Optimizing Memory Usage on modern computers

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November 26^{th} 2018

Foreword

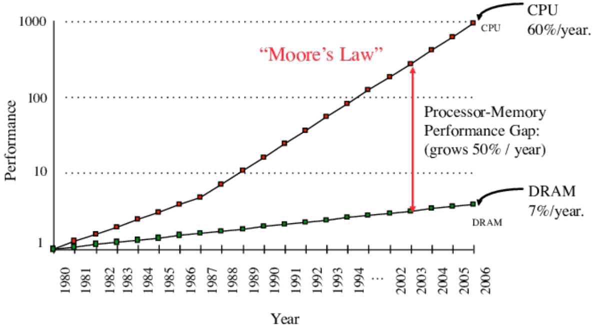
- the concepts and techniques presented here are generic
- they apply to basically all languages and data structures
- however, examples shown are based on C^{++} and the STL

Outline

1. Context
   - What is the problem with memory ?
2. How to be efficient
   - Basics of memory allocation
   - Efficient memory allocation
   - Cache optimization, SoA
3. Measuring efficiency
   - Detection of suboptimal allocations

What is the problem with memory ?

Evolution of memory in the past decades

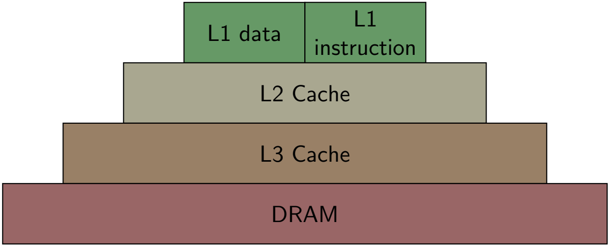


Due to Moore's law in the 80s and 90s, there is a gap between CPU and memory performances

Consequences :

- access to memory is now extremely slow (relatively)
- level of caches have been introduced to mitigate
- good usage of caches has become a key parameter

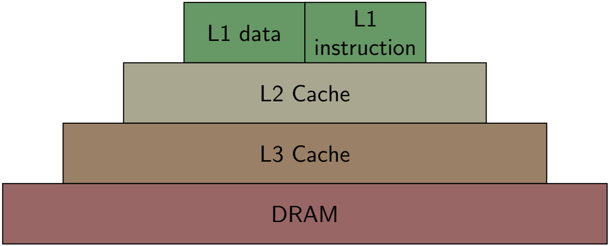
Typical cache structure



size	latency
64 kB	4 cycles
256 kB	10 cycles
10 MB	40 cycles
64 GB	400 cycles

Typical data, on an Haswell architecture

Typical cache structure



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Typical data, on an Haswell architecture

Basics of memory allocation

Process memory organization

4 main areas

- **the code segment** for the code of the executable
- **the data segment** for global variables
- **the heap** for dynamically allocated variables
- **the stack** for parameters of functions and local variables

Memory layout

heap
$\downarrow$ ... $\downarrow$
$\uparrow$ ... $\uparrow$
stack
data segment
code segment

Process memory organization

Stack allocation usage and cost

- small objects
- lifetime limited to current scope
- allocation is almost free : one CPU cyle

Heap allocation usage and cost

- any size
- lifetime infinite, until explicit deallocation
- allocation is costly :
    - find an empty piece of memory
    - going though a list/map hold by the linux kernel
    - and taking a lock to make it thread safe

Basic container in memory

Simple vector / array case

x_0	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	$\cdots$

Basic container in memory

Simple vector / array case

x_0	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	$\cdots$

Array / Vector of objects

```
struct A { float x, y, z; };
```

x_0	y_0	z_0	x_1	y_1	z_1	x_2	y_2	z_2	x_2	$\cdots$

A_0 A_1 A_2

Container of pointers

Naïve view

```
struct A { float x, y, z; };
std::vector<A*> v;   std::array<A*> a;
```

ptr_0	ptr_1	ptr_2	ptr_3	ptr_4	ptr_5	ptr_6	ptr_7	ptr_8	ptr_9	...

