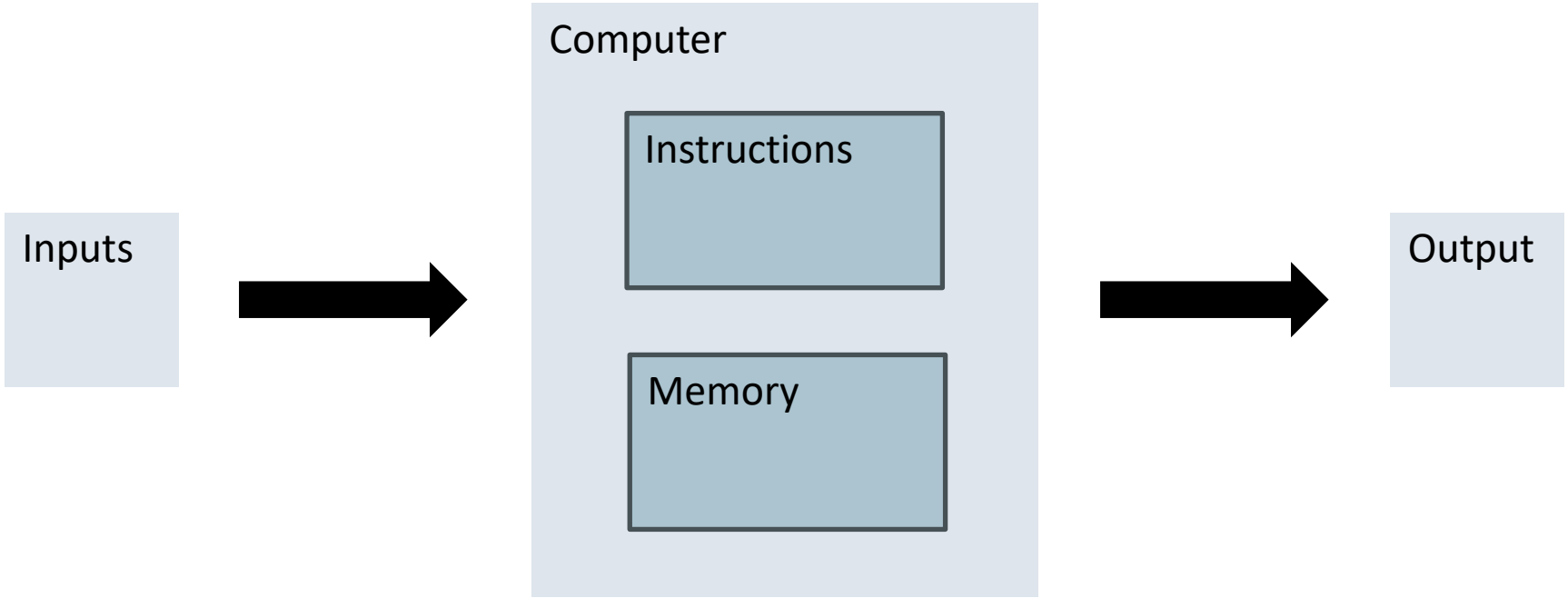
Memory fragmentation

Non-deterministic runtime

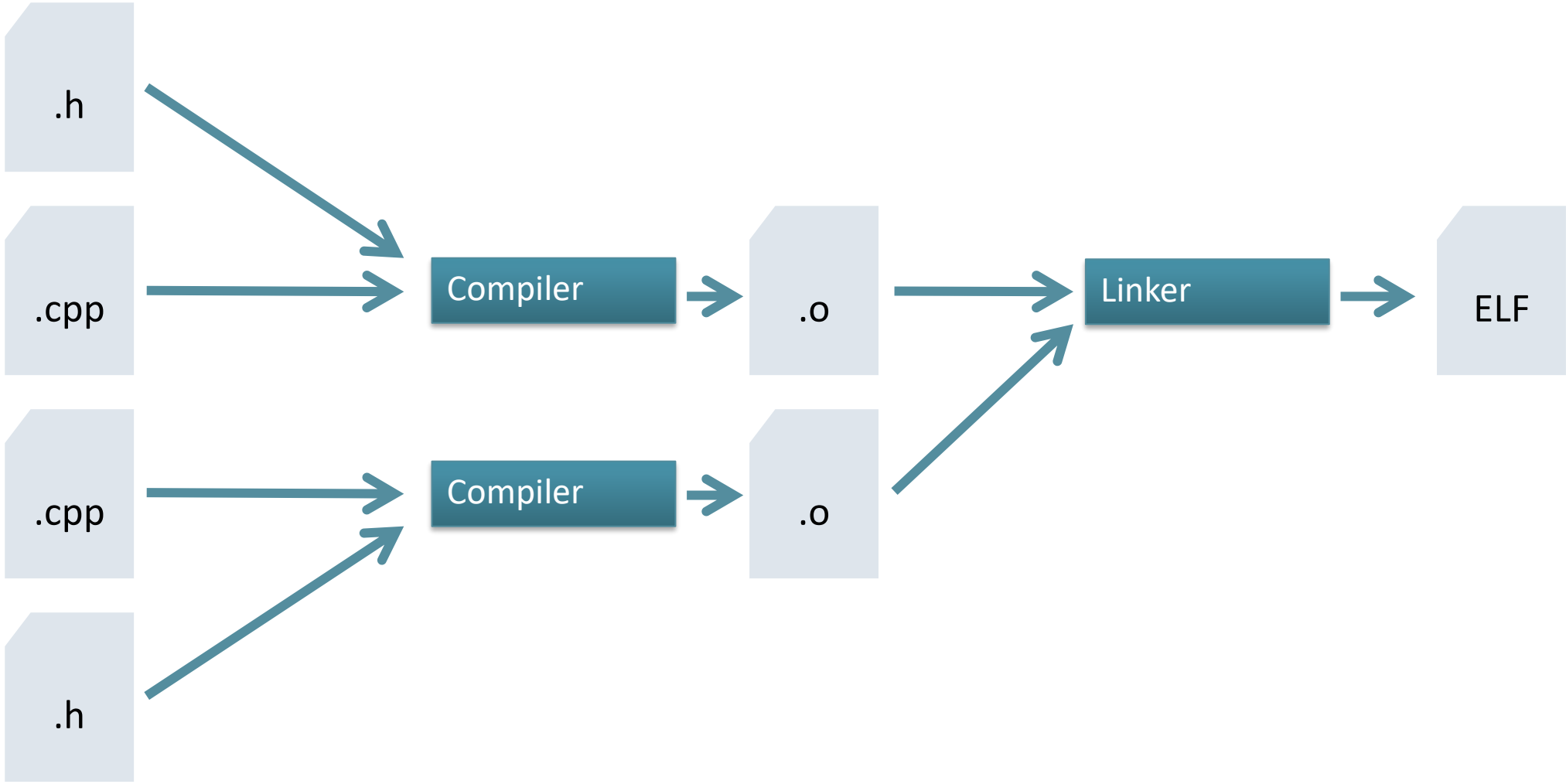
Use after free

ANATOMY OF A COMPUTER PROGRAM

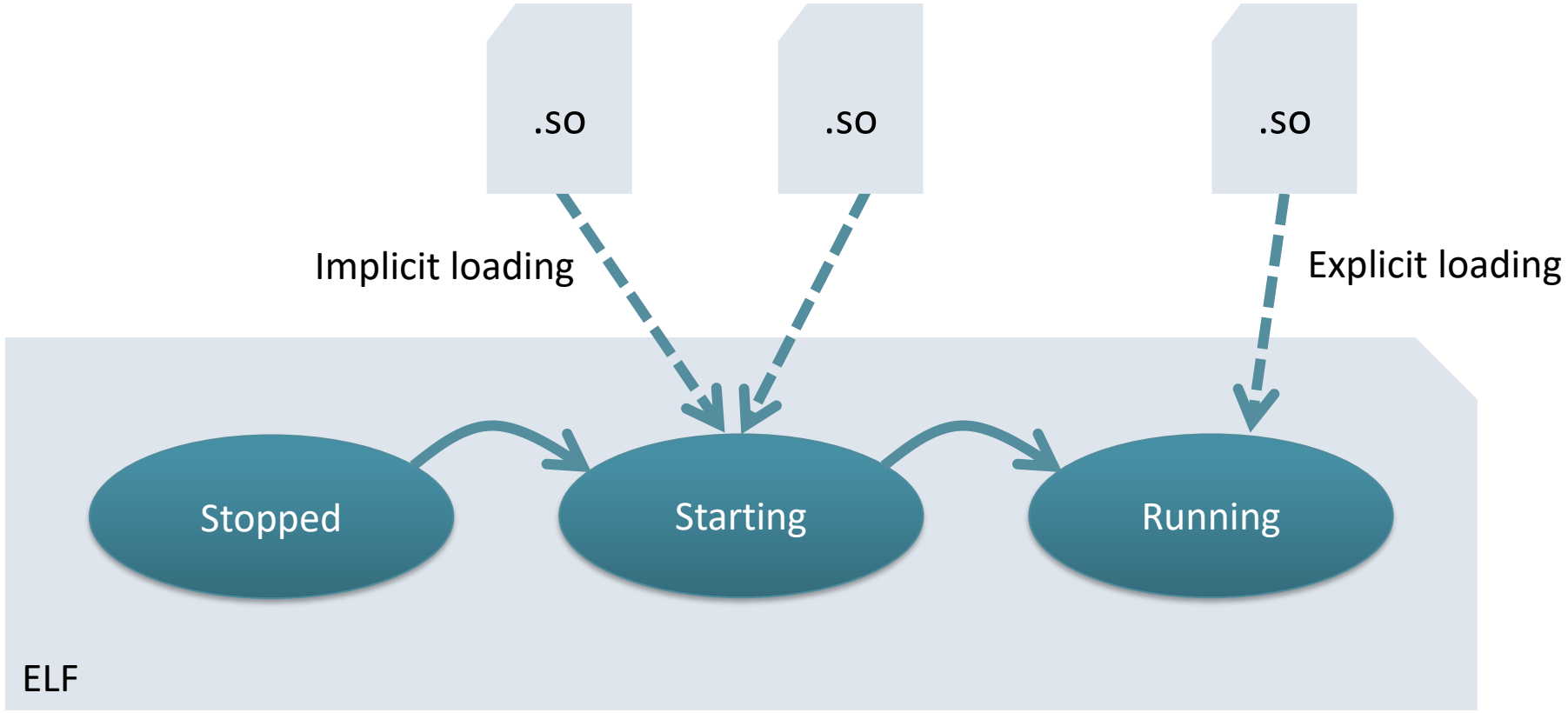
- A program is nothing else than a bunch of instructions modifying chunks of memory based on some inputs to produce some outputs



