LAPP
Laboratoire d'Annecy de Physique des Particules

Introduction :
C++ Algorithms

Pierre Aubert

Introduction

Introduction

Application

Introduction

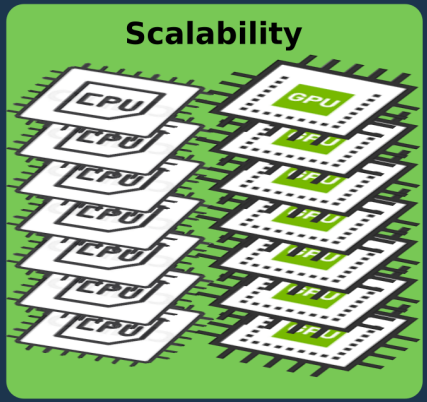
Performances

Application

Introduction

Performances

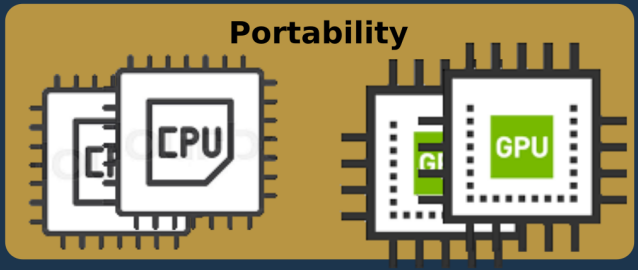
Application

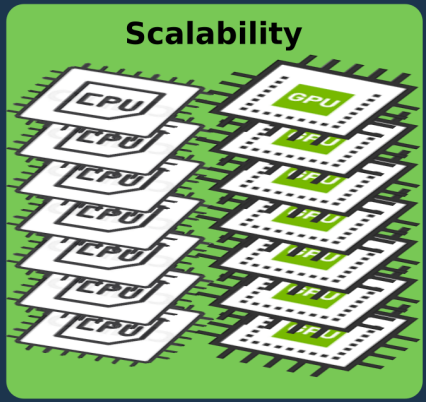


Introduction

Performances

Application



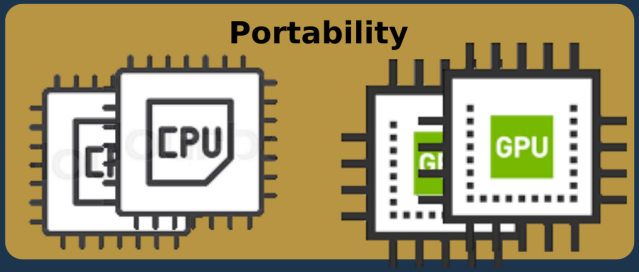


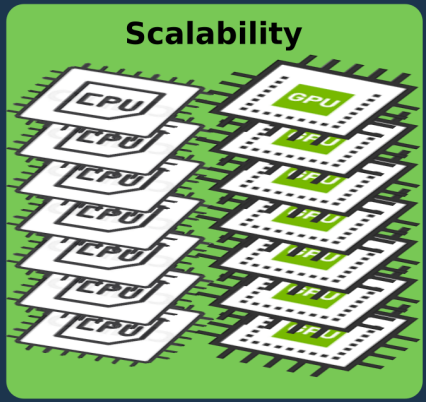
Introduction

Less Development As Possible

Performances

Application





Express Parallelism

Express Parallelism

Event

Express Parallelism

Event

Independent Events => Independent Computing => Parallelism

Express Parallelism

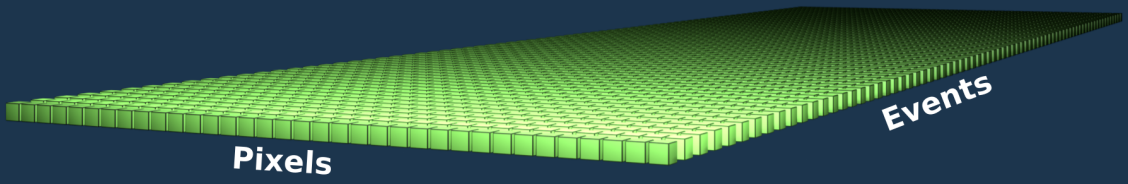
Event

Independent Events => Independent Computing => Parallelism

Express Parallelism

Event

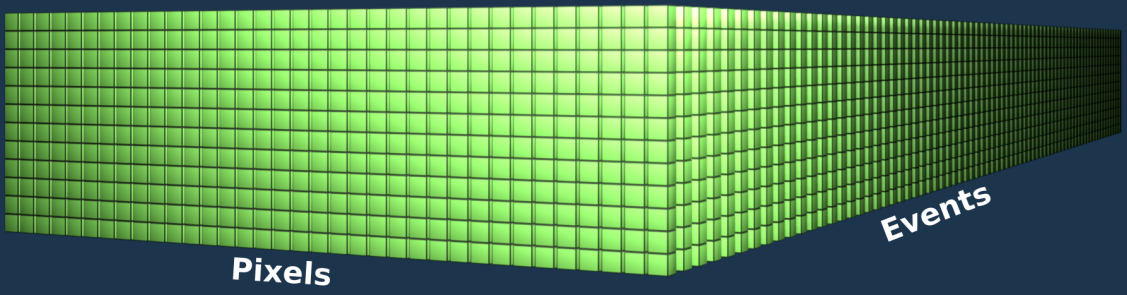
Independent Events => Independent Computing => Parallelism



Express Parallelism

Event

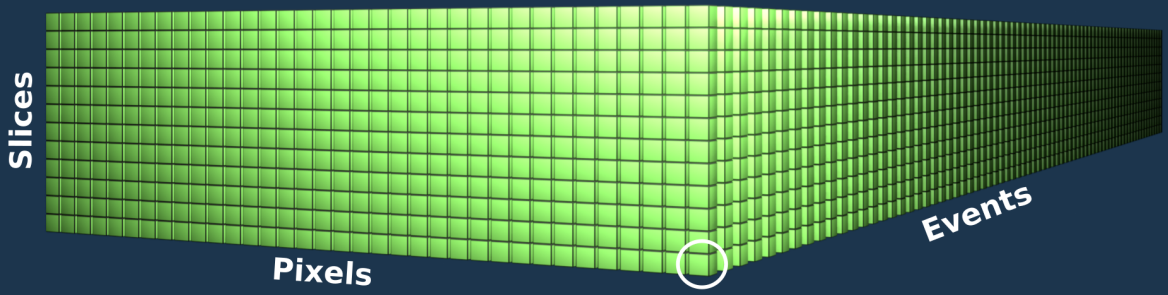
Independent Events => Independent Computing => Parallelism



Express Parallelism

Event

Independent Events => Independent Computing => Parallelism

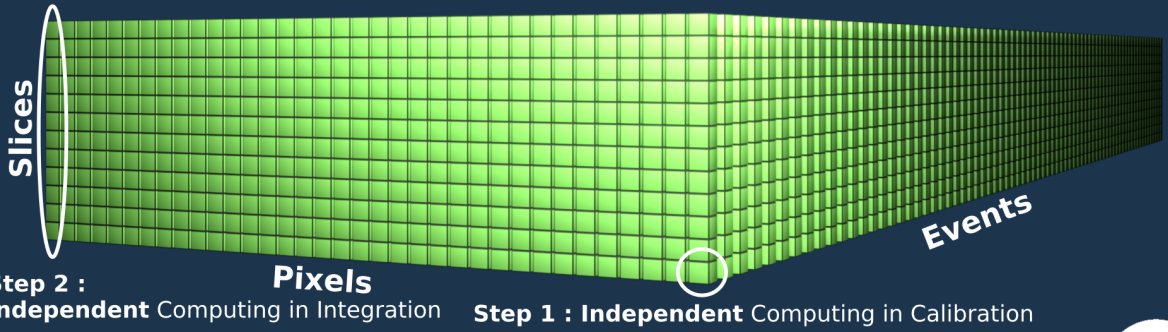


Step 1 : Independent Computing in Calibration

Express Parallelism

Event

Independent Events => Independent Computing => Parallelism



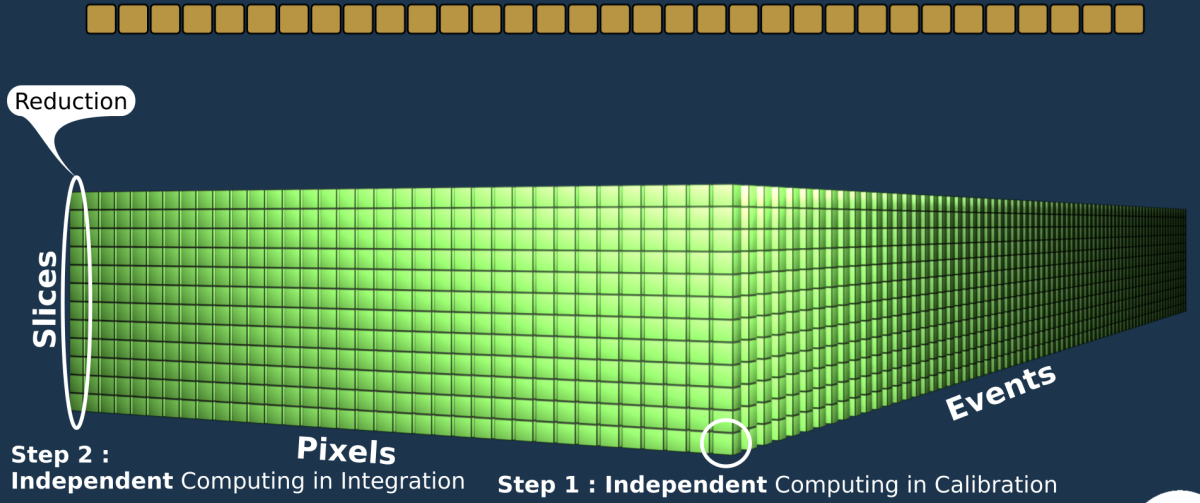
Step 2 :
Independent Computing in Integration

Step 1 : Independent Computing in Calibration

Express Parallelism

Event

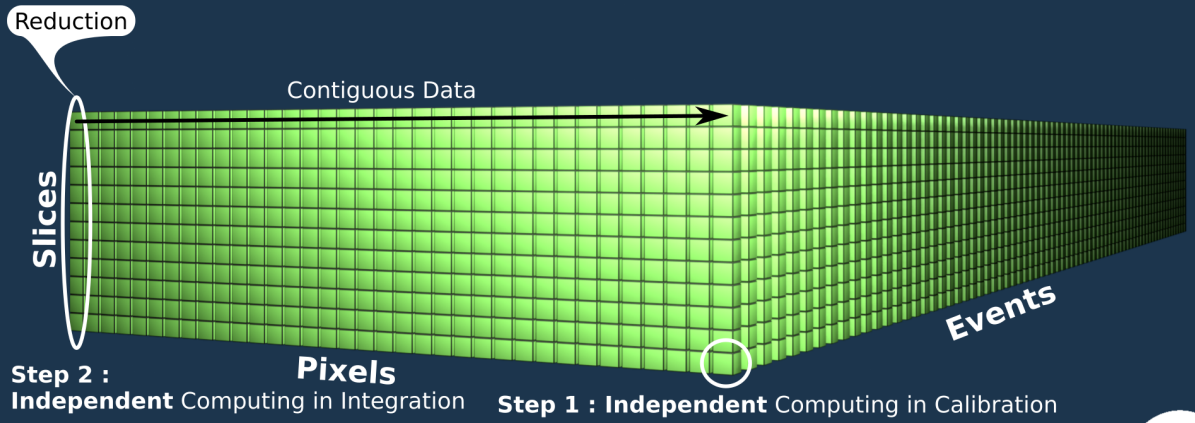
Independent Events => Independent Computing => Parallelism



Express Parallelism

Event

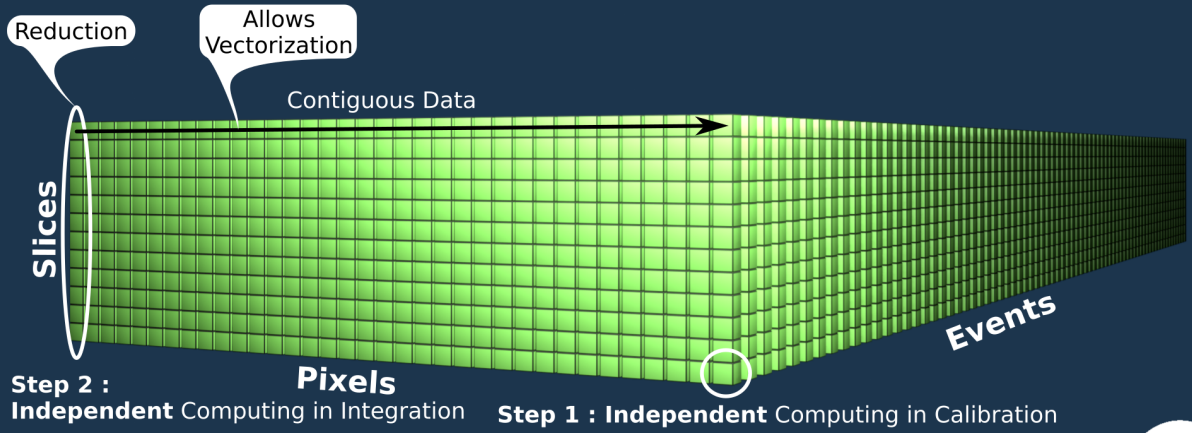
Independent Events => Independent Computing => Parallelism