Container of pointers

Naïve view

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struct A { float x, y, z; };
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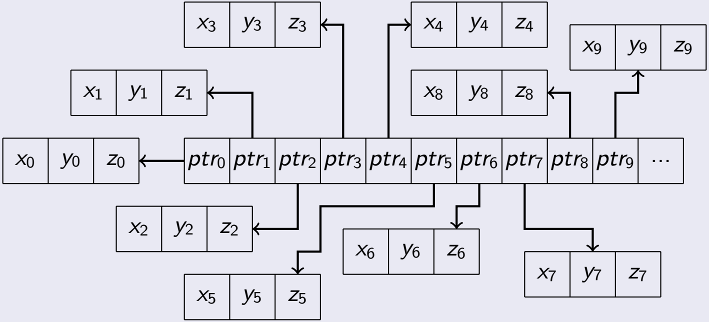
```

ptr_0	ptr_1	ptr_2	ptr_3	ptr_4	ptr_5	ptr_6	ptr_7	ptr_8	ptr_9	...

Realistic view



Consequences : memory allocations

Optimal number of allocations

- Container of A $\rightarrow$ optimally 1 allocation, possibly on stack
- Container of A* $\rightarrow$ minimum n+1 allocations, n on heap

More consequences : reading data

Memory view for container of objects

Each line corresponds to a cache line (64 bytes, 16 floats)

0x00C0	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
0x0080	x_0	y_0	z_0	x_1	y_1	z_1	x_2	y_2	z_2	x_3	y_3	z_3	x_4	y_4	z_4	x_5
0x0040	y_5	z_5	x_6	y_6	z_6	x_7	y_7	z_7	x_8	y_8	z_8	x_9	y_9	z_9	·	·
0x0000	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·

More consequences : reading data

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0x0040	y_5	z_5	x_6	y_6	z_6	x_7	y_7	z_7	x_8	y_8	z_8	x_9	y_9	z_9	·	·
0x0000	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·

One read from RAM to Level 1 Cache is enough (2 lines in one go)

More consequences : reading data

Memory view for Container of pointers to objects

Each line corresponds to a cache line (64 bytes, 16 floats)

0x0240																
0x0200	x_8	y_8	z_8								x_9	y_9	z_9			
0x01C0						x_7	y_7	z_7								
0x0180								x_5	y_5	z_5				x_6	y_6	z_6
0x0140																
0x0100		x_3	y_3	z_3									x_4	y_4	z_4	
0x00C0						x_2	y_2	z_2								
0x0080					x_0	y_0	z_0	x_1	y_1	z_1						
0x0040	p_0	p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8	p_9						
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More consequences : reading data

Memory view for Container of pointers to objects

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0x0140																
0x0100		x_3	y_3	z_3									x_4	y_4	z_4	
0x00C0						x_2	y_2	z_2								
0x0080					x_0	y_0	z_0	x_1	y_1	z_1						
0x0040	p_0	p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8	p_9						
0x0000																

You need to read many lines, in several accesses
Remember each RAM access is 400 cycles...

Practical consequences

Guidelines

- we want as few heap memory allocations as possible
  - stack usage is much better !
- we want continuous memory blocks, allocated in one go
  - that means containers of objects, no pointers involved

Efficient memory allocation

How does a dynamic container grow ?

```
struct A { float x, y, z; };
std::vector<A> v;
```

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struct A { float x, y, z; };
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Construction

Initially, container is empty, no storage allocated

start	0x0
finish	0x0
end_of_storage	0x0

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```cpp
struct A { float x, y, z; };
std::vector<A> v;
```

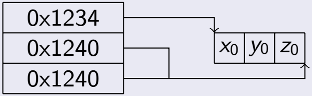
Construction

Initially, container is empty, no storage allocated

start	0x0
finish	0x0
end_of_storage	0x0

Adding first element

for std::vector, allocates storage for the first element only !