PROCESS LAYOUT IN MEMORY



PROCESS LAYOUT IN MEMORY



EXECUTABLE LAYOUT – ELF FORMAT

- Demo:
  - https://github.com/limdor/accu-2025/tree/master/dynamic_memory/elf_format
    - bazel build //dynamic_memory/elf_format:main -c dbg
    - readelf bazel-bin/dynamic_memory/elf_format/main --all

EXECUTABLE LAYOUT – ELF FORMAT

```cpp
constexpr auto c_foo = "ACCU 2025";
static constexpr auto sc_foo = "ACCU 2025";

int bar;
static int s_bar;

int d = 42;
static int s_d = 42;

const int c_d = 42;
static const int sc_d = 42;

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

EXECUTABLE LAYOUT – ELF FORMAT

```
:~/dynamic_memory$ readelf bazel-bin/dynamic_memory/elf_format/main --sections
```

```
There are 39 section headers, starting at offset 0x1bc0:

Section Headers:
  [Nr] Name              Type            Address          Offset    Size              EntSize          Flags  Link  Info  Align
  [ 0]                   NULL            0000000000000000 00000000  0000000000000000  0000000000000000           0     0     0
  [ 1] .interp           PROGBITS        0000000000000270 00000270  000000000000001c  0000000000000000   A       0     0     1
  [ 2] .note.gnu.pr[...] NOTE            0000000000000290 00000290  0000000000000030  0000000000000000   A       0     0     8
  [ 3] .note.ABI-tag     NOTE            00000000000002c0 000002c0  0000000000000020  0000000000000000   A       0     0     4
  [ 4] .note.gnu.bu[...] NOTE            00000000000002e0 000002e0  0000000000000024  0000000000000000   A       0     0     4
  [ 5] .dynsym           DYNSYM          0000000000000308 00000308  0000000000000090  0000000000000018   A       6     1     8
  [ 6] .dynstr           STRTAB          0000000000000398 00000398  00000000000000a1  0000000000000000   A       0     0     1
  [ 7] .gnu.hash         GNU_HASH        0000000000000440 00000440  000000000000001c  0000000000000000   A       5     0     8
  [ 8] .gnu.version      VERSYM          000000000000045c 0000045c  000000000000000c  0000000000000002   A       5     0     2
  [ 9] .gnu.version_r    VERNEED         0000000000000468 00000468  0000000000000030  0000000000000000   A       6     1     4
  [10] .rela.dyn         RELA            0000000000000498 00000498  00000000000000f0  0000000000000018   A       5     0     8
  [11] .rela.plt         RELA            0000000000000588 00000588  0000000000000018  0000000000000018  AI       5    13     8
  [12] .init             PROGBITS        00000000000005a0 000005a0  000000000000001b  0000000000000000  AX       0     0     4
  [13] .plt              PROGBITS        00000000000005c0 000005c0  0000000000000030  0000000000000010  AX       0     0     16
  [14] .text             PROGBITS        00000000000005f0 000005f0  00000000000000f8  0000000000000000  AX       0     0     16
  [15] .fini             PROGBITS        00000000000006e8 000006e8

Key to Flags:
  W (write), A (alloc), X (execute), M (merge), S (strings), I (info),
  L (link order), O (extra OS processing required), G (group), T (TLS),
  C (compressed), x (unknown), o (OS specific), E (exclude),
  D (mbind), l (large), p (processor specific)
```

EXECUTABLE LAYOUT – ELF FORMAT

```
:~/dynamic_memory$ readelf bazel-bin/dynamic_memory/elf_format/main --symbols
```

```
Symbol table '.symtab' contains 41 entries:
   Num:    Value          Size Type    Bind   Vis      Ndx Name
     0: 0000000000000000     0 NOTYPE  LOCAL  DEFAULT  UND
     1: 00000000000002c0    32 OBJECT  LOCAL  DEFAULT    3 __abi_tag
     2: 0000000000000000     0 FILE    LOCAL  DEFAULT  ABS crtstuff.c
     3: 0000000000002018     0 OBJECT  LOCAL  DEFAULT   26 __TMC_LIST__
     4: 0000000000000620     0 FUNC    LOCAL  DEFAULT   14 deregister_tm_clones
     5: 0000000000000650     0 FUNC    LOCAL  DEFAULT   14 register_tm_clones
     6: 0000000000000690     0 FUNC    LOCAL  DEFAULT   14 __do_global_dtors_aux
     7: 0000000000002018     1 OBJECT  LOCAL  DEFAULT   27 completed.0
     8: 0000000000001d88     0 OBJECT  LOCAL  DEFAULT   20 __do_global_dtor[...]
     9: 00000000000006d0     0 FUNC    LOCAL  DEFAULT   14 frame_dummy
    10: 0000000000001d90     0 OBJECT  LOCAL  DEFAULT   21 __frame_dummy_in[...]
    11: 0000000000000000     0 FILE    LOCAL  DEFAULT  ABS main.cpp
    12: 0000000000001d78     8 OBJECT  LOCAL  DEFAULT   19 _ZL5c_foo
    13: 0000000000001d80     8 OBJECT  LOCAL  DEFAULT   19 _ZL6sc_foo
    14: 0000000000002020     4 OBJECT  LOCAL  DEFAULT   27 _ZL5s_bar
    15: 0000000000002014     4 OBJECT  LOCAL  DEFAULT   25 _ZL3s_d
    16: 0000000000000714     4 OBJECT  LOCAL  DEFAULT   16 _ZL3c_d
    17: 0000000000000718     4 OBJECT  LOCAL  DEFAULT   16 _ZL4sc_d
    18: 0000000000000000     0 FILE    LOCAL  DEFAULT  ABS crtstuff.c
```

EXECUTABLE LAYOUT – ELF FORMAT

```cpp
constexpr auto c_foo = "ACCU 2025";
static constexpr auto sc_foo = "ACCU 2025";

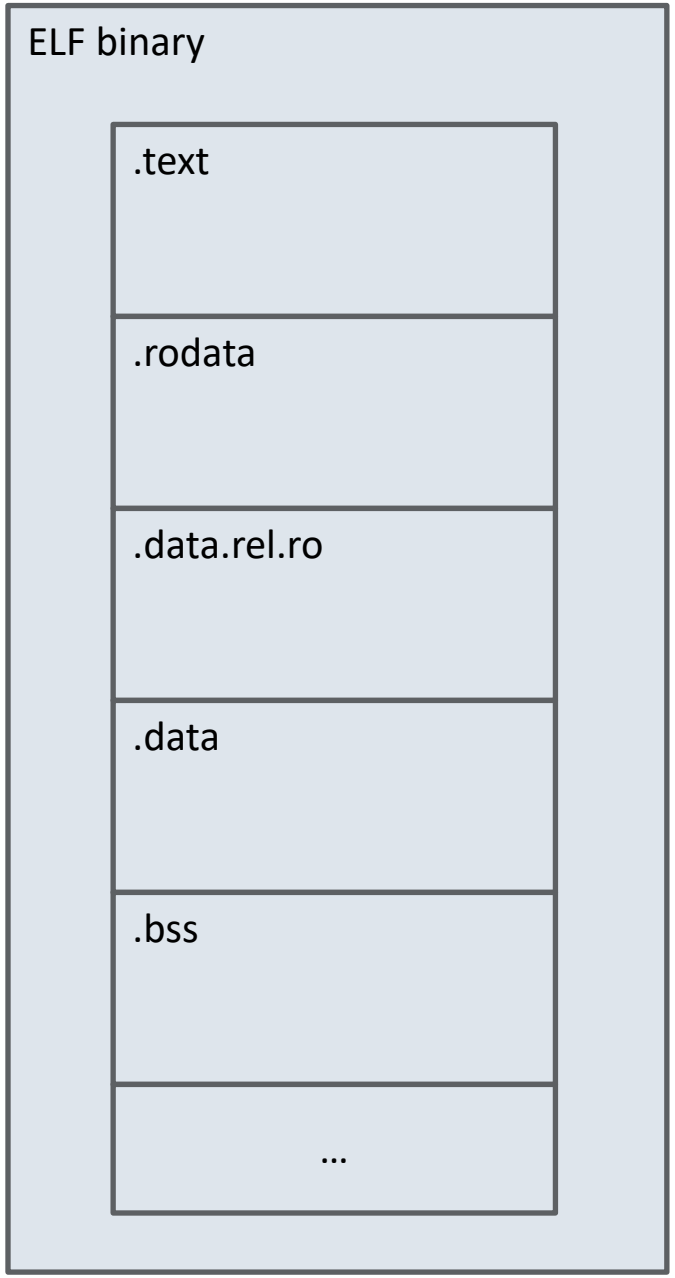

int bar;
static int s_bar;