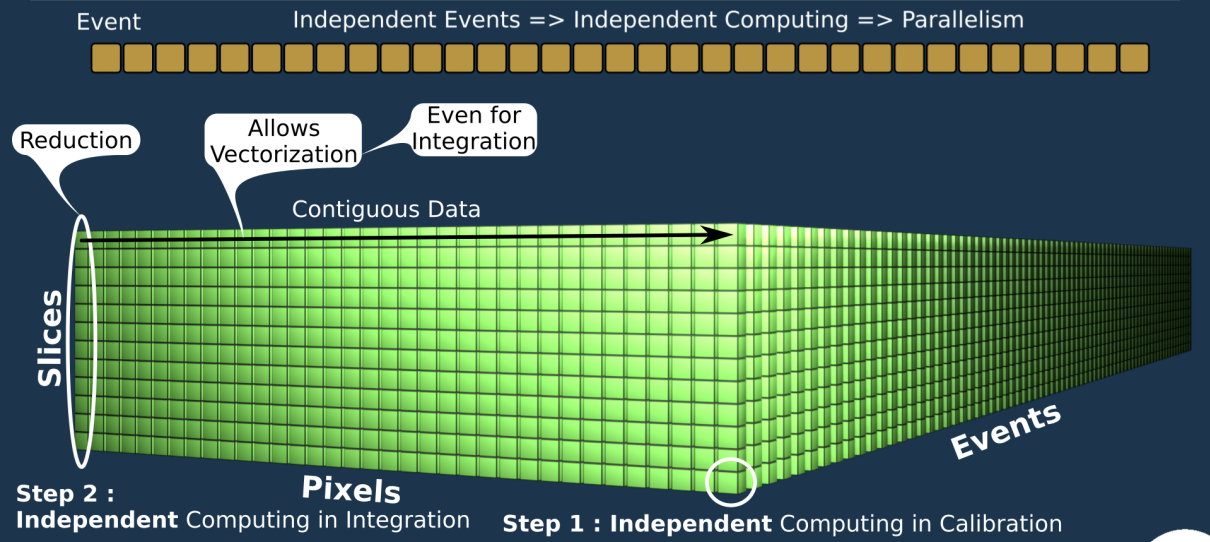
Express Parallelism

Event

Independent Events => Independent Computing => Parallelism



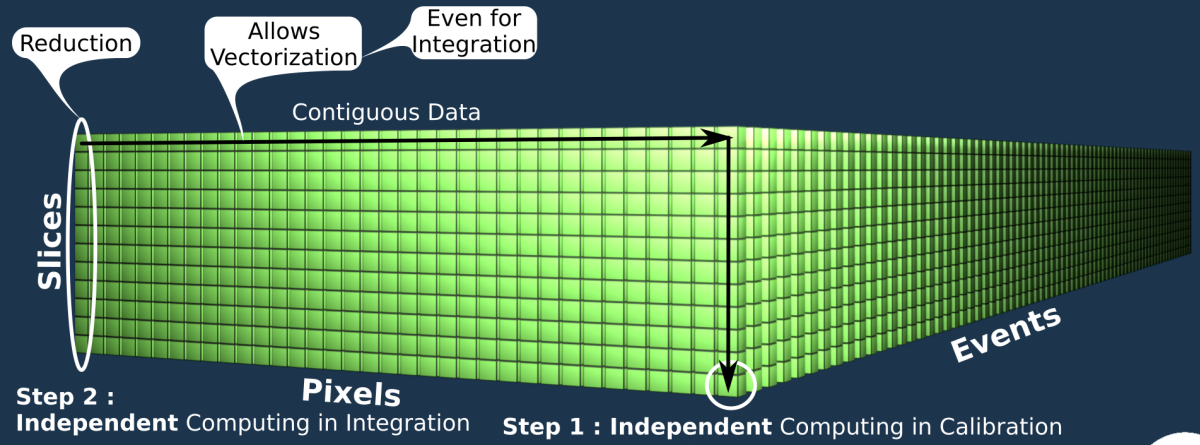
Express Parallelism



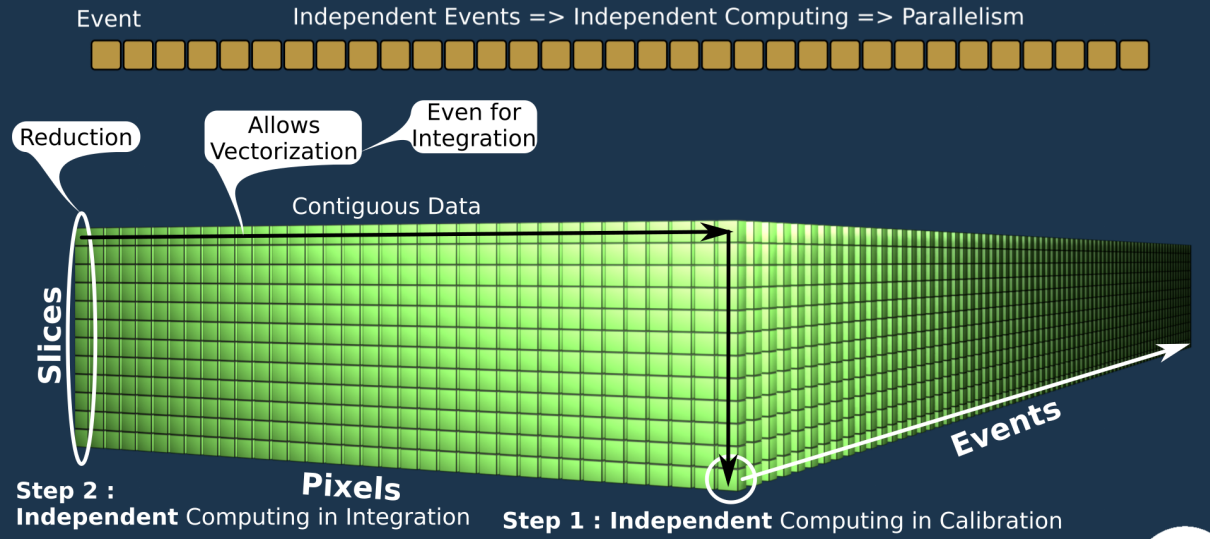
Express Parallelism

Event

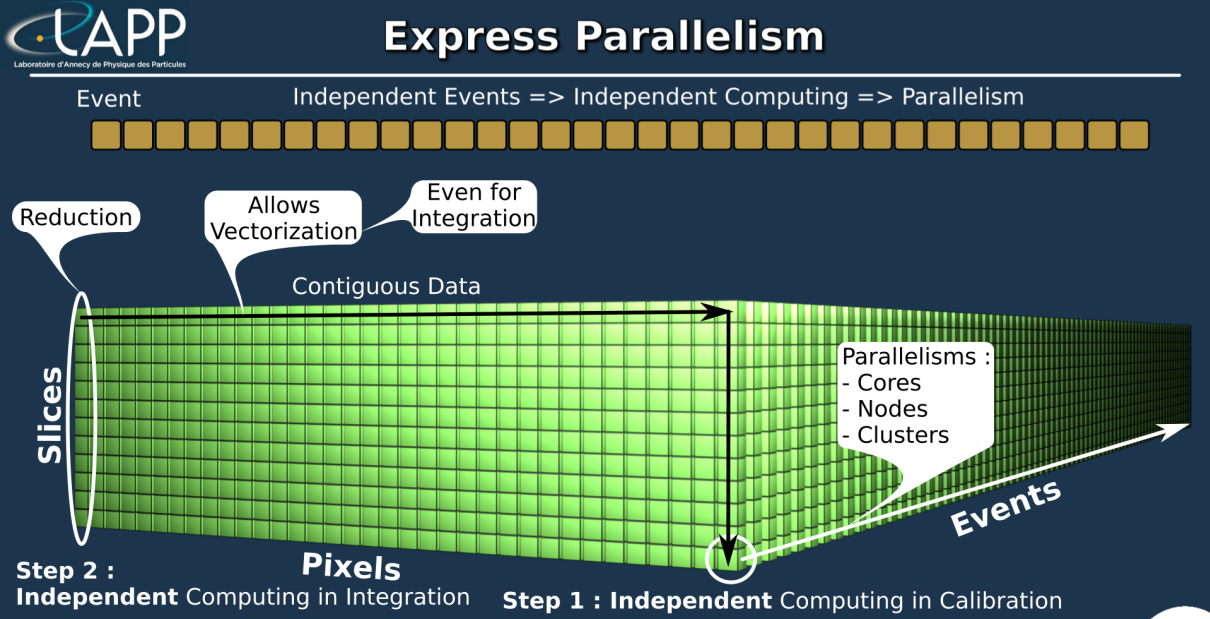
Independent Events => Independent Computing => Parallelism



Express Parallelism



Express Parallelism



Express Parallelism

Event — Independent Events => Independent Computing => Parallelism

Reduction

Allows Vectorization

Even for Integration

Computing Drives Data Storage

Contiguous Data

Slices

Parallelisms :
- Cores
- Nodes
- Clusters

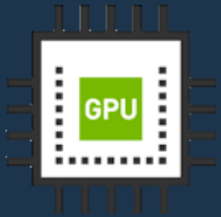
Events

Pixels

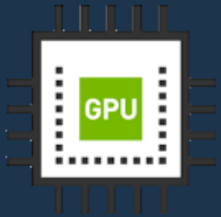
Step 2 : Independent Computing in Integration