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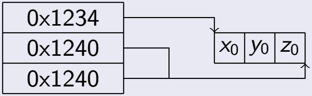
Adding second element



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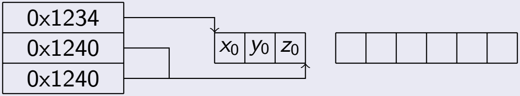
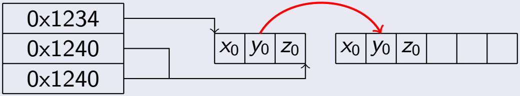


1. allocate new piece of memory for 2 items

How does a dynamic container grow ?

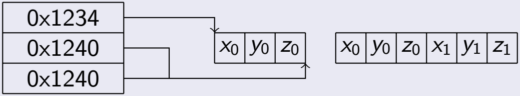
Adding second element



1. allocate new piece of memory for 2 items
2. copy existing content

How does a dynamic container grow ?

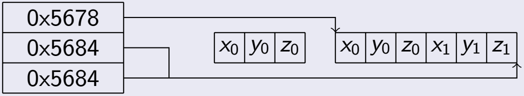
Adding second element



1. allocate new piece of memory for 2 items
2. copy existing content
3. write new content

How does a dynamic container grow ?

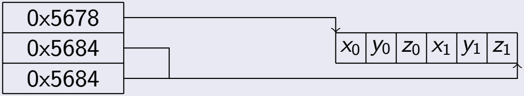
Adding second element



1. allocate new piece of memory for 2 items
2. copy existing content
3. write new content
4. update pointers

How does a dynamic container grow ?

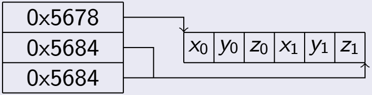
Adding second element



1. allocate new piece of memory for 2 items
2. copy existing content
3. write new content
4. update pointers
5. Deallocate original piece of memory

How does a dynamic container grow ?

Adding third element



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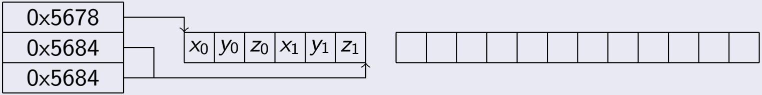
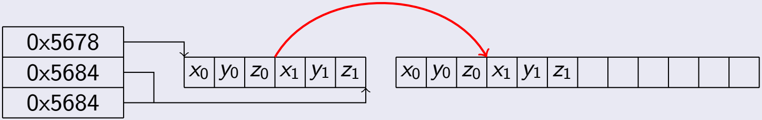


1. allocate new piece of memory for 4 items
   - double size at each iteration

How does a dynamic container grow ?

Adding third element



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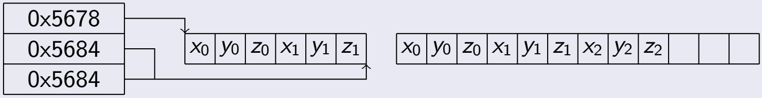

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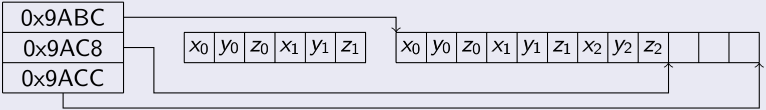

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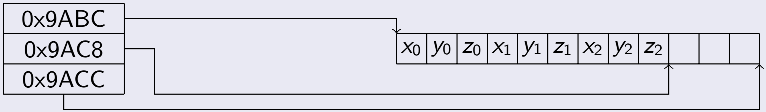

1. allocate new piece of memory for 4 items
   - double size at each iteration
2. copy existing content
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5. Deallocate original piece of memory

Proper container allocation

You may want to avoid default behavior

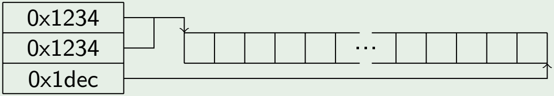
- content of container is reallocated and copied when they grow
- first item of a 1000 nodes vector is copied 10 times in C^{++} !
- when reaching 1000 items, you will have copied 1023 items in total and allocated 11 pieces of memory, releasing 10