int d = 42;
static int s_d = 42;


const int c_d = 42;
static const int sc_d = 42;

int main()
{

    return 0;
}
```



EXECUTABLE LAYOUT – ELF FORMAT

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constexpr auto c_foo = "ACCU 2025";
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int bar;
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int main()
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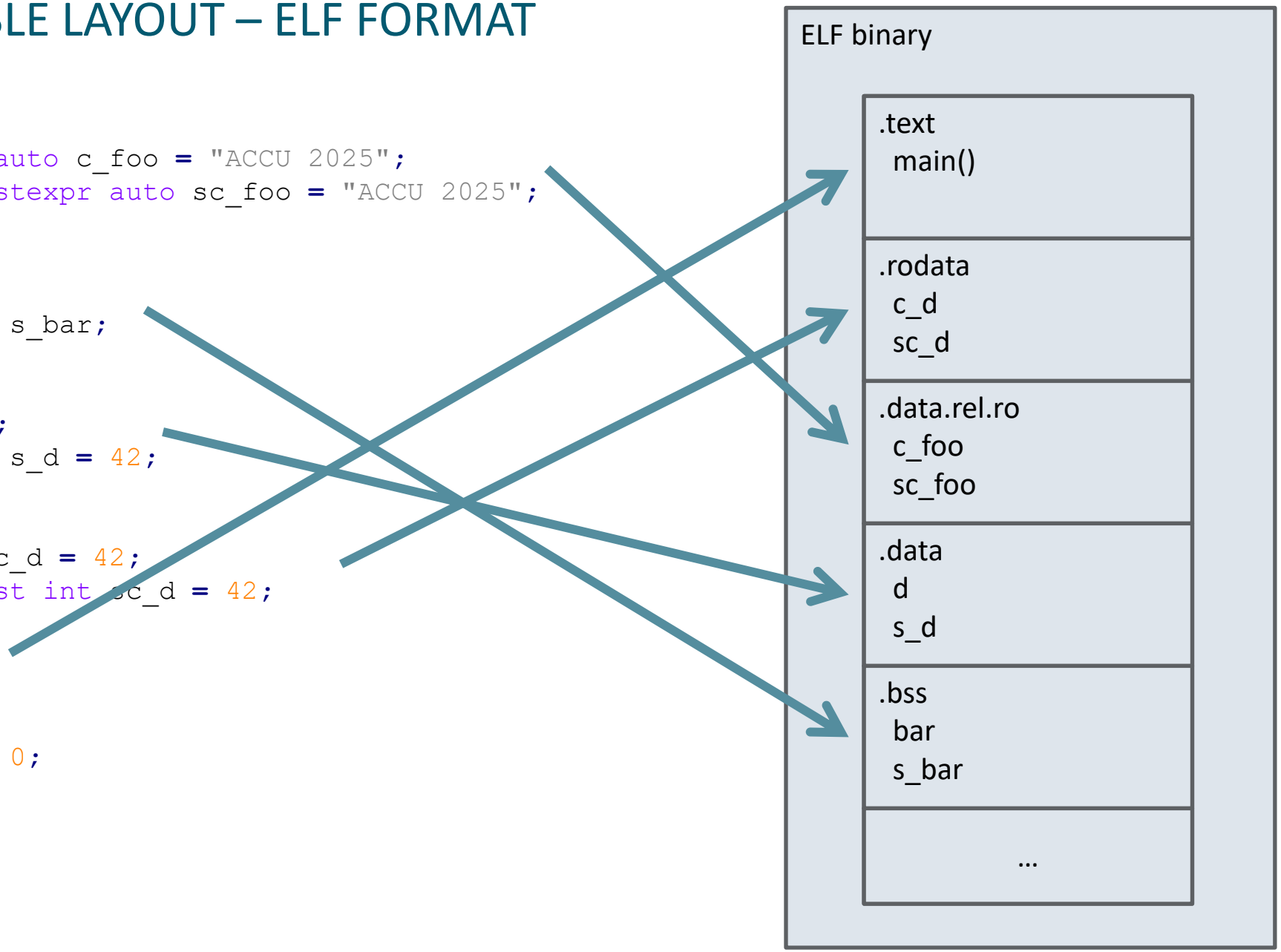
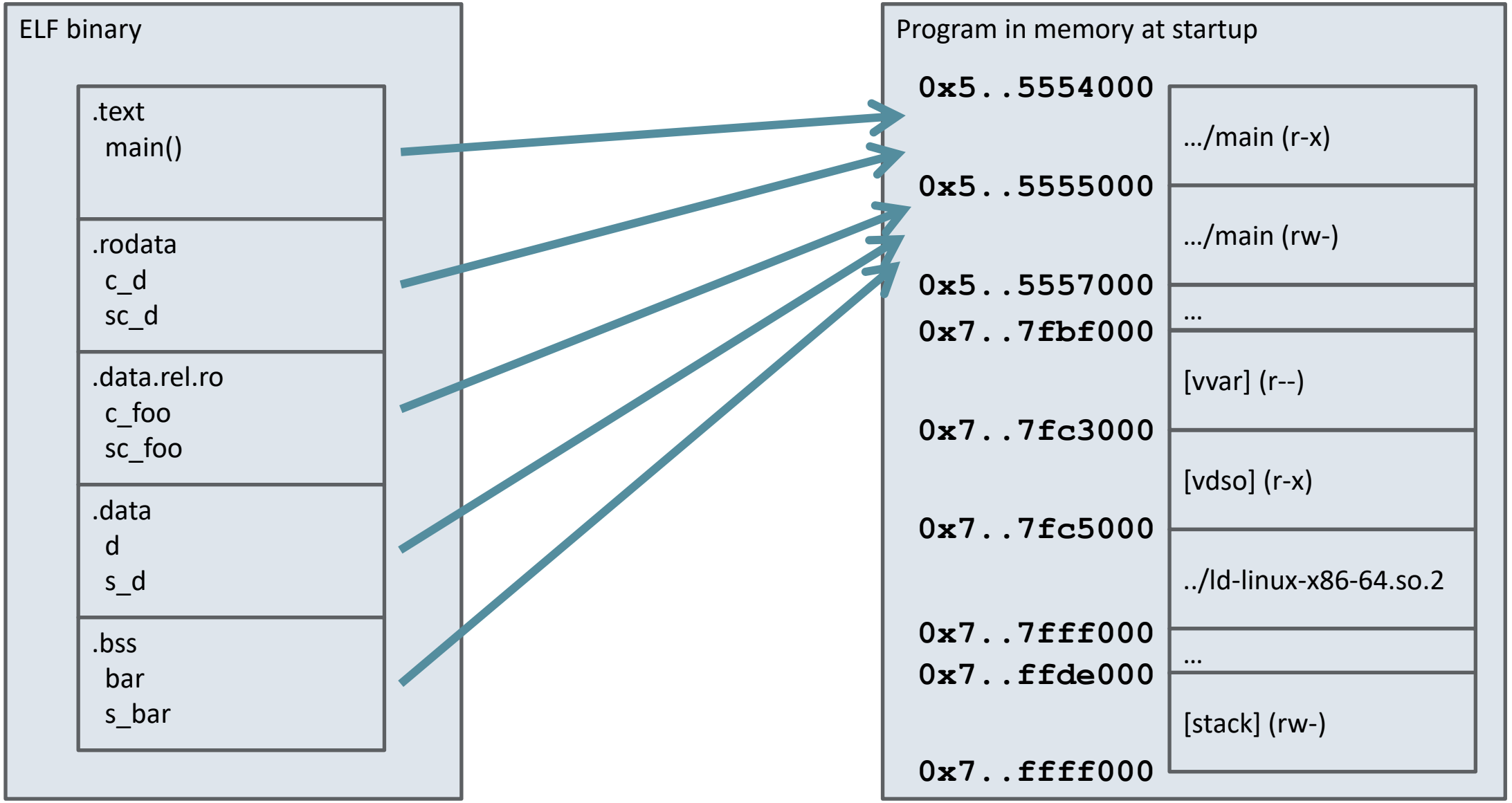
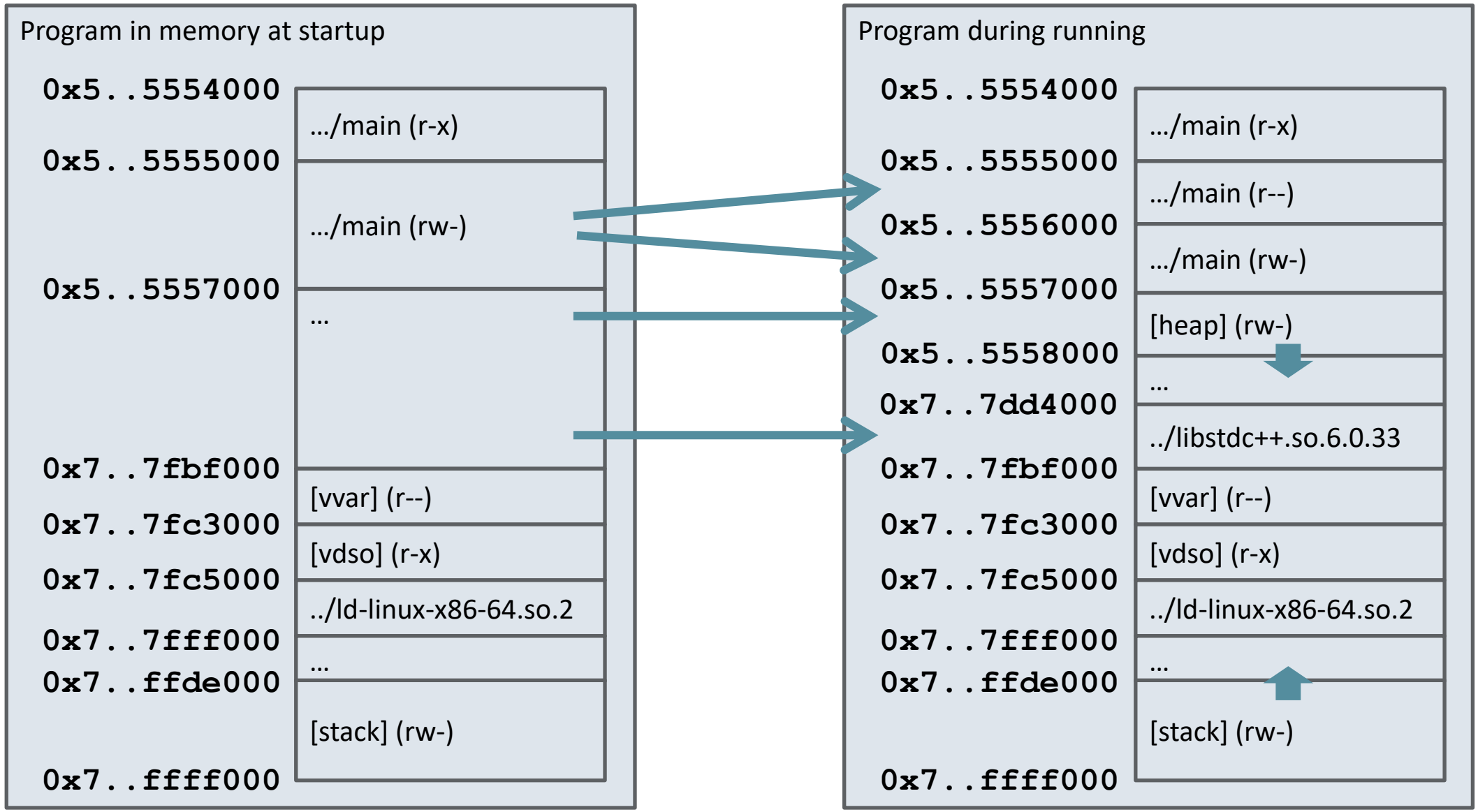
    return 0;
}
```