Step 1 : Independent Computing in Calibration

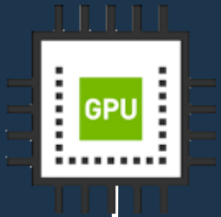
Standard C++ for CPU and GPU



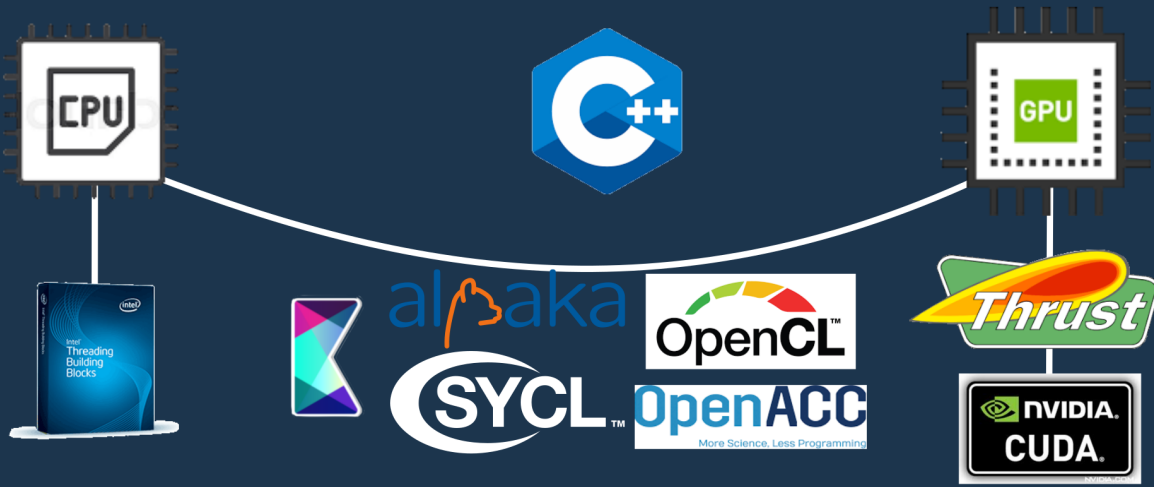
Standard C++ for CPU and GPU



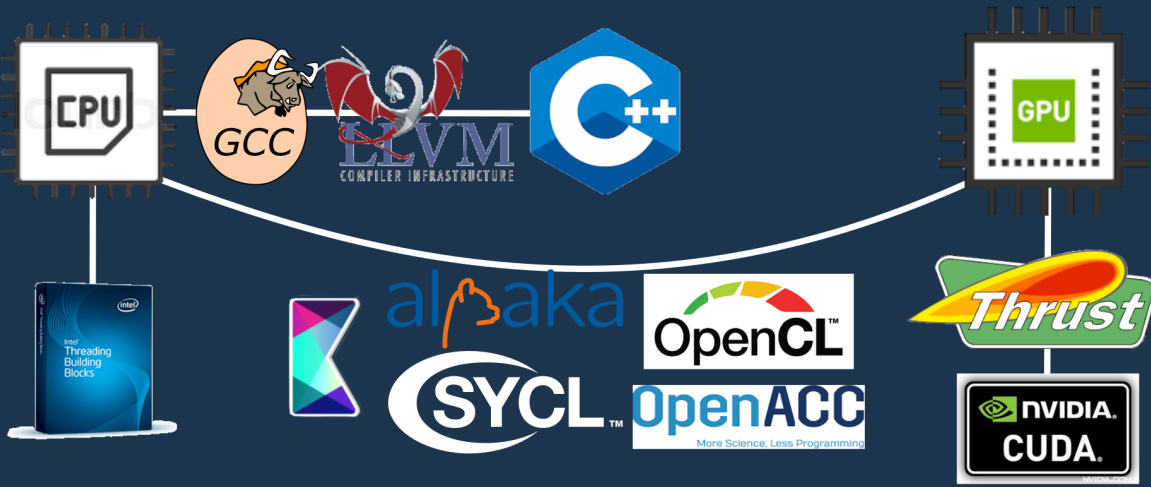
Standard C++ for CPU and GPU



Standard C++ for CPU and GPU

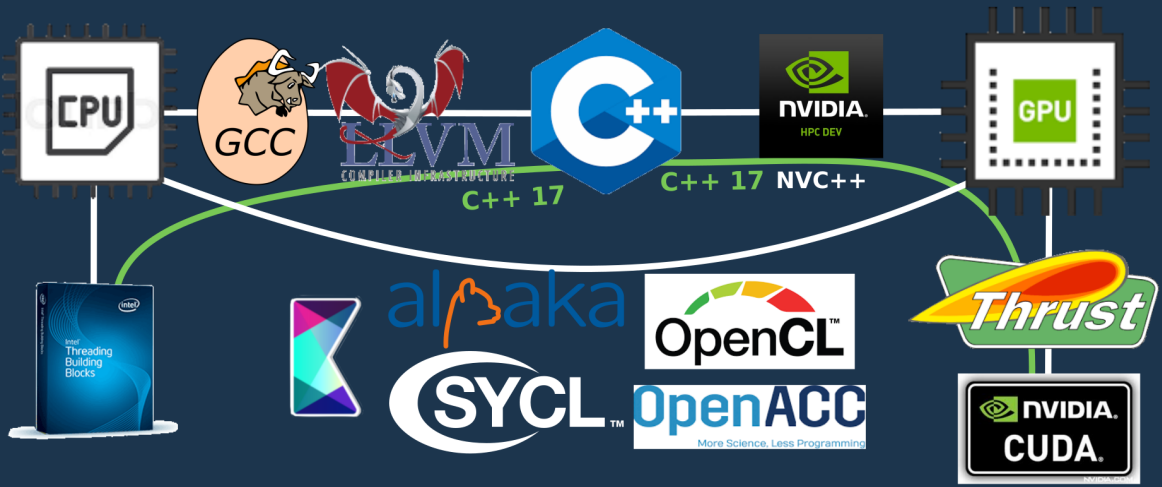


Standard C++ for CPU and GPU

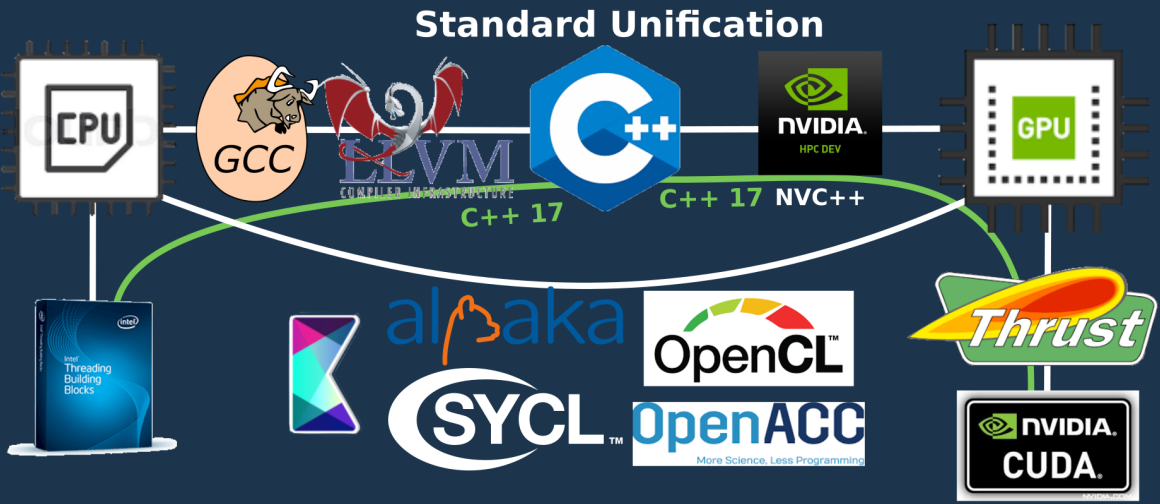


Standard C++ for CPU and GPU

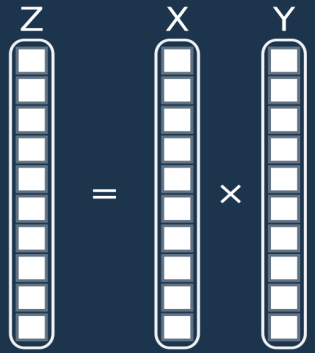
Standard C++ for CPU and GPU



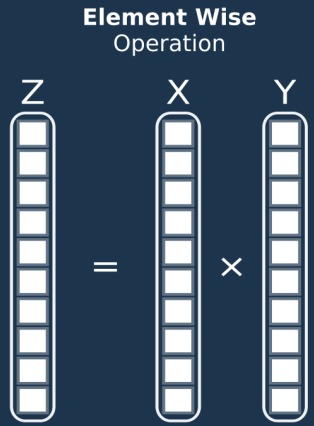
Standard C++ for CPU and GPU



Example : Hadamard Product



Example : Hadamard Product

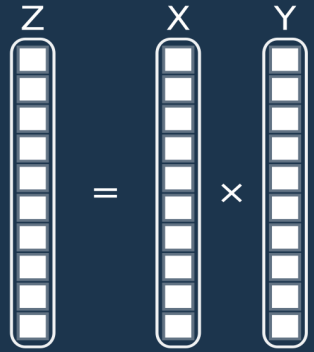


Example : Hadamard Product

C++

```
for(long unsigned int i(0lu); i < nbElement; ++i){
»       tabResult[i] = tabX[i]*tabY[i];
}
```

Element Wise
Operation



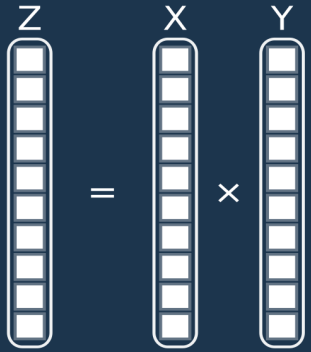
Example : Hadamard Product

C++

```
for(long unsigned int i(0lu); i < nbElement; ++i){
»       tabResult[i] = tabX[i]*tabY[i];
}
```

Explicit order **not** necessary

Element Wise Operation



Example : Hadamard Product

C++

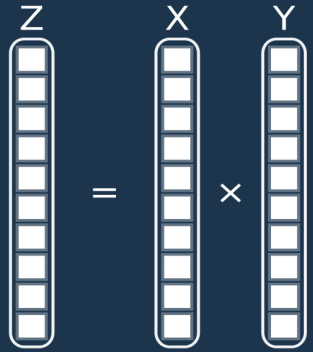
```
for(long unsigned int i(0lu); i < nbElement; ++i){
»       tabResult[i] = tabX[i]*tabY[i];
}
```

Explicit order **not** necessary

C++ Algorithm : std::transform

```
std::transform(std::begin(tabX), std::end(tabX),
»        std::begin(tabY), std::begin(tabRes),
»        [](float xi, float yi){ return xi * yi; });
```

Element Wise Operation



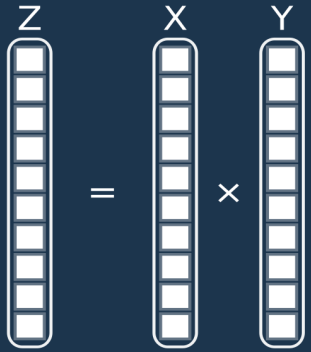
Example : Hadamard Product

C++

Explicit order **not** necessary

```
for(long unsigned int i(0lu); i < nbElement; ++i){
»       tabResult[i] = tabX[i]*tabY[i];
}
```

Element Wise Operation



C++ Algorithm : std::transform

```
std::transform(std::begin(tabX), std::end(tabX),
»       std::begin(tabY), std::begin(tabRes),
»       [](float xi, float yi){ return xi * yi; });
```

C++ 17 / C++ 20

```
std::transform(std::execution::par_unseq,
»       std::begin(tabX), std::end(tabX),
»       std::begin(tabY), std::begin(tabRes),
»       [](float xi, float yi){ return xi * yi; });
```

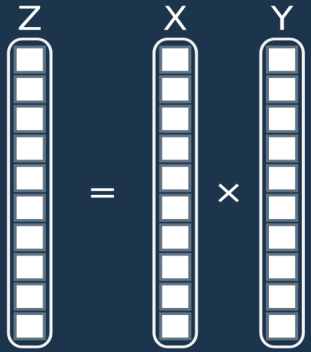
Example : Hadamard Product

C++

```
for(long unsigned int i(0lu); i < nbElement; ++i){
»       tabResult[i] = tabX[i]*tabY[i];
}
```

Explicit order **not** necessary

Element Wise Operation



C++ Algorithm : std::transform

```
std::transform(std::begin(tabX), std::end(tabX),
»       std::begin(tabY), std::begin(tabRes),
»       [](float xi, float yi){ return xi * yi; });
```

C++ 17 / C++ 20

Execution Policy

```
std::transform(std::execution::par_unseq,
»       std::begin(tabX), std::end(tabX),
»       std::begin(tabY), std::begin(tabRes),
»       [](float xi, float yi){ return xi * yi; });
```

Example : Hadamard Product

C++

```
for(long unsigned int i(0lu); i < nbElement; ++i){
»       tabResult[i] = tabX[i]*tabY[i];
}
```

Explicit order **not** necessary

C++ Algorithm : std::transform

```
std::transform(std::begin(tabX), std::end(tabX),
»       std::begin(tabY), std::begin(tabRes),
»       [](float xi, float yi){ return xi * yi; });
```

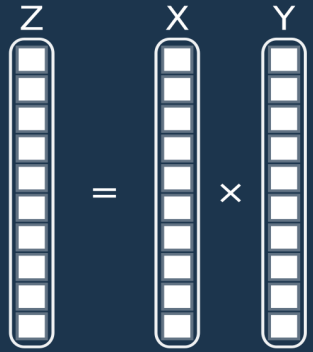
C++ 17 / C++ 20

Execution Policy

- seq
- unseq
- par
- par_unseq

```
std::transform(std::execution::par_unseq,
»       std::begin(tabX), std::end(tabX),
»       std::begin(tabY), std::begin(tabRes),
»       [](float xi, float yi){ return xi * yi; });
```

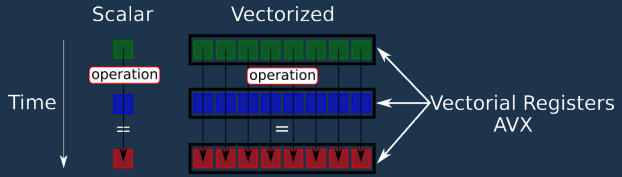
Element Wise Operation



What is vectorization ?

The idea is to compute several elements at the same time.

Architecture	Instruction Set	CPU	Nb **float** Computed at the same time
SSE4	2006	2007	4
AVX	2008	2011	8
AVX 512	2013	2016	16



LINUX : **cat /proc/cpuinfo** | **grep avx** MAC : **sysctl -a** | **grep machdep.cpu** | **grep AVX**

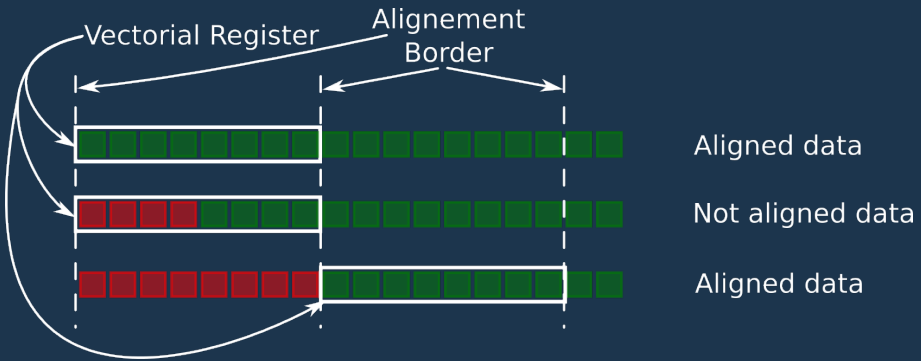
What is vectorization ?

CPU has to read several elements at the same time.

- Data **contiguousness** :
  - All data to be used have to be adjacent with others.
  - Always the case with pointers but be careful with your applications.

What is vectorization ?

- Data alignement :
  - All data have to be aligned on vectorial registers size.
  - Change **new** or **malloc** to **memalign**, **posix_memalign**, or **std::aligned_malloc** since **C++17**



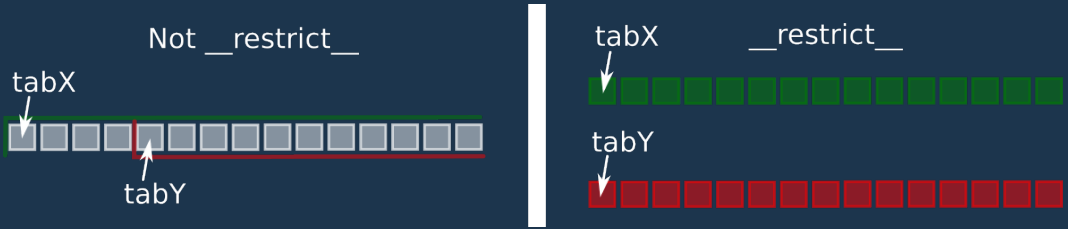
What do we have to do with the code ?