You want to control the allocation

- and "reserve" the space manually at the start

```
std::vector<int> v;
v.reserve(1000);
```

- ensures single allocation, no copies, no reallocations



Main lessons

- use stack as much as possible, avoid heap when feasible
- use container of objects, not of pointers
- use container reservation

Cache optimization, SoA

Back to cache considerations

Memory view for container of objects

```
struct A { float a,b,c,d,e,f,g,h,i,j,k,l,m,n,o,p; }
std::vector<A> v;
```

Each `A` corresponds to a cache line (64 bytes, 16 floats)

0x01C0	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
0x0180	a_5	b_5	c_5	d_5	e_5	f_5	g_5	h_5	i_5	j_5	k_5	l_5	m_5	n_5	o_5	p_5
0x0140	a_4	b_4	c_4	d_4	e_4	f_4	g_4	h_4	i_4	j_4	k_4	l_4	m_4	n_4	o_4	p_4
0x0100	a_3	b_3	c_3	d_3	e_3	f_3	g_3	h_3	i_3	j_3	k_3	l_3	m_3	n_3	o_3	p_3
0x00C0	a_2	b_2	c_2	d_2	e_2	f_2	g_2	h_2	i_2	j_2	k_2	l_2	m_2	n_2	o_2	p_2
0x0080	a_1	b_1	c_1	d_1	e_1	f_1	g_1	h_1	i_1	j_1	k_1	l_1	m_1	n_1	o_1	p_1
0x0040	a_0	b_0	c_0	d_0	e_0	f_0	g_0	h_0	i_0	j_0	k_0	l_0	m_0	n_0	o_0	p_0
0x0000	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.

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0x0140	a_4	b_4	c_4	d_4	e_4	f_4	g_4	h_4	i_4	j_4	k_4	l_4	m_4	n_4	o_4	p_4
0x0100	a_3	b_3	c_3	d_3	e_3	f_3	g_3	h_3	i_3	j_3	k_3	l_3	m_3	n_3	o_3	p_3
0x00C0	a_2	b_2	c_2	d_2	e_2	f_2	g_2	h_2	i_2	j_2	k_2	l_2	m_2	n_2	o_2	p_2
0x0080	a_1	b_1	c_1	d_1	e_1	f_1	g_1	h_1	i_1	j_1	k_1	l_1	m_1	n_1	o_1	p_1
0x0040	a_0	b_0	c_0	d_0	e_0	f_0	g_0	h_0	i_0	j_0	k_0	l_0	m_0	n_0	o_0	p_0
0x0000	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.

Computing $\sum g_n$ requires usage of all cache lines

Structure o Arrays (SoA) approach

Let's put together what goes together

```
struct As {
  std::vector<float> a,b,c,d,e,f,g,h,i,j,k,l,m,n,o,p;
} v;
```

Memory now looks like this :

0x01C0	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
0x0180	e_0	e_1	e_2	e_3	e_4	e_5	e_6	e_7	e_8	e_9	e_{10}	e_{11}	e_{12}	-	-	-
0x0140	f_0	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	f_9	f_{10}	f_{11}	f_{12}	-	-	-
0x0100	g_0	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9	g_{10}	g_{11}	g_{12}	-	-	-
0x00C0	h_0	h_1	h_2	h_3	h_4	h_5	h_6	h_7	h_8	h_9	h_{10}	h_{11}	h_{12}	-	-	-
0x0080	i_0	i_1	i_2	i_3	i_4	i_5	i_6	i_7	i_8	i_9	i_{10}	i_{11}	i_{12}	-	-	-
0x0040	j_0	j_1	j_2	j_3	j_4	j_5	j_6	j_7	j_8	j_9	j_{10}	j_{11}	j_{12}	-	-	-
0x0000	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.