PROCESS LAYOUT IN MEMORY – LINUX



PROCESS LAYOUT IN MEMORY – LINUX



GROWING STACK

- Demo:
  - https://github.com/limdor/accu-2025/tree/master/dynamic_memory/growing_stack
    - bazel build //dynamic_memory/growing_stack:main -c dbg
    - gdb bazel-bin/dynamic_memory/growing_stack/main
      - break main.cpp:5 if n == 0

GROWING STACK

```cpp
unsigned long compute(unsigned long n)
{
    if (n == 0)
    {
        return 0;
    }
    return 1 + compute(n - 1);
}

int main()
{
    int n;
    do
    {
        std::cout << "Number to be computed: ";
        std::cin >> n;
        std::cout << "Computed number: " << compute(n) << "\n";
    } while (n != 0);
    return 0;
}
```

GROWING STACK

```
(gdb) info proc mappings
process 24235
Mapped address spaces:

          Start Addr           End Addr       Size     Offset  Perms  objfile
      0x555555554000     0x555555555000     0x1000        0x0  r-xp   /growing_stack/main
      0x555555555000     0x555555557000     0x2000        0x0  rw-p   /growing_stack/main
      0x7ffff7fbf000     0x7ffff7fc3000     0x4000        0x0  r--p   [vvar]
      0x7ffff7fc3000     0x7ffff7fc5000     0x2000        0x0  r-xp   [vdso]
      0x7ffff7fc5000     0x7ffff7fc6000     0x1000        0x0  r--p   /usr/lib/x86_64-linux-gnu/ld-linux-x86-64.so.2
      0x7ffff7fc6000     0x7ffff7ff1000    0x2b000     0x1000  r-xp   /usr/lib/x86_64-linux-gnu/ld-linux-x86-64.so.2
      0x7ffff7ff1000     0x7ffff7ffb000     0xa000    0x2c000  r--p   /usr/lib/x86_64-linux-gnu/ld-linux-x86-64.so.2
      0x7ffff7ffb000     0x7ffff7fff000     0x4000    0x36000  rw-p   /usr/lib/x86_64-linux-gnu/ld-linux-x86-64.so.2
      0x7ffffffde000     0x7ffffffff000    0x21000        0x0  rw-p   [stack]
```

132 KB

GROWING STACK

```
unsigned long compute(unsigned long n)
{
    if (n == 0)
    {
        return 0;
    }
    return 1 + compute(n - 1);
}

int main()
{
    int n;
    do
    {
        std::cout << "Number to be computed: ";
        std::cin >> n;
        std::cout << "Computed number: " << compute(n) << "\n";
    } while (n != 0);
    return 0;
}
```

```
0x21000          0x0  rw-p   [stack]
```

132 KB

```
Number to be computed: 20000
```

```
0x9e000          0x0  rw-p   [stack]
```

632 KB

```
Number to be computed: 0
```

```
0x9e000          0x0  rw-p   [stack]
```

632 KB

GROWING HEAP

- Demo:
  - https://github.com/limdor/accu-2025/tree/master/dynamic_memory/growing_heap
    - bazel run //dynamic_memory/growing_heap:main

GROWING HEAP

```
--- Heap memory region info for pid 41035 (start) ---
Pathname: [heap]         Size: 135168 bytes
Start address: 93999983702016 (0x557e13a33000)
End address: 93999983837184 (0x557e13a54000)
 --- Heap memory region info for pid 41035 (start) ---
 Pathname: [heap]         Size: 270336 bytes
 Start address: 93999983702016 (0x557e13a33000)
 End address: 93999983972352 (0x557e13a75000)
 --- Heap memory region info (end) ---
 p - Print pointer addresses
 d - Deallocate
 q - Quit
```

GROWING HEAP

```
--- Heap memory region info for pid 41035 (start) ---
Pathname: [heap]        Size: 135168 bytes
Start address: 93999983702016 (0x557e13a33000)
End address: 93999983837184 (0x557e13a54000)
--- Heap memory region info (end) ---
```


Allocate 50.000 bytes

```
--- Heap memory region info for pid 41035 (start) ---
Pathname: [heap]        Size: 270336 bytes
Start address: 93999983702016 (0x557e13a33000)
End address: 93999983972352 (0x557e13a75000)
--- Heap memory region info (end) ---
```

GROWING HEAP

```
--- Heap memory region info for pid 41035 (start) ---
Pathname: [heap]         Size: 270336 bytes
Start address: 93999983702016 (0x557e13a33000)
End address: 93999983972352 (0x557e13a75000)
--- Heap memory region info (end) ---
```


Allocate 100.000 bytes (150.000 bytes until now)

```
--- Heap memory region info for pid 41035 (start) ---
Pathname: [heap]         Size: 270336 bytes
Start address: 93999983702016 (0x557e13a33000)
End address: 93999983972352 (0x557e13a75000)
--- Heap memory region info (end) ---
```

GROWING HEAP

```
--- Heap memory region info for pid 41035 (start) ---
Pathname: [heap]         Size: 270336 bytes
Start address: 93999983702016 (0x557e13a33000)
End address: 93999983972352 (0x557e13a75000)
--- Heap memory region info (end) ---
```


Allocate 200.000 bytes (350.000 bytes until now)

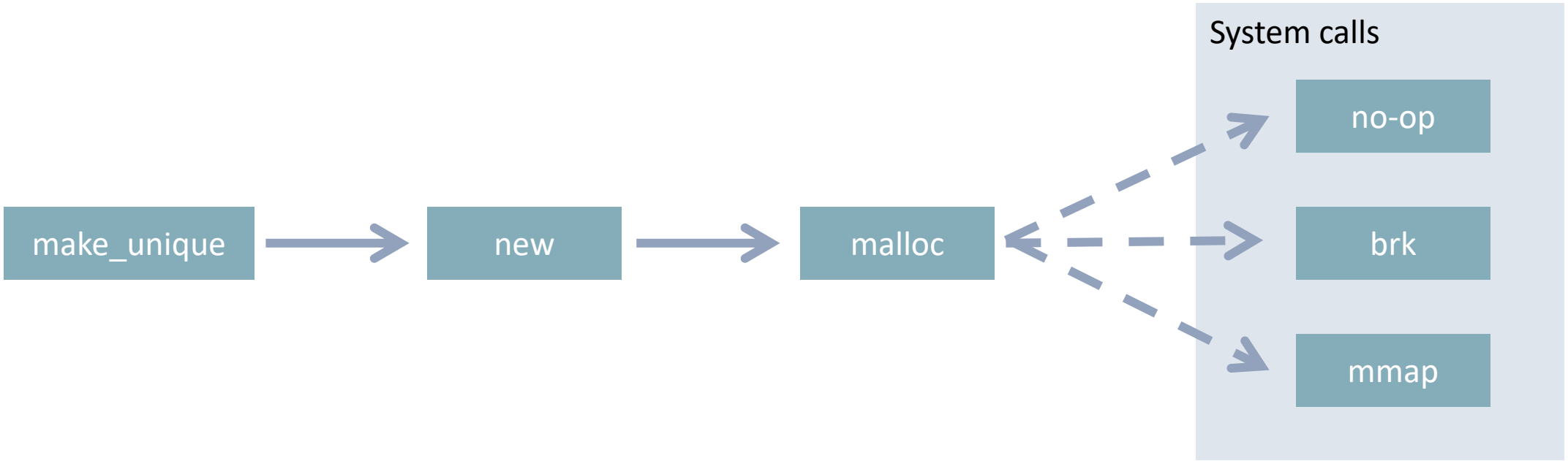
```
--- Heap memory region info for pid 41035 (start) ---
Pathname: [heap]         Size: 270336 bytes
Start address: 93999983702016 (0x557e13a33000)
End address: 93999983972352 (0x557e13a75000)
--- Heap memory region info (end) ---
```