- The __**restrict**__ keyword :
  - Specify to the compiler there is no overhead between pointers

```
float* tabResult,
const float* tabX,
const float* tabY,
```

$\Longrightarrow$

```
float* __restrict__ tabResult,
const float* __restrict__ tabX,
const float* __restrict__ tabY,
```



What do we have to do with the code ?

- The **__builtin_assume_aligned** function (or **std::assume_aligned** since **C++17**) :
  - Specify to the compiler pointers are aligned
    - If this is not true, you will get a **Segmentation Fault**.
  - Here **VECTOR_ALIGNEMENT** = 32 (for **float** in **AVX** or **AVX2** extensions).

```
const float* tabX = (const float*)__builtin_assume_aligned(ptabX, VECTOR_ALIGNEMENT);
const float* tabY = (const float*)__builtin_assume_aligned(ptabY, VECTOR_ALIGNEMENT);
float* tabResult = (float*)__builtin_assume_aligned(ptabResult, VECTOR_ALIGNEMENT);
```

Definition in the **CMakeLists.txt** :

```
set(VECTOR_ALIGNEMENT 32)
add_definitions(-DVECTOR_ALIGNEMENT=${VECTOR_ALIGNEMENT})
```

Compilation Options

- The Compilation Options become :
  - **-O3 -ftree-vectorize -march=native -mtune=native -mavx2**

- **-ftree-vectorize**
  - Activate the vectorization
- **-march=native**
  - Target only the host CPU architecture for binary
- **-mtune=native**
  - Target only the host CPU architecture for optimization
- **-mavx2**
  - Vectorize with AVX2 extention (not needed with **g++ 11** or **clang++ 14**)

Modifications Summary

- Data alignement :
  - All the data to be aligned on vectorial registers size.
  - Change **new** or **malloc** to **memalign** or **posix_memalign**

You can use **asterics_malloc** to have LINUX/MAC compatibility (in **evaluateHadamardProduct**):

```
(float*)asterics_malloc(sizeof(float)*nbElement);
```

The __**restrict**__ keyword (arguments of **hadamard_product** function):

```
float*  __restrict__ tabResult,
const float*  __restrict__ tabX,
const float*  __restrict__ tabY,
```

The __**builtin_assume_aligned** function call (in **hadamard_product** function):

```
const float* tabX = (const float*)__builtin_assume_aligned(ptabX, VECTOR_ALIGNEMENT);
const float* tabY = (const float*)__builtin_assume_aligned(ptabY, VECTOR_ALIGNEMENT);
float* tabResult = (float*)__builtin_assume_aligned(ptabResult, VECTOR_ALIGNEMENT);
```

- The Compilation Options become :
  - **-O3 -ftree-vectorize -march=native -mtune=native -mavx2**

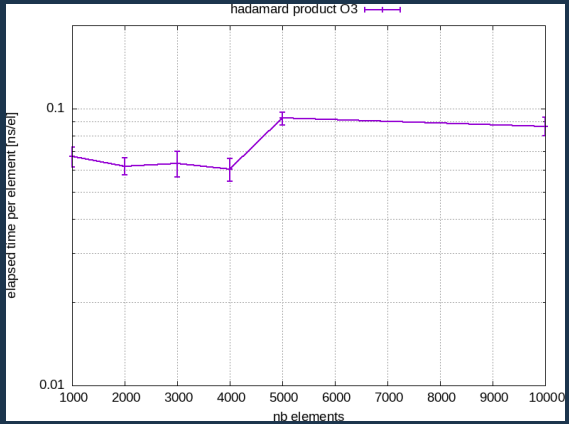
Code Correction

```
void hadamard_product(float* __restrict__ ptabResult, const float* __restrict__ ptabX, const float* __restrict__ ptabY, long unsigned int nbElement){
	const float* tabX = (const float*)__builtin_assume_aligned(ptabX, VECTOR_ALIGNEMENT);
	const float* tabY = (const float*)__builtin_assume_aligned(ptabY, VECTOR_ALIGNEMENT);
	float* tabResult = (float*)__builtin_assume_aligned(ptabResult, VECTOR_ALIGNEMENT);

	for(long unsigned int i(0lu); i < nbElement; ++i){
		tabResult[i] = tabX[i]*tabY[i];
	}
}
```

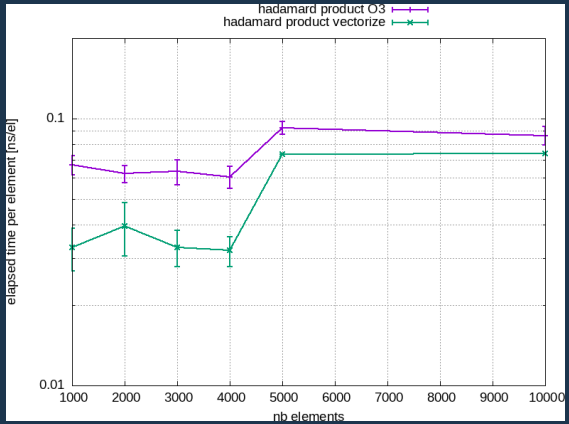
Performance : unseq ?

G++ 11



Performance : unseq ?

G++ 11

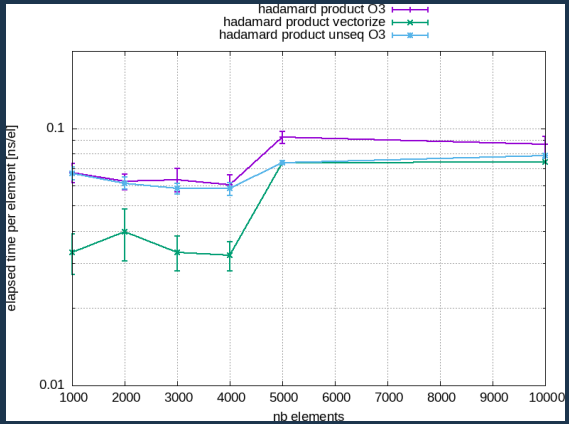


Performance : unseq ?

std::execution::unseq

- Only **-O3** : some improvement

G++ 11

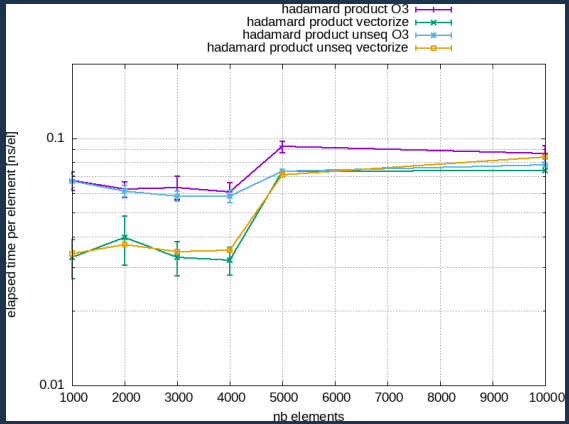


Performance : unseq ?

std::execution::unseq

- Only **-O3** : some improvement
- Add **-ftree-vectorize -march=native -mtune=native (-mavx2)**

G++ 11

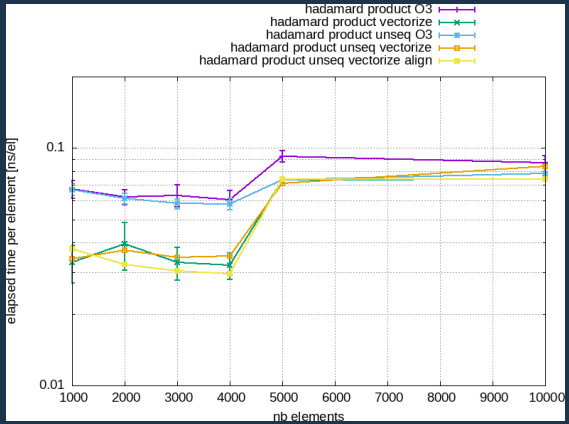


Performance : unseq ?

std::execution::unseq

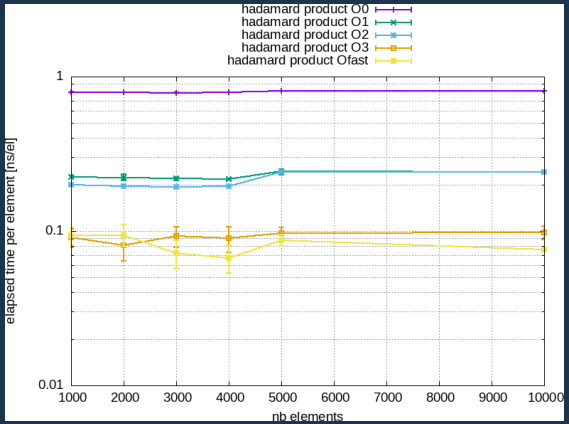
- Only **-O3** : some improvement
- Add **-ftree-vectorize -march=native -mtune=native (-mavx2)**
- On **aligned** data : very efficient

G++ 11

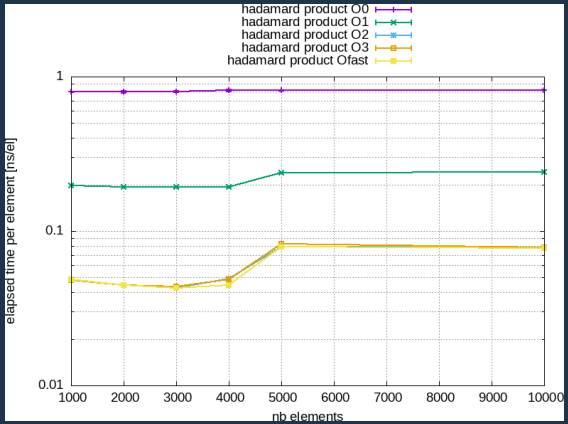


The Hadamard product : Basic Options

G++ 11

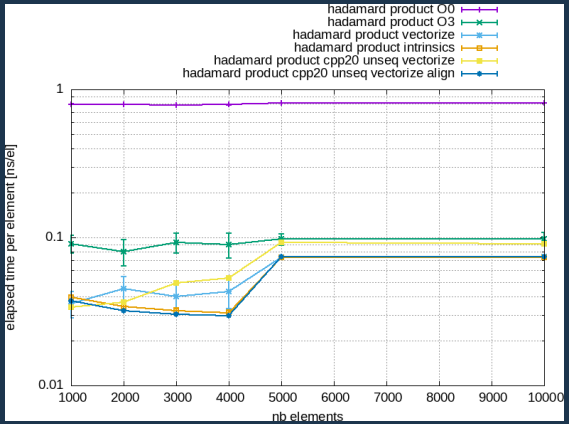


CLang++ 14

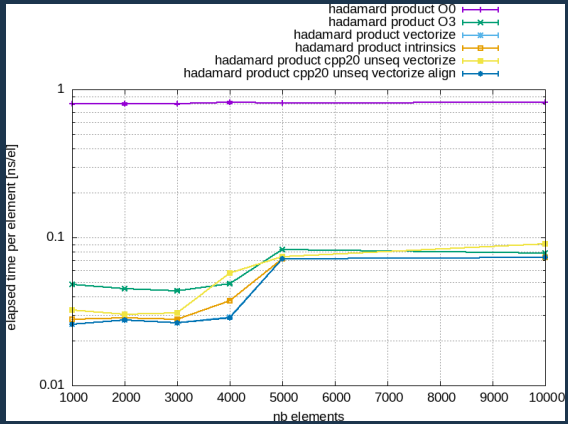


The Hadamard product : Vectorization

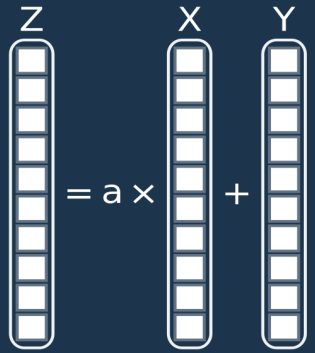
G++ 11



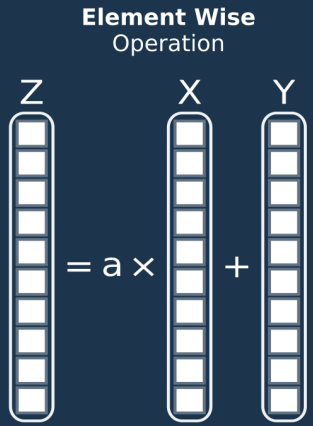
CLang++ 14



Example : Saxpy



Example : Saxpy

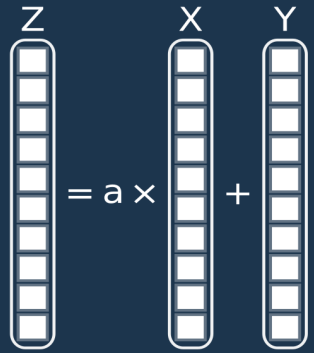


Example : Saxpy

C++

```
for(long unsigned int i(0lu); i < nbElement; ++i){
»       tabResult[i] = a*tabX[i] + tabY[i];
}
```