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0x01C0	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
0x0180	e_0	e_1	e_2	e_3	e_4	e_5	e_6	e_7	e_8	e_9	e_{10}	e_{11}	e_{12}	-	-	-
0x0140	f_0	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	f_9	f_{10}	f_{11}	f_{12}	-	-	-
0x0100	g_0	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9	g_{10}	g_{11}	g_{12}	-	-	-
0x00C0	h_0	h_1	h_2	h_3	h_4	h_5	h_6	h_7	h_8	h_9	h_{10}	h_{11}	h_{12}	-	-	-
0x0080	i_0	i_1	i_2	i_3	i_4	i_5	i_6	i_7	i_8	i_9	i_{10}	i_{11}	i_{12}	-	-	-
0x0040	j_0	j_1	j_2	j_3	j_4	j_5	j_6	j_7	j_8	j_9	j_{10}	j_{11}	j_{12}	-	-	-
0x0000	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.

Computing $\sum g_n$ uses a single cache line

Consequences

- only one line loaded in L1 cache
- only one line dropped from that cache to fit the new one
- better chances to find data in cache for next instruction
- potential gain : factor 2 to 100 on memory access

Main lesson

- Colocate in memory what is used at the same time
- Drawback : optimization of the memory structure depends on the consumer

Detection of suboptimal allocations

The main tools : profilers

Find out where allocation really costs time

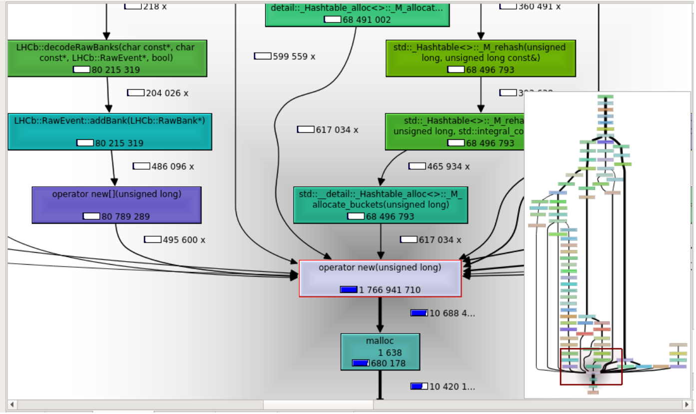
vtune from Intel

- uses internal processor counters to see where time is spent
- in particular number of cycles spent in memory allocations
- and cache misses

callgrind - open source

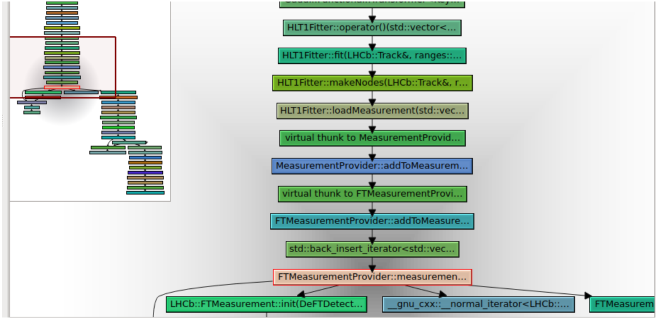
- simulates a processor and allows to count what is going on
- in particular number of cycles spent in memory allocations
- and (simulated) cache misses

callgrind in practice



- graph of function calls leading to memory allocation
- and the time spent for each case

callgrind in practice



- all comes from the HLT1Fitter, where you find :

```
unsigned int HLT1Fitter::fit(LHCb::Track& ...) const {
  // Store results of the Kalman fit
  std::vector<LHCb::Measurement*> measurements;
```

Conclusions

- Memory allocation/deallocations are not cheap
- Optimizing them can lead to substantial gains
- key directions are :
  - container of objects
  - preallocate containers aka "reservation"
  - optimize your data structures for caches, aka SoA
  - use profilers to detect potential issues