GROWING HEAP

```
What would you like to do?
  a - Allocate
  i - Random initialize memory
  p - Print pointer addresses
  d - Deallocate
  q - Quit
```

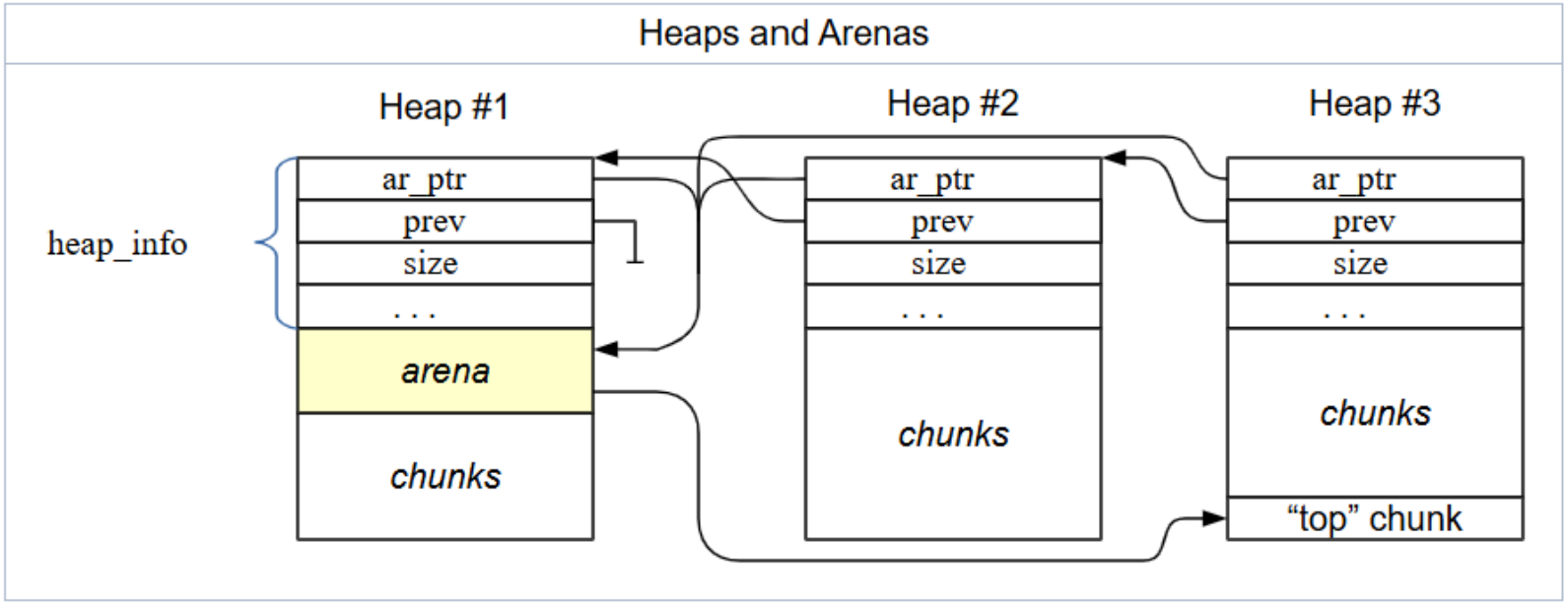
```
50000 bytes at 0x557e13a47cc0
Pathname: [heap]         Size: 270336 bytes
Start address: 93999983702016 (0x557e13a33000)
End address: 93999983972352 (0x557e13a75000)
100000 bytes at 0x557e13a54020
Pathname: [heap]         Size: 270336 bytes
Start address: 93999983702016 (0x557e13a33000)
End address: 93999983972352 (0x557e13a75000)
200000 bytes at 0x7f4781bc8010
Pathname:          Size: 221184 bytes
Start address: 139945096019968 (0x7f4781bc8000)
End address: 139945096241152 (0x7f4781bfe000)
```