Element Wise
Operation



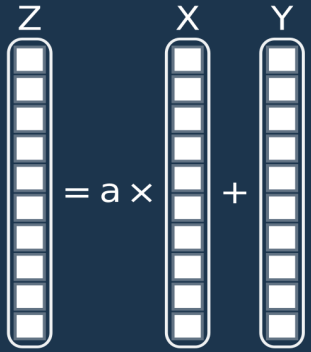
Example : Saxpy

C++

```
for(long unsigned int i(0lu); i < nbElement; ++i){
»       tabResult[i] = a*tabX[i] + tabY[i];
}
```

Explicit order **not** necessary

Element Wise Operation



Example : Saxpy

C++

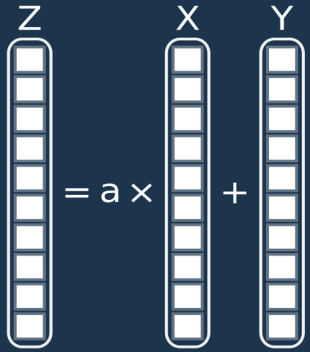
```
for(long unsigned int i(0lu); i < nbElement; ++i){
»       tabResult[i] = a*tabX[i] + tabY[i];
}
```

Explicit order **not** necessary

C++ Algorithm : std::transform

```
std::transform(std::begin(tabX), std::end(tabX),
»        std::begin(tabY), std::begin(tabResult),
»        [=](float xi, float yi){ return a*xi + yi; });
```

Element Wise Operation



Example : Saxpy

C++

```
for(long unsigned int i(0lu); i < nbElement; ++i){
»       tabResult[i] = a*tabX[i] + tabY[i];
}
```

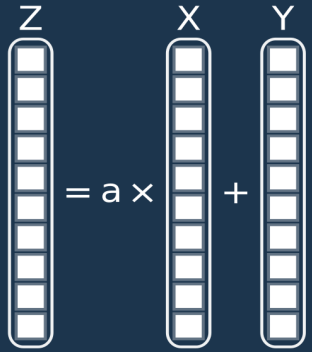
Explicit order **not** necessary

C++ Algorithm : std::transform

```
std::transform(std::begin(tabX), std::end(tabX),
»       std::begin(tabY), std::begin(tabResult),
»       [=](float xi, float yi){ return a*xi + yi; });
```

Catches Extra variables by copy

Element Wise Operation



Example : Saxpy

C++

```
for(long unsigned int i(0lu); i < nbElement; ++i){
»       tabResult[i] = a*tabX[i] + tabY[i];
}
```

Explicit order **not** necessary

C++ Algorithm : std::transform

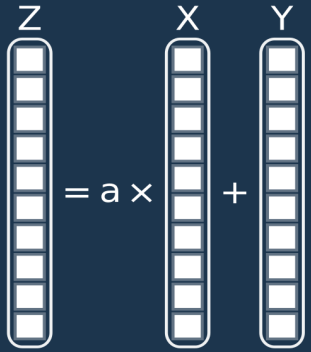
```
std::transform(std::begin(tabX), std::end(tabX),
»       std::begin(tabY), std::begin(tabResult),
»       [=](float xi, float yi){ return a*xi + yi; });
```

Catches Extra variables by copy

C++ 17 / C++ 20

```
std::transform(std::execution::par_unseq,
»       std::begin(tabX), std::end(tabX),
»       std::begin(tabY), std::begin(tabResult),
»       [=](float xi, float yi){ return a*xi + yi; });
```

Element Wise Operation



Example : Saxpy

C++

```
for(long unsigned int i(0lu); i < nbElement; ++i){
»       tabResult[i] = a*tabX[i] + tabY[i];
}
```

Explicit order **not** necessary

C++ Algorithm : std::transform

```
std::transform(std::begin(tabX), std::end(tabX),
»       std::begin(tabY), std::begin(tabResult),
»       [=](float xi, float yi){ return a*xi + yi; });
```

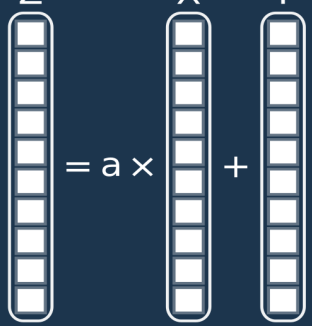
Catches Extra variables by copy

C++ 17 / C++ 20

Execution Policy

```
std::transform(std::execution::par_unseq,
»       std::begin(tabX), std::end(tabX),
»       std::begin(tabY), std::begin(tabResult),
»       [=](float xi, float yi){ return a*xi + yi; });
```

Element Wise Operation



Example : Saxpy

C++

```
for(long unsigned int i(0lu); i < nbElement; ++i){
»       tabResult[i] = a*tabX[i] + tabY[i];
}
```

Explicit order **not** necessary

C++ Algorithm : std::transform

```
std::transform(std::begin(tabX), std::end(tabX),
»       std::begin(tabY), std::begin(tabResult),
»       [=](float xi, float yi){ return a*xi + yi; });
```

Catches Extra variables by copy

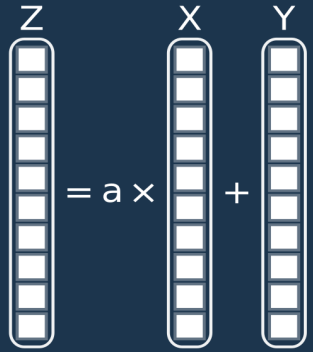
C++ 17 / C++ 20

Execution Policy

```
std::transform(std::execution::par_unseq,
»       std::begin(tabX), std::end(tabX),
»       std::begin(tabY), std::begin(tabResult),
»       [=](float xi, float yi){ return a*xi + yi; });
```

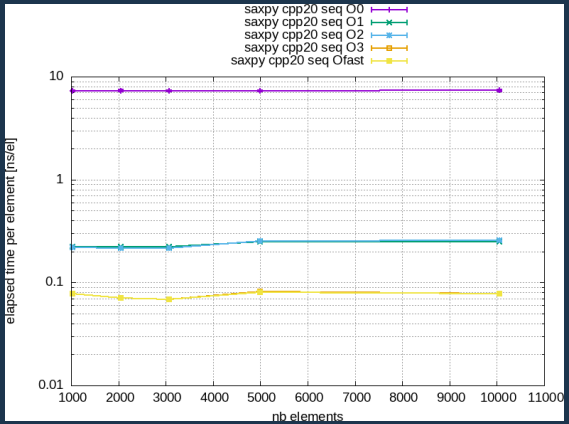
- seq
- unseq
- par
- par_unseq

Element Wise Operation

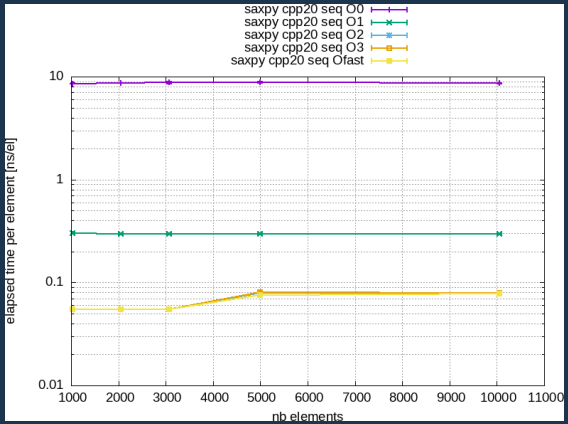


Saxpy : Basic Options

G++ 11

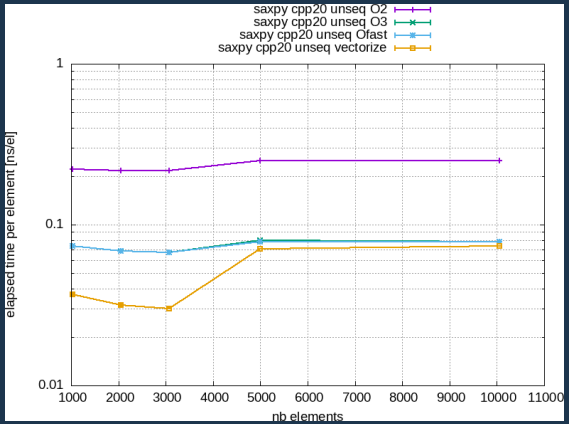


CLang++ 14

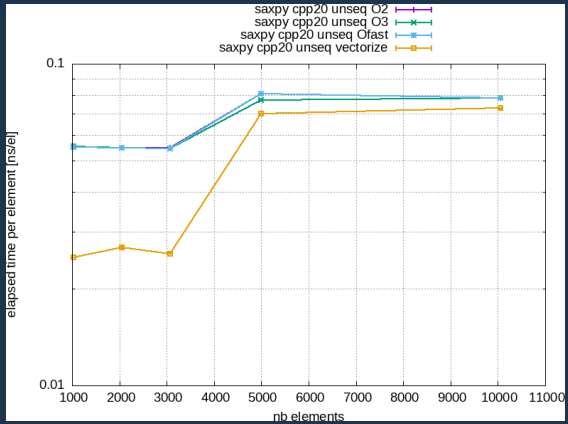


Saxpy : Vectorization

G++ 11



CLang++ 14



Example : Reduction

Example : Reduction

C++

```
float res(0.0f);
for(long unsigned int i(0lu); i < nbElement; ++i){
»       res += tabValue[i];
}
return res;
```

Example : Reduction

C++

```
float res(0.0f);
for(long unsigned int i(0lu); i < nbElement; ++i){
»       res += tabValue[i];
}
return res;
```

Explicit order **not** necessary every time

Example : Reduction

C++

```
float res(0.0f);
for(long unsigned int i(0lu); i < nbElement; ++i){
»       res += tabValue[i];
}
return res;
```

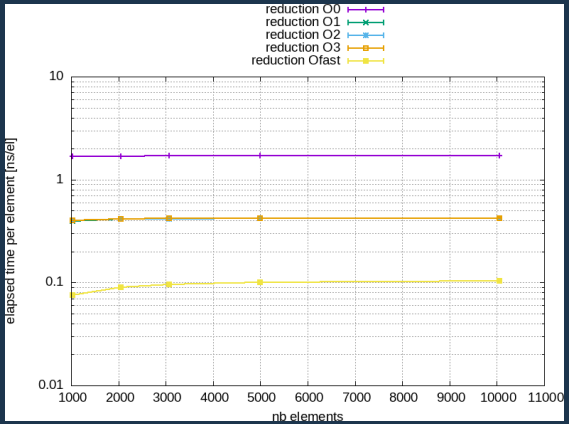
Explicit order **not** necessary every time

C++ 17 / C++ 20

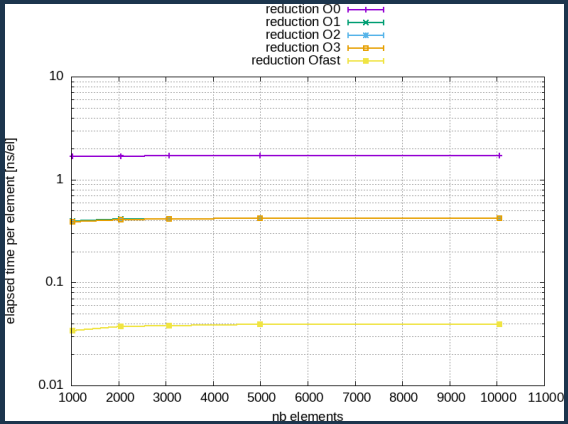
```
return std::reduce(std::execution::par_unseq,
»       std::begin(vecX), std::end(vecX),
»       0.0f, std::plus{});
```

Reduction : Basic Options

G++ 11

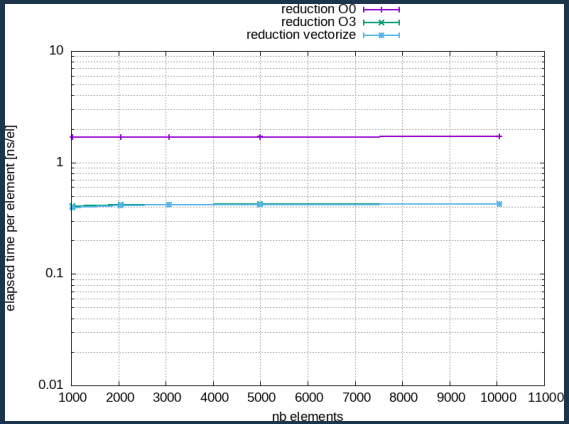


CLang++ 14

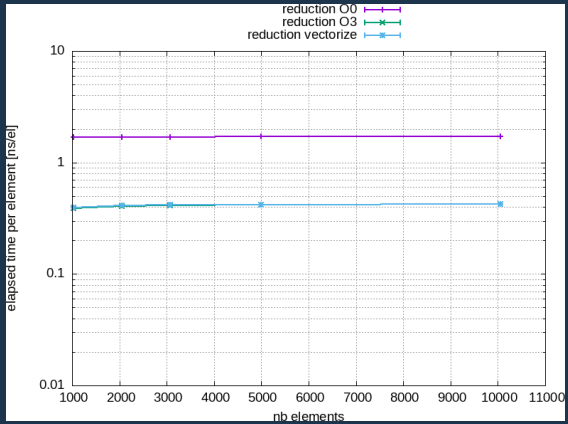


Reduction : Vectorization

G++ 11

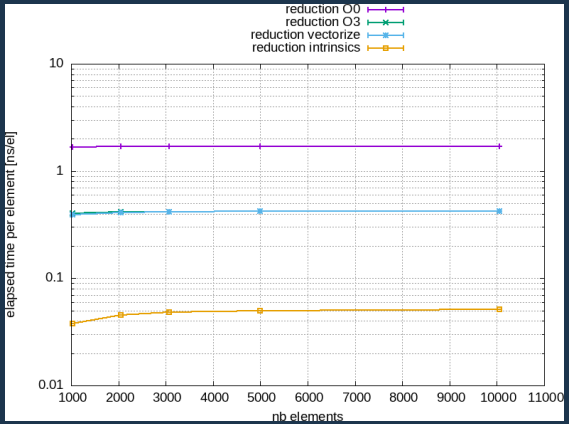


CLang++ 14

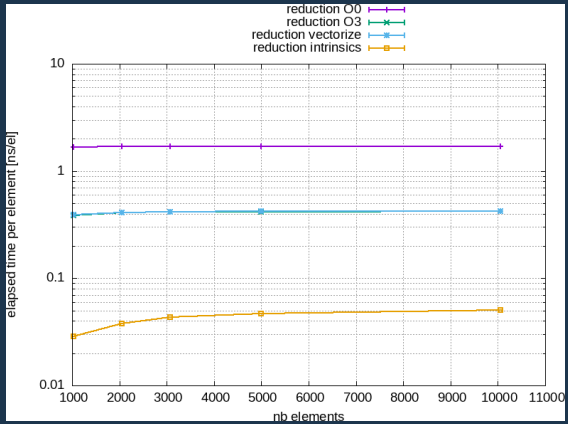


Reduction : Vectorization

G++ 11

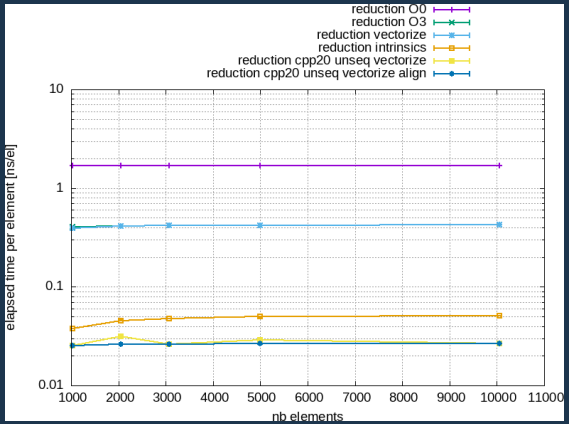


CLang++ 14

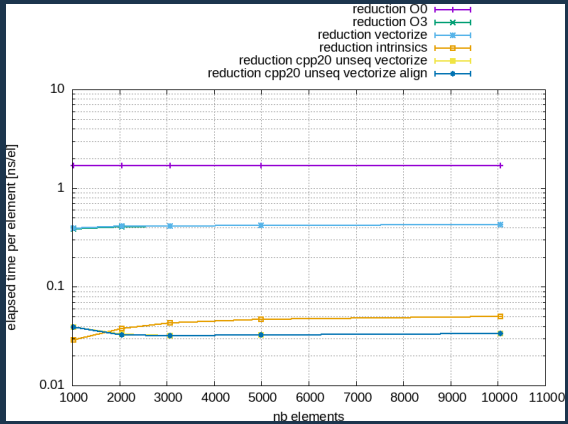


Reduction : Vectorization

G++ 11

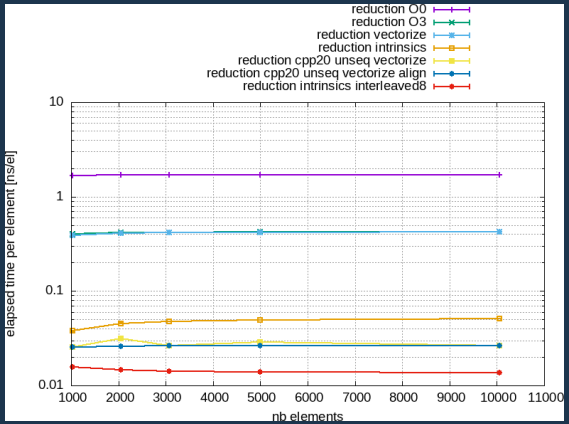


CLang++ 14

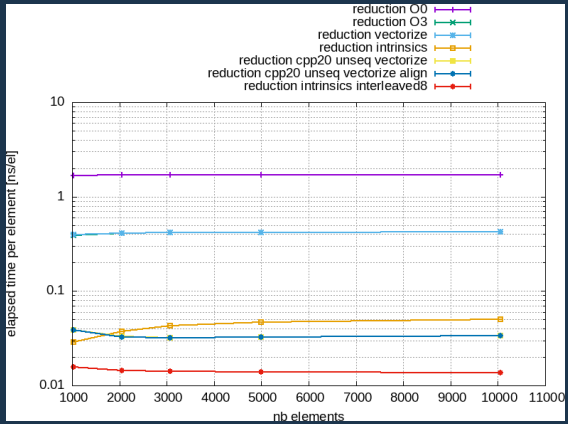


Reduction : Vectorization

G++ 11

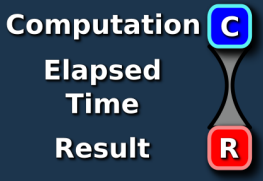


CLang++ 14

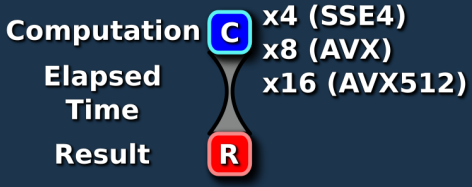


Reduction optimisation

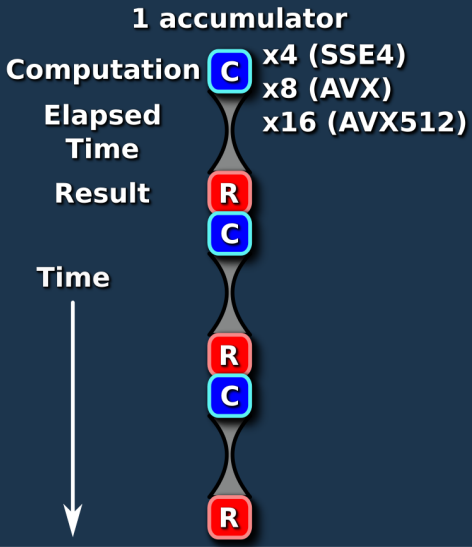
Reduction optimisation



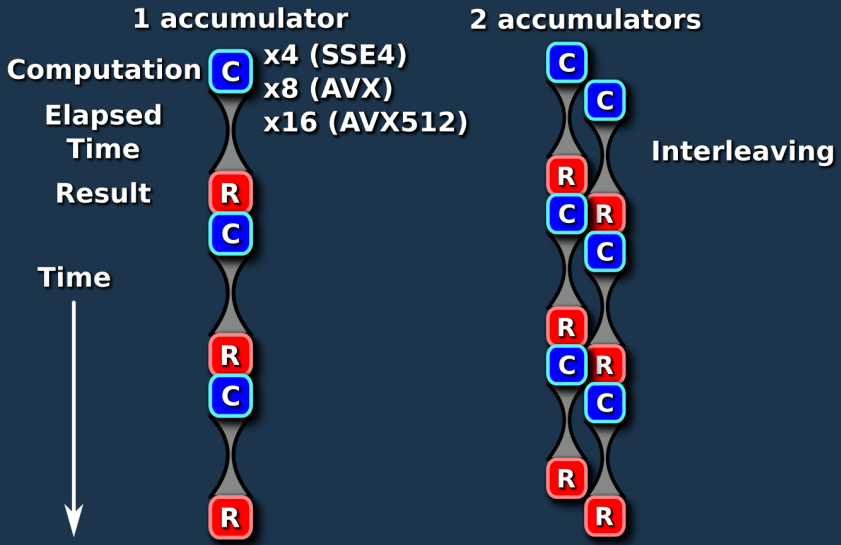
Reduction optimisation



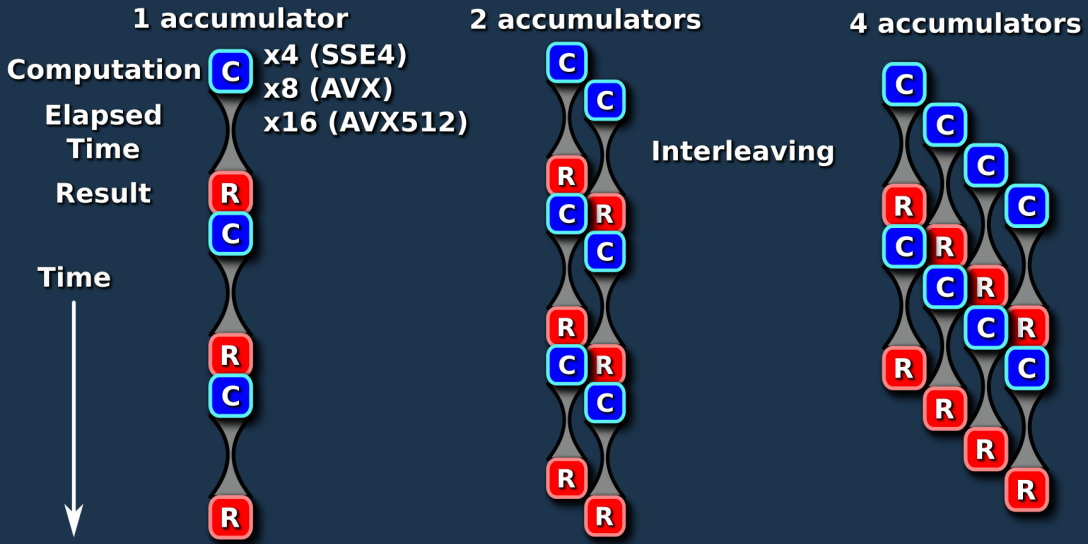
Reduction optimisation



Reduction optimisation

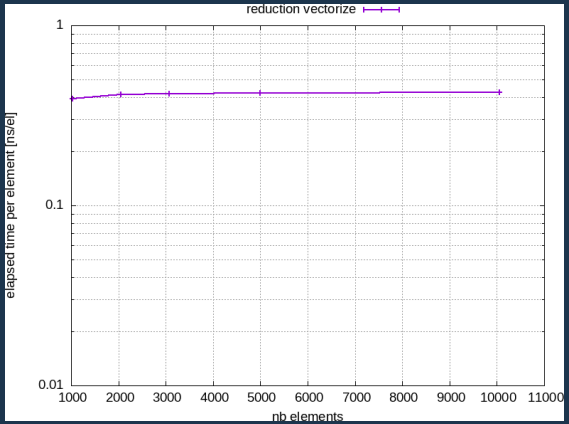


Reduction optimisation

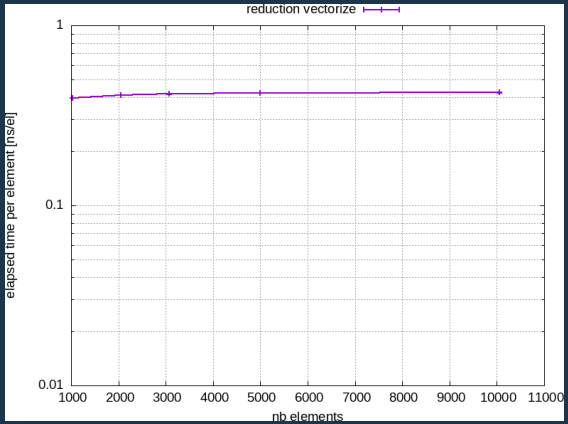


Reduction : Intrinsics Interleaved

G++ 11

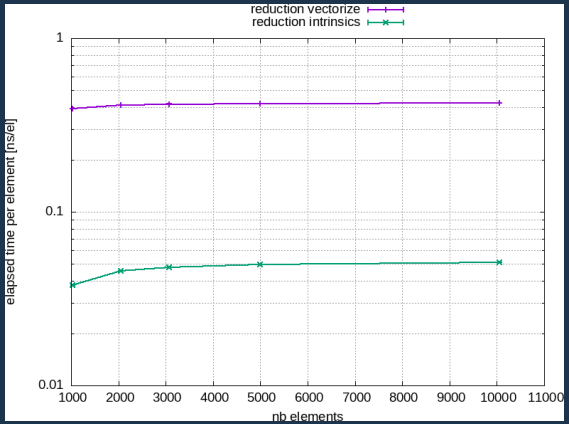


CLang++ 14

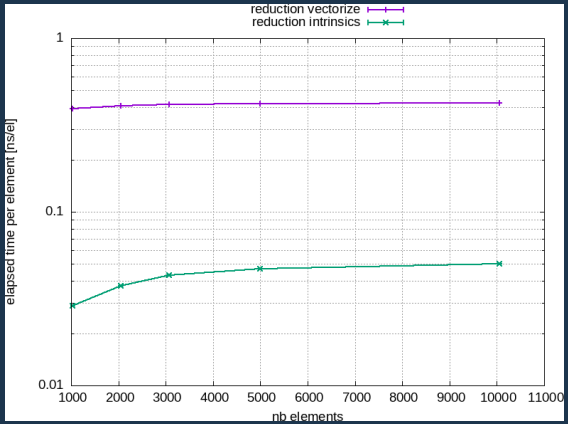


Reduction : Intrinsics Interleaved

G++ 11

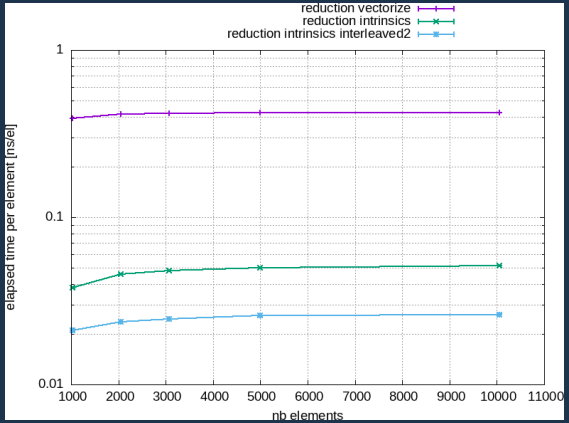


CLang++ 14

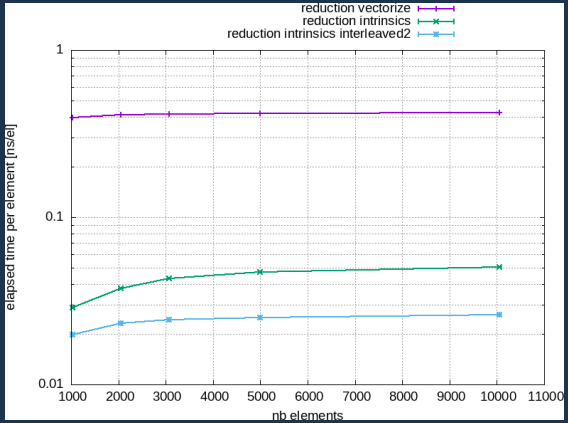


Reduction : Intrinsics Interleaved

G++ 11

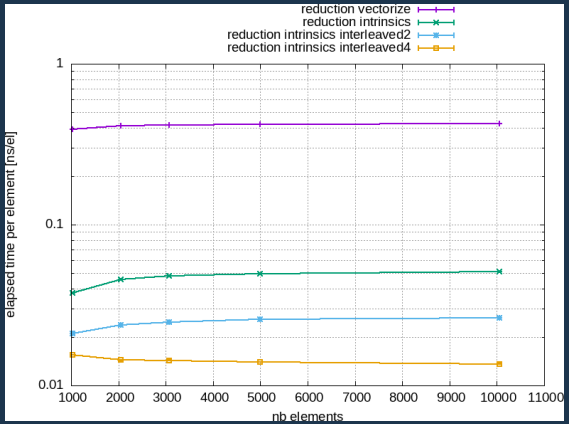


CLang++ 14

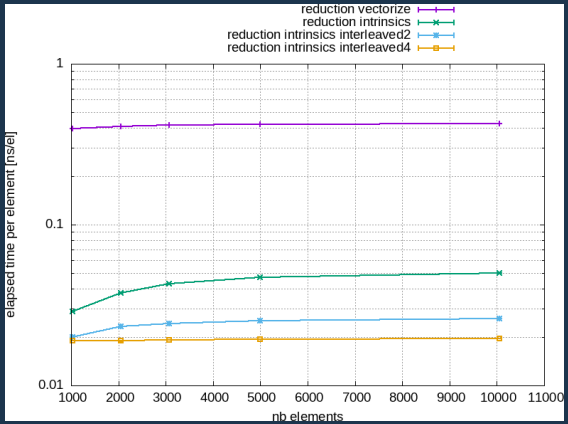


Reduction : Intrinsics Interleaved

G++ 11

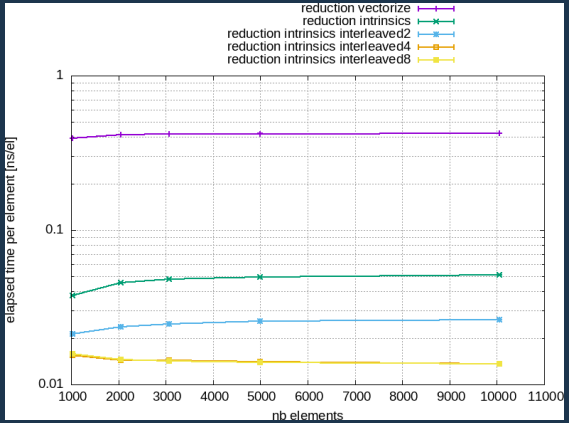


CLang++ 14

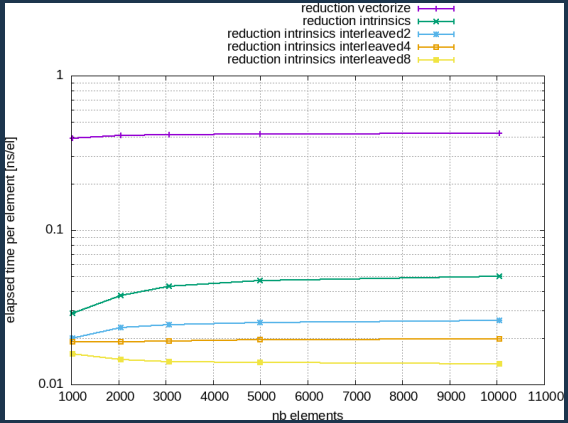


Reduction : Intrinsics Interleaved

G++ 11



CLang++ 14



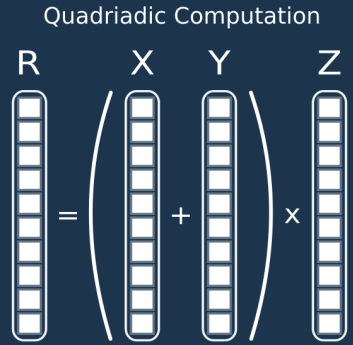
std::transform : triadic

std::transform : triadic

Triadic : **z = x + y**

std::transform : triadic

Triadic : **z = x + y**



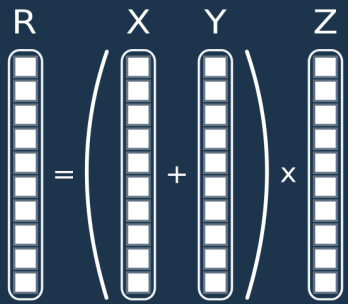
std::transform : triadic

Triadic : **z = x + y**

Classic C++

```
for(long unsigned int i(0lu); i < nbElement; ++i){
»       tabRes[i] = (tabX[i] + tabY[i])*tabZ[i];
}
```

Quadriadic Computation



std::transform : triadic

Triadic : **z = x + y**

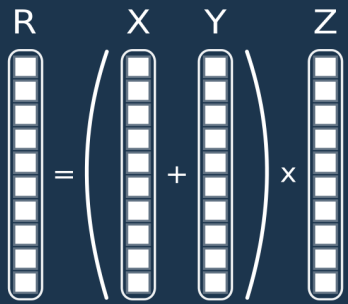
Classic C++

```
for(long unsigned int i(0lu); i < nbElement; ++i){
»       tabRes[i] = (tabX[i] + tabY[i])*tabZ[i];
}
```

C++ 17 / 20 / 23

```
std::transform(std::execution::par_unseq,
»       std::begin(vecIndex), std::end(vecIndex),
»       std::begin(vecX), std::begin(vecRes),
»       [=](int i, float x){
»       »       return (x + vecY[i]) * vecZ[i];
»       });
```

Quadriadic Computation



std::transform : triadic

Triadic : **z = x + y**

Classic C++

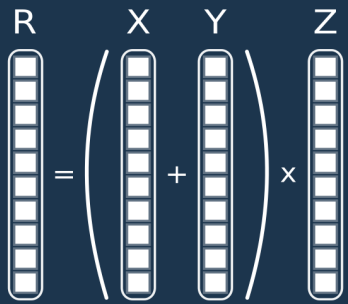
```
for(long unsigned int i(0lu); i < nbElement; ++i){