THERE IS NO SINGLE HEAP MEMORY REGION



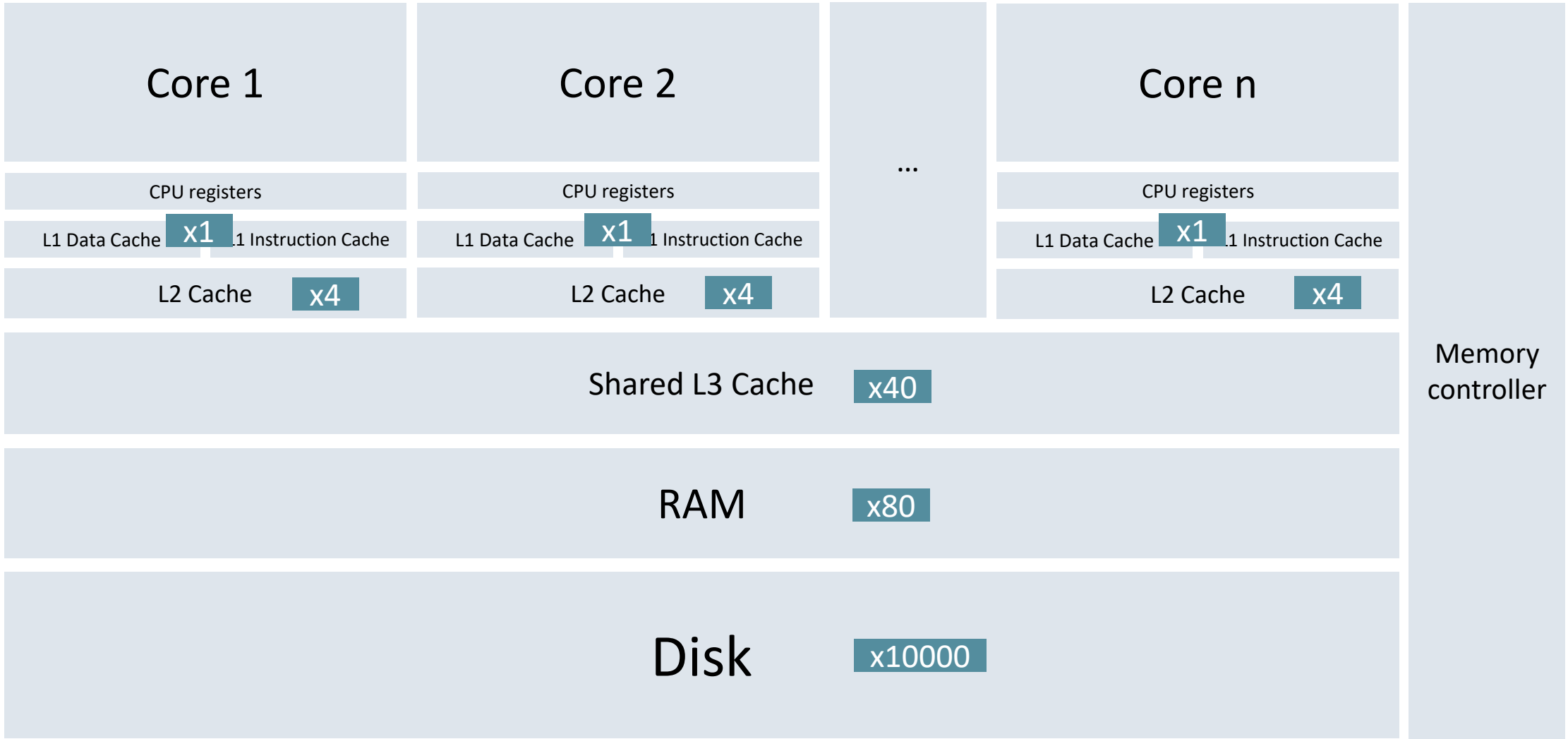
THERE IS NO SINGLE HEAP MEMORY REGION

- Behavior of malloc depends on the implementation

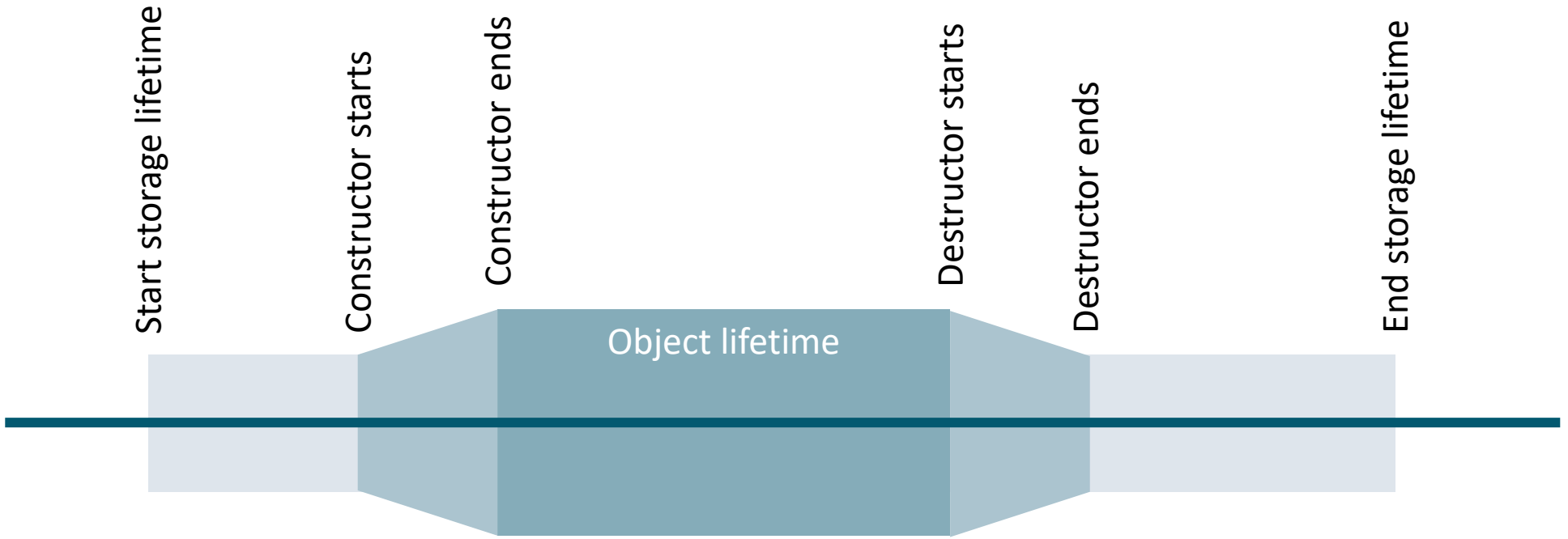


- https://sourceware.org/glibc/wiki/MallocInternals

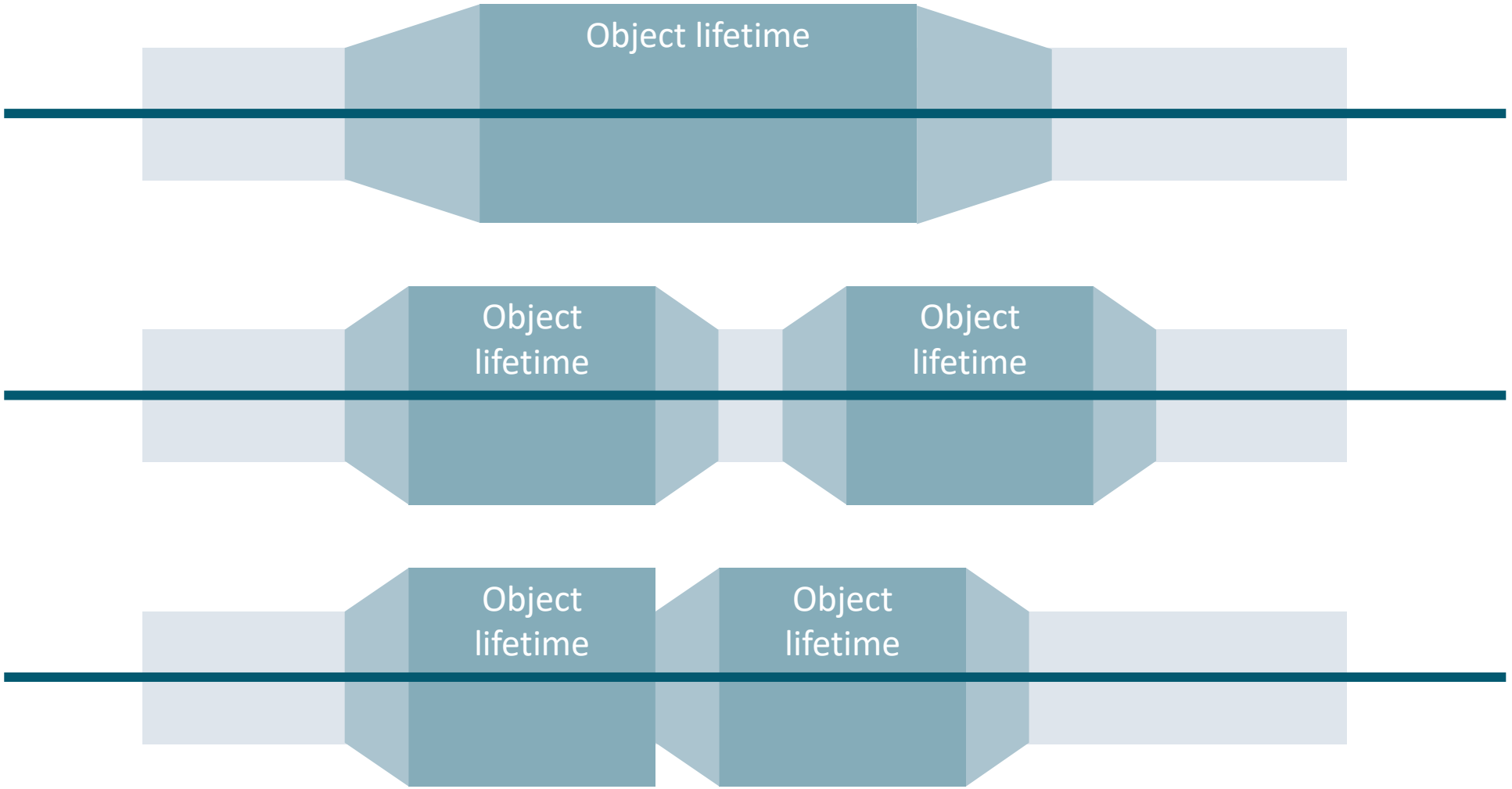
COMPUTER ARCHITECTURE



OBJECT AND STORAGE ARE DIFFERENT THINGS



OBJECT AND STORAGE ARE DIFFERENT THINGS



STORAGE DURATION

Static storage duration

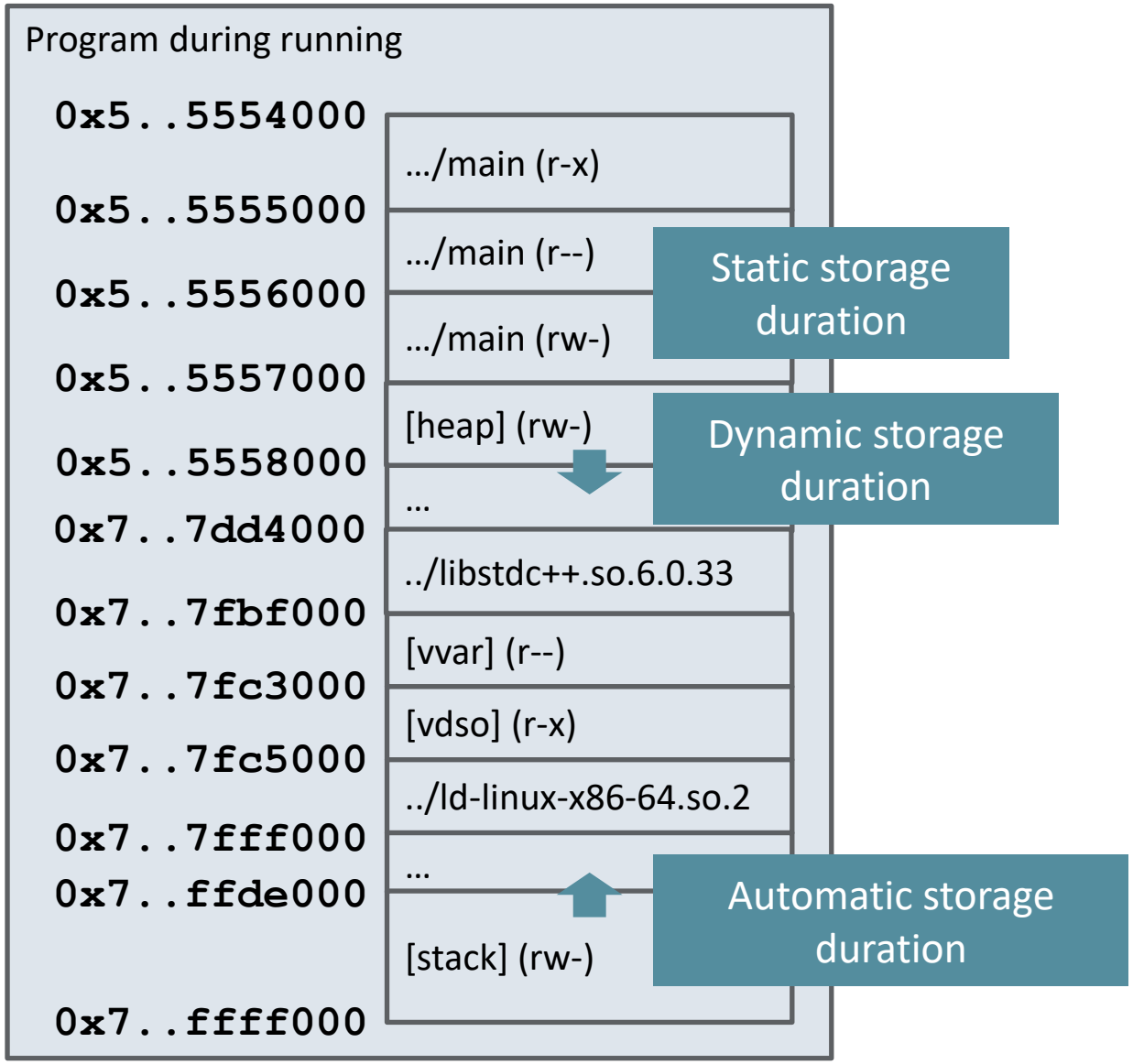
Thread storage duration

Automatic storage duration

Dynamic storage duration*

*Note: Special Storage for exceptions

STORAGE DURATION



ALLOCATING/DEALLOCATING OBJECTS IN THE HEAP WITH NEW AND DELETE

- New and delete expressions can be used to allocate and deallocate objects on the heap
- How many forms of the new operator are available?

```
void* operator new(std::size_t size);
void* operator new(std::size_t size, std::align_val_t alignment);
void* operator new(std::size_t size, const std::nothrow_t&) noexcept;
void* operator new(std::size_t size, std::align_val_t alignment, const std::nothrow_t&) noexcept;
void* operator new[](std::size_t size);
void* operator new[](std::size_t size, std::align_val_t alignment);
void* operator new[](std::size_t size, const std::nothrow_t&) noexcept;
void* operator new[](std::size_t size, std::align_val_t alignment, const std::nothrow_t&) noexcept;
```

- How many forms of the delete are available?