»       tabRes[i] = (tabX[i] + tabY[i])*tabZ[i];
}
```

C++ 17 / 20 / 23

vecY, **vecZ** have to be **std::vector**

```
std::transform(std::execution::par_unseq,
»       std::begin(vecIndex), std::end(vecIndex),
»       std::begin(vecX), std::begin(vecRes),
»       [=](int i, float x){
»       »       return (x + vecY[i]) * vecZ[i];
»       });
```

Quadriadic Computation



std::transform : triadic

Triadic : **z = x + y**

Classic C++

```
for(long unsigned int i(0lu); i < nbElement; ++i){
»       tabRes[i] = (tabX[i] + tabY[i])*tabZ[i];
}
```

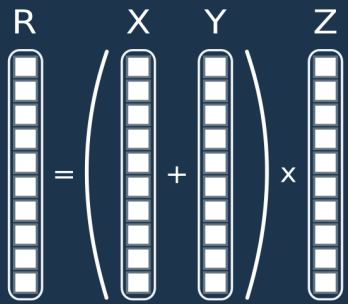
C++ 17 / 20 / 23

```
std::transform(std::execution::par_unseq,
»       std::begin(vecIndex), std::end(vecIndex),
»       std::begin(vecX), std::begin(vecRes),
»       [=](int i, float x){
»       »       return (x + vecY[i]) * vecZ[i];
»       });
```

vecY, **vecZ** have to be **std::vector**

Fully Vectorized

Quadriadic Computation



std::transform : triadic

Triadic : **z = x + y**

Classic C++

```
for(long unsigned int i(0lu); i < nbElement; ++i){
»       tabRes[i] = (tabX[i] + tabY[i])*tabZ[i];
}
```

C++ 17 / 20 / 23

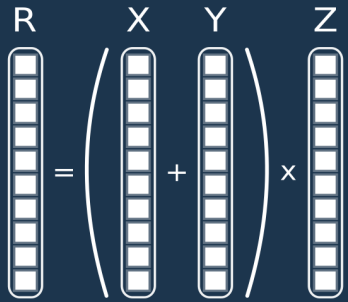
vecY, **vecZ** have to be **std::vector**

```
std::transform(std::execution::par_unseq,
»       std::begin(vecIndex), std::end(vecIndex),
»       std::begin(vecX), std::begin(vecRes),
»       [=](int i, float x){
»       »       return (x + vecY[i]) * vecZ[i];
»       });
```

Fully Vectorized

Needs extra index table

Quadriadic Computation



std::transform : triadic

Triadic : **z = x + y**

Classic C++

```
for(long unsigned int i(0lu); i < nbElement; ++i){
»       tabRes[i] = (tabX[i] + tabY[i])*tabZ[i];
}
```

C++ 17 / 20 / 23

vecY, **vecZ** have to be **std::vector**

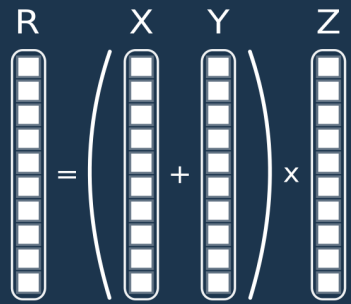
```
std::transform(std::execution::par_unseq,
»       std::begin(vecIndex), std::end(vecIndex),
»       std::begin(vecX), std::begin(vecRes),
»       [=](int i, float x){
»       »       return (x + vecY[i]) * vecZ[i];
»       });
```

Fully Vectorized

Needs extra index table

Not vectorized with **std::for_each**

Quadriadic Computation



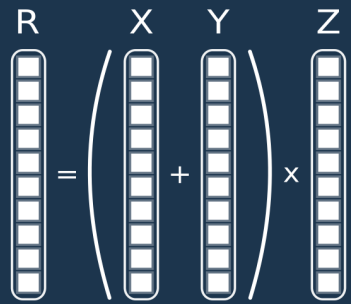
std::transform : triadic

Triadic : **z = x + y**

Classic C++

```
for(long unsigned int i(0lu); i < nbElement; ++i){
»       tabRes[i] = (tabX[i] + tabY[i])*tabZ[i];
}
```

Quadriadic Computation



C++ 17 / 20 / 23

vecY, **vecZ** have to be **std::vector**

```
std::transform(std::execution::par_unseq,
»       std::begin(vecIndex), std::end(vecIndex),
»       std::begin(vecX), std::begin(vecRes),
»       [=](int i, float x){
»       »       return (x + vecY[i]) * vecZ[i];
»       });
```