They are replaceable

```
void operator delete(void* ptr) noexcept;
void operator delete(void* ptr, std::size_t size) noexcept;
void operator delete(void* ptr, std::align_val_t alignment) noexcept;
void operator delete(void* ptr, std::size_t size, std::align_val_t alignment) noexcept;
void operator delete(void* ptr, const std::nothrow_t&) noexcept;
void operator delete(void* ptr, std::align_val_t alignment, const std::nothrow_t&) noexcept;
void operator delete[](void* ptr) noexcept;
void operator delete[](void* ptr, std::size_t size) noexcept;
void operator delete[](void* ptr, std::align_val_t alignment) noexcept;
void operator delete[](void* ptr, std::size_t size, std::align_val_t alignment) noexcept;
void operator delete[](void* ptr, const std::nothrow_t&) noexcept;
void operator delete[](void* ptr, std::align_val_t alignment, const std::nothrow_t&) noexcept;
```

ALLOCATING/DEALLOCATING OBJECTS IN THE HEAP WITH NEW AND DELETE

- New and delete expression

```
::opt new new-placementopt new-type-id new-initializeropt
::opt new new-placementopt (type-id) new-initializeropt

::opt delete cast-expression
::opt delete[] cast-expression
```

- Parameters of the new operator

```
...new(std::size_t size, std::align_val_t alignment, const std::nothrow_t&)
```

Number of bytes to allocate

Alignment to use

Do not throw when not enough memory

ALLOCATING/DEALLOCATING OBJECTS IN THE HEAP WITH NEW AND DELETE

- Allocate an integer

```
auto p = new int;
auto p = new int(2);
auto p = new int{3};

auto p = new (int);
auto p = new (int)(2);
auto p = new (int){3};

delete p;
```

- Allocate a class

```
auto p = new Foo;
auto p = new Foo(2);
auto p = new Foo{3};

auto p = new (Foo);
auto p = new (Foo)(2);
auto p = new (Foo){3};

delete p;
```

Throw std::bad_alloc when not enough memory

- Allocate an array of integers

```
auto p = new int[]{3,4,5};
auto p = new int[3];
auto p = new (int[]){3,4,5};
auto p = new (int[3]);

delete[] p;
```

- Allocate an array of classes

```
auto p = new Foo[]{3,4,5};
auto p = new Foo[3];
auto p = new (Foo[]){3,4,5};
auto p = new (Foo[3]);

delete[] p;
```

SELECTION OF THE NEW/DELETE VERSION

- Which new version is selected?

```
auto p = new int;                    auto p = new (int);
auto p = new int(2);                 auto p = new (int)(2);
auto p = new int{3};                 auto p = new (int){3};
```

```
... new(std::size_t);
... new(std::size_t, std::align_val_t);
... new(std::size_t, const std::nothrow_t&) noexcept;
... new(std::size_t, std::align_val_t, const std::nothrow_t&) noexcept;
```

- Which delete version is selected?

```
delete p;
```

```
... delete(void* ptr) noexcept;
... delete(void* ptr, std::size_t) noexcept;
... delete(void* ptr, std::align_val_t) noexcept;
... delete(void* ptr, std::size_t, std::align_val_t) noexcept;
... delete(void* ptr, const std::nothrow_t&) noexcept;
... delete(void* ptr, std::align_val_t, const std::nothrow_t&) noexcept;
```

ALLOCATING WITH NEW WITHOUT THROWING

- Allocating with new without throwing

::$_{opt}$ new *new-placement*$_{opt}$ *new-type-id new-initializer*$_{opt}$

```
auto p = new (std::nothrow) int;
auto p = new (std::nothrow) int{3};

auto p = new (std::nothrow) int[]{3,4,5};
auto p = new (std::nothrow) int[3];
```

- Which new version is selected?

```
    ... new/new[](std::size_t);
    ... new/new[](std::size_t, std::align_val_t);
=>  ... new/new[](std::size_t, const std::nothrow_t&) noexcept;
=>  ... new/new[](std::size_t, std::align_val_t, const std::nothrow_t&) noexcept;
```

ALLOCATING WITH NEW WITHOUT THROWING

- Deallocating with delete after allocating with new without throwing

```
delete p;
delete[] p;
```

- Which new version is selected?

```
... delete(void* ptr) noexcept;
... delete(void* ptr, std::size_t) noexcept;
... delete(void* ptr, std::align_val_t) noexcept;
... delete(void* ptr, std::size_t, std::align_val_t) noexcept;
... delete(void* ptr, const std::nothrow_t&) noexcept;
... delete(void* ptr, std::align_val_t, const std::nothrow_t&) noexcept;
```

- No placement new version of delete

```
::opt delete cast-expression
::opt delete[] cast-expdression
```

ALLOCATING WITH EXTENDED ALIGNMENT

- Allocating with extended alignment

```
auto p = new (std::align_val_t{64}) int{3};

auto p = new (std::align_val_t{64}) int[]{3,4,5};
```

- Can we?

GCC 

Clang 

MSVC 

```
error C2956:
    usual deallocation function 'void operator delete(void *,std::align_val_t) noexcept'
    would be chosen as placement deallocation function.
predefined C++ types (compiler internal)(37):
    note: see declaration of 'operator delete'
```

ALLOCATING WITH EXTENDED ALIGNMENT

- Allocating with extended alignment

```
auto p = new (std::align_val_t{64}) int{3};

delete p;
```

- Can we?

```
... new(std::size_t);
... new(std::size_t, std::align_val_t);
... new(std::size_t, const std::nothrow_t&) noexcept;
... new(std::size_t, std::align_val_t, const std::nothrow_t&) noexcept;
```



```
... delete(void* ptr) noexcept;
... delete(void* ptr, std::size_t) noexcept;
... delete(void* ptr, std::align_val_t) noexcept;
... delete(void* ptr, std::size_t, std::align_val_t) noexcept;
... delete(void* ptr, const std::nothrow_t&) noexcept;
... delete(void* ptr, std::align_val_t, const std::nothrow_t&) noexcept;
```

ALLOCATING WITH EXTENDED AND NOTHROW

- Allocating with extended alignment

```
auto p = new (std::align_val_t{64},std::nothrow) int{3};

auto p = new (std::align_val_t{64},std::nothrow) int[]{3,4,5};
```

- Can we?

GCC  Clang  MSVC 

- Still same issue with delete

```
... delete(void* ptr) noexcept;
... delete(void* ptr, std::size_t) noexcept;
... delete(void* ptr, std::align_val_t) noexcept;
... delete(void* ptr, std::size_t, std::align_val_t) noexcept;
... delete(void* ptr, const std::nothrow_t&) noexcept;
... delete(void* ptr, std::align_val_t, const std::nothrow_t&) noexcept;
```

ALLOCATING WITH EXTENDED ALIGNMENT (THE RIGHT WAY)

- Make the alignment requirement part of the type

```
struct alignas(64) Foo
{
    int bar{42};
};
```

```
auto p = new Foo{3};

delete p;
```

```
... new(std::size_t);
... new(std::size_t, std::align_val_t);
... new(std::size_t, const std::nothrow_t&) noexcept;
... new(std::size_t, std::align_val_t, const std::nothrow_t&) noexcept;
```

```
... delete(void* ptr) noexcept;
... delete(void* ptr, std::size_t) noexcept;
... delete(void* ptr, std::align_val_t) noexcept;
... delete(void* ptr, std::size_t, std::align_val_t) noexcept;
... delete(void* ptr, const std::nothrow_t&) noexcept;
... delete(void* ptr, std::align_val_t, const std::nothrow_t&) noexcept;
```

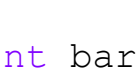
ALLOCATING WITH EXTENDED ALIGNMENT (THE RIGHT WAY)

- Make the alignment requirement part of the type

```
struct alignas(64) Foo
{
    int bar{42};
};
```

```
auto p = new (std::nothrow) Foo{3};

delete p;
```



```
... new(std::size_t);
... new(std::size_t, std::align_val_t);
... new(std::size_t, const std::nothrow_t&) noexcept;
... new(std::size_t, std::align_val_t, const std::nothrow_t&) noexcept;
```

```
... delete(void* ptr) noexcept;
... delete(void* ptr, std::size_t) noexcept;
... delete(void* ptr, std::align_val_t) noexcept;
... delete(void* ptr, std::size_t, std::align_val_t) noexcept;
... delete(void* ptr, const std::nothrow_t&) noexcept;
... delete(void* ptr, std::align_val_t, const std::nothrow_t&) noexcept;
```

DYNAMIC MEMORY ALLOCATION USING C++ STD LIBRARY

- Using the C API

```
void *malloc( size_t size );
void* calloc( size_t num, size_t size );
void *realloc( void *ptr, size_t new_size );
void *aligned_alloc( size_t alignment, size_t size );

void free( void *ptr );
```

- Using smart pointers

```
template< class T, class... Args >
constexpr unique_ptr<T> make_unique( Args&&... args );
shared_ptr<T> make_shared( Args&&... args );

template< class T >
constexpr unique_ptr<T> make_unique_for_overwrite();
shared_ptr<T> make_shared_for_overwrite();
```

DYNAMIC MEMORY ALLOCATION USING C++ STD LIBRARY

- Using indirect and polymorphic (planned for C++26)
  - Dynamic allocated objects with value semantics
    - https://eel.is/c++draft/indirect
    - https://eel.is/c++draft/polymorphic
  - Reference implementation
    - https://github.com/jbcoe/value_types

IMPLICIT DYNAMIC MEMORY ALLOCATION IN THE C++ STD LIBRARY

- Does it dynamically allocate memory? And how much?

```
auto pointer = std::make_unique<int>(2);
```

Dynamic allocation: Yes

Number of allocations: 1

Allocated bytes: 4

```
auto pointer = std::make_shared<int>(2);
```

Dynamic allocation: Yes

Number of allocations: 1

Allocated bytes: 24

IMPLICIT DYNAMIC MEMORY ALLOCATION IN THE C++ STD LIBRARY

- Does it dynamically allocate memory? And how much?

```
const std::string small_string = "my_small_string";
```

Dynamic allocation: No

```
const std::string big_string = "my_big_string_that_does_not_fit_for_small_string_optimizatio
```

Dynamic allocation: Yes

Number of allocations: 1

Allocated bytes: 62

```
const std::string_view big_string = "my_big_string_that_does_not_fit_for_small_string_optimi
```

Dynamic allocation: No

IMPLICIT DYNAMIC MEMORY ALLOCATION IN THE C++ STD LIBRARY

- Does it dynamically allocate memory? And how much?

```
const std::array array_of_ints = {4, 3, 5, 6, 7, 8, 9, 10};
```

Dynamic allocation: No

```
const std::vector<std::string> default_constructed_vector{};
```

Dynamic allocation: No

```
const std::vector<int> vector_of_ints = {4, 3, 5, 6, 7, 8, 9, 10};
```

Dynamic allocation: Yes

Number of allocations: 1

Allocated bytes: 32

IMPLICIT DYNAMIC MEMORY ALLOCATION IN THE C++ STD LIBRARY

- Does it dynamically allocate memory? And how much?

```
void answer_to_live_or_abort(int value)
{
    if (value != 42)
    {
        std::terminate();
    }
}

std::function<void(int)> f = answer_to_live_or_abort;
```

Dynamic allocation: No

IMPLICIT DYNAMIC MEMORY ALLOCATION IN THE C++ STD LIBRARY

- Does it dynamically allocate memory? And how much?

```
struct universe_t
{
    void answer_or_abort(int value)
    {
        ::answer_to_live_or_abort(value);
    }
};

universe_t universe;
std::function<void(int)> f = std::bind(&universe_t::answer_or_abort, &universe, _1);
```

Dynamic allocation: Yes

Number of allocations: 1

Allocated bytes: 24

IMPLICIT DYNAMIC MEMORY ALLOCATION IN THE C++ STD LIBRARY

- Does it dynamically allocate memory? And how much?

```
std::thread thread{answer_to_live_or_abort, 42};
thread.join();
```

Dynamic allocation: Yes

Number of allocations: 1

Allocated bytes: 24

```
std::jthread thread{answer_to_live_or_abort, 42};
```

Dynamic allocation: Yes

Number of allocations: 2

Allocated bytes: 48

IMPLICIT DYNAMIC MEMORY ALLOCATION IN THE C++ STD LIBRARY

- Does it dynamically allocate memory? And how much?

```
std::promise<void> promise;
```

Dynamic allocation: Yes

Number of allocations: 2

Allocated bytes: 64

```
auto future = promise.get_future();
```

Dynamic allocation: No

```
promise.set_value();
```

Dynamic allocation: No

```
std::future<int> future;
```

Dynamic allocation: No

IMPLICIT DYNAMIC MEMORY ALLOCATION IN THE C++ STD LIBRARY

- Does it dynamically allocate memory? And how much?

```
std::any a = 42;
```

Dynamic allocation: No

```
const std::string small_string = "my_small_string";
std::any a = small_string;
```

Dynamic allocation: Yes

Number of allocations: 1

Allocated bytes: 32

IMPLICIT DYNAMIC MEMORY ALLOCATION IN THE C++ STD LIBRARY

- Does it dynamically allocate memory? And how much?

```
std::stacktrace::current();
```

Dynamic allocation: Yes

Number of allocations: 1

Allocated bytes: 512

HOW TO KNOW IF SOMETHING DYNAMICALLY ALLOCATES?

- Class satisfies AllocationAwareContainer

  `std::vector` (for T other than `bool`) meets the requirements of *Container*, *AllocatorAwareContainer*(since C++11), *SequenceContainer*, *ContiguousContainer*(since C++17) and *ReversibleContainer*.

- One template parameter is an Allocator

```
template< class BidirIt, class Alloc, class CharT, class Traits >
bool regex_match( BidirIt first, BidirIt last,
                  std::match_results<BidirIt, Alloc>& m,
                  const std::basic_regex<CharT, Traits>& e,
                  std::regex_constants::match_flag_type flags =
                      std::regex_constants::match_default );
```

(1) (since C++11)

Snapshots from https://en.cppreference.com/w/cpp

HOW TO KNOW IF SOMETHING DYNAMICALLY ALLOCATES?

- Throws bad_alloc if memory could not be allocated

Exceptions

1) `std::bad_alloc` if memory could not be allocated for the stop-state.

- You know that the only way to implement it is dynamically allocating memory

- You provide a replacement for the global operator new and delete and you see if it dynamically allocates

Snapshots from https://en.cppreference.com/w/cpp

CUSTOMIZING DYNAMIC MEMORY ALLOCATION

- Global new and delete
  - One new/delete to rule them all.
  - Multiple overloads that should follow same semantics. If you define one, define them all.
  - It replaces the default new/delete. Once replaced you have no longer access to the default ones.
  - If you do not follow the allocation/deallocation semantics required by the standard, the behavior is undefined.

```
void *operator new(std::size_t count)
{
    if (g_tracking)
    {
        g_allocated_bytes += count;
        g_number_of_allocations++;
    }
    void *pointer_to_storage = malloc(count);
    if (!pointer_to_storage)
    {
        throw std::bad_alloc();
    }
    return pointer_to_storage;
}
```

CUSTOMIZING DYNAMIC MEMORY ALLOCATION

- Class new and delete
  - Custom new/delete per type.
  - All instance of the same type, will use the same allocator.
  - Only called when the object is allocated on the heap (new, make_unique, make_shared, etc.).
  - It does not propagate to the members. If a member requires dynamic memory allocation, it will not use the class allocator.

```
class Foo
{
public:
    static void *operator new(std::size_t size)
    {
        if (free_slot + size >= storage.size())
        {
            throw std::bad_alloc();
        }
        void *pointer = &storage[free_slot];
        free_slot += size;
        return pointer;
    }
    static void operator delete(void *) {}

private:
    int bar;
};
```

CUSTOMIZING DYNAMIC MEMORY ALLOCATION

- Custom allocator
  - Multiple instances for the same type allocator.
  - It needs to follow the Allocator requirements.
  - Several traits are optional.
  - Default traits are provided via allocator_traits.
  - When copy/move a type with a custom allocator, you can choose at allocator level if allocator gets propagated.

```
template <class T>
class MallocAllocator
{

public:
    using value_type = T;

    [[nodiscard]] T *allocate(std::size_t size)
    {
        auto p = std::malloc(sizeof(T) * size);
        return static_cast<T *>(p);
    }
    void deallocate(T *pointer, std::size_t size)
    {
        std::free(pointer);
    }
};
```

CUSTOMIZING DYNAMIC MEMORY ALLOCATION

- Polymorphic allocator (pmr) (since C++17)
  - Allocation behavior can be configured at runtime.
  - Functionality is divided between polymorphic_allocator and memory_resource.
  - Standard library provides multiple memory resources.
    - Including null memory resource and new and delete memory resource
  - Polymorphic allocators do not propagate on move/copy assignment of the container.
  - Swapping two containers that allocators do not compare equal is undefined behavior.
  - It does propagate to the members that use polymorphic allocators.

```
std::array<std::byte, 50> storage;

std::pmr::monotonic_buffer_resource resource{
    storage.data(), storage.size(),
    std::pmr::null_memory_resource()
};

std::pmr::vector<int> vector{
    {1, 2, 3, 4, 5, 6, 7, 8, 9, 10},
    &resource
};
```

IN SUMMARY, DYNAMIC MEMORY ALLOCATION IS HARD

- The end goal is to achieve functional safety

- The C++ mental model is one part, but the implementation plays a big role
  - OS, std library, compiler, etc.

- When using allocators, still remember what you wanted to solve
  - Memory leaks
  - Out of memory
  - Allocation/deallocation mismatch
  - Memory fragmentation
  - None deterministic runtime
  - Use after free

ACKNOWLEDGEMENTS

- Thanks to everyone from the Munich C++ user group that provided feedback to make this talk better

DYNAMIC MEMORY ALLOCATION CHALLENGES IN SAFETY CRITICAL SYSTEMS

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BMW Group

FURTHER READING

- PE Format (Windows executables)
  - https://learn.microsoft.com/en-us/archive/msdn-magazine/2002/february/inside-windows-win32-portable-executable-file-format-in-detail
  - https://learn.microsoft.com/en-us/archive/msdn-magazine/2002/march/inside-windows-an-in-depth-look-into-the-win32-portable-executable-file-format-part-2