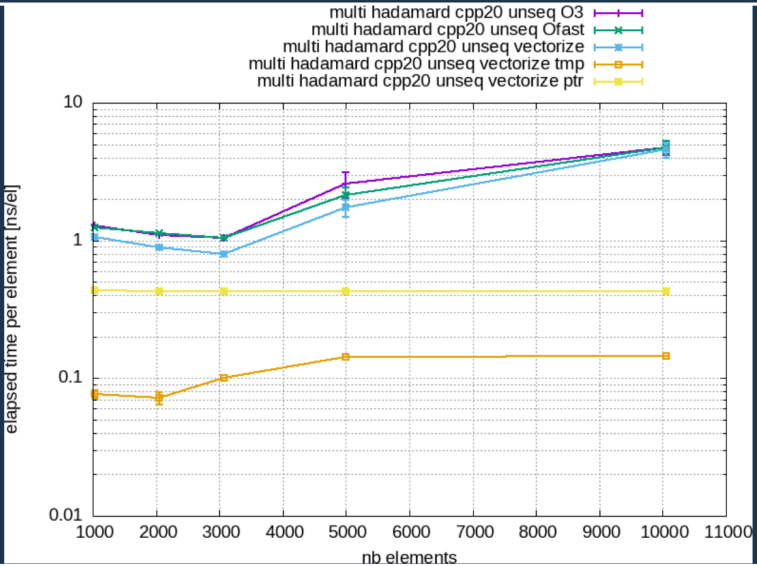
Fully Vectorized

Needs extra index table

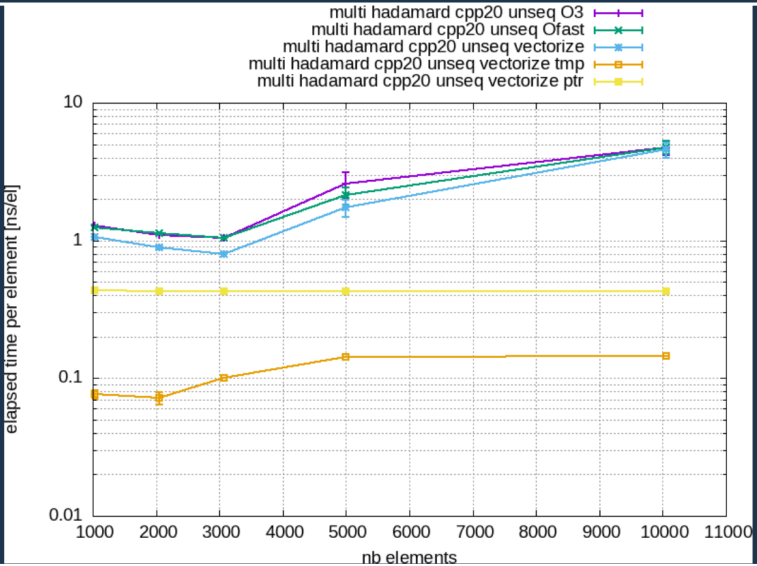
Not vectorized with **std::for_each**

Not vectorized with pointers **vecX**, **vecY**

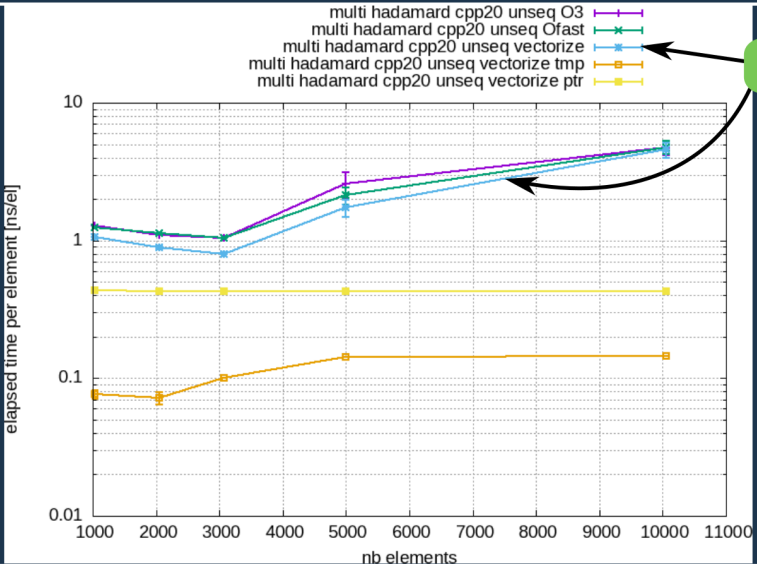
std::transform : (X + Y) x Z



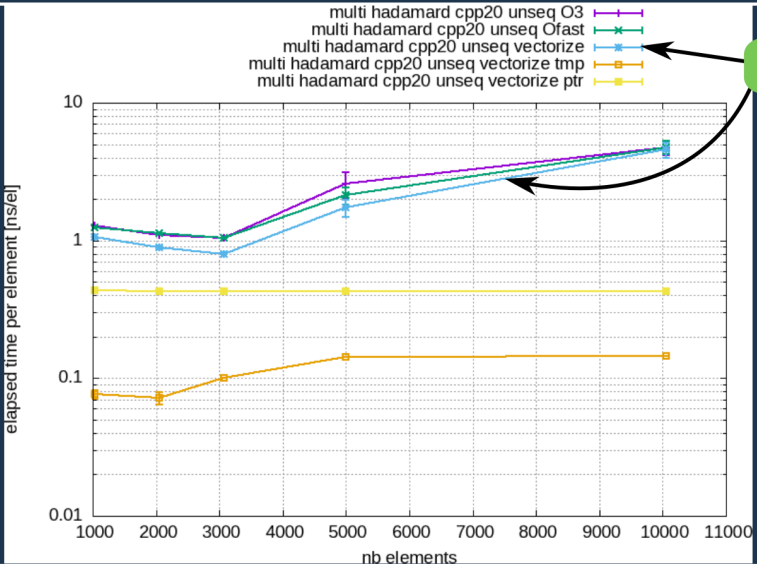
std::transform : (X + Y) x Z



std::transform : (X + Y) x Z



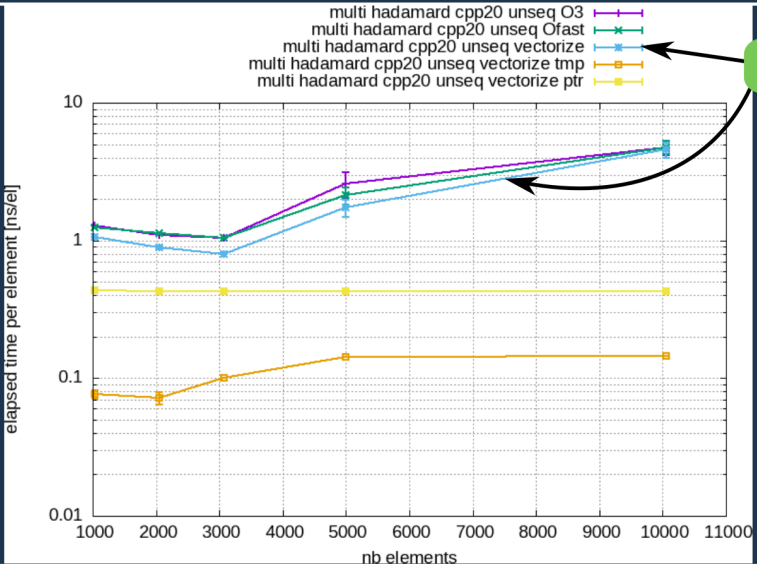
std::transform : (X + Y) x Z



Vectorised

But too much **branching** and **data copy**

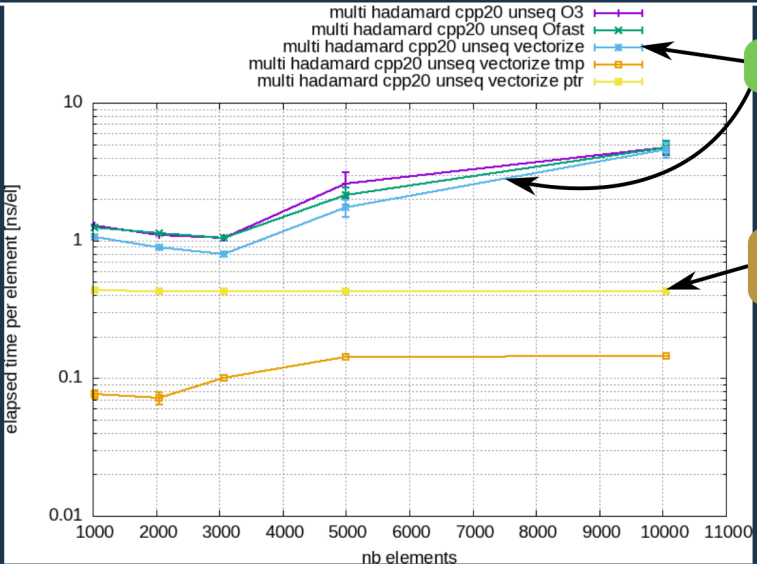
std::transform : (X + Y) x Z



Vectorised

But too much **branching** and **data copy**

std::transform : (X + Y) x Z

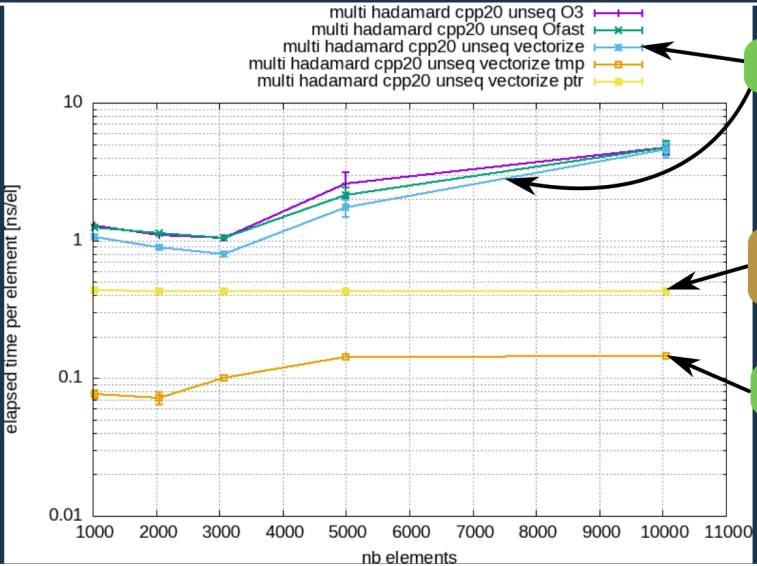


Vectorised

But too much **branching** and **data copy**

Not Vectorized but no **data copy**

std::transform : (X + Y) x Z



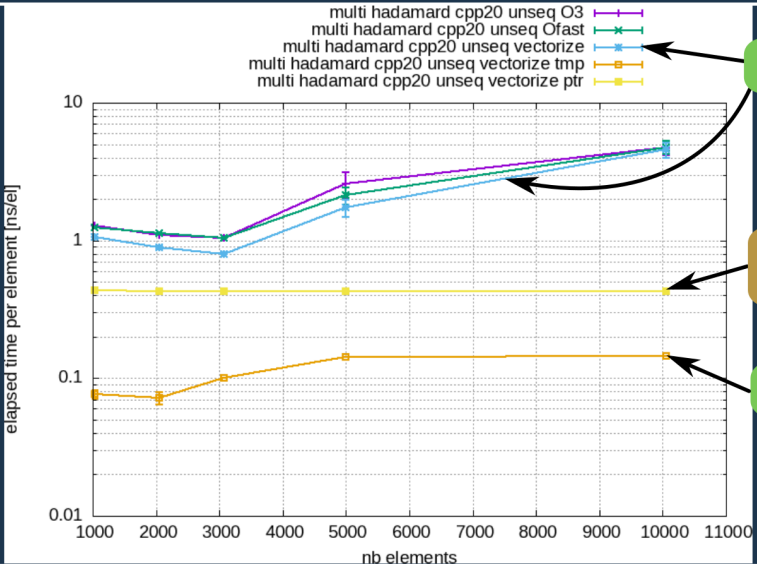
Vectorised

But too much **branching** and **data copy**

Not Vectorized but no **data copy**

Vectorised

std::transform : (X + Y) x Z



Vectorised

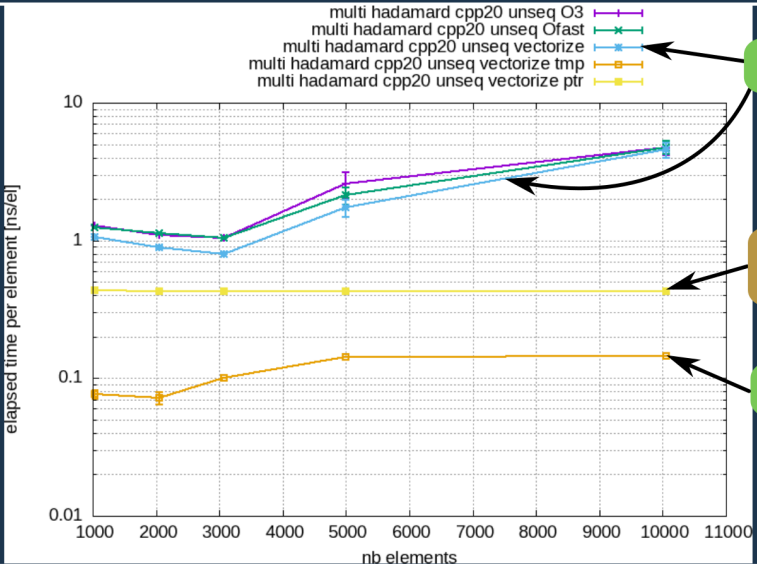
But too much **branching** and **data copy**

Not Vectorized but no **data copy**

Vectorised

But use **temporary vecXY**

std::transform : (X + Y) x Z



Vectorised

But too much **branching** and **data copy**

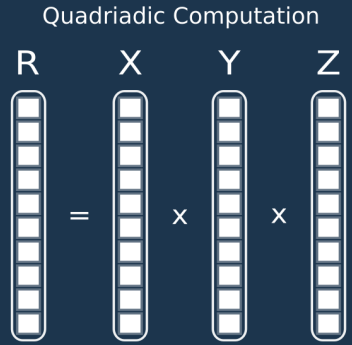
Not Vectorized but no **data copy**

Vectorised

But use **temporary vecXY**

2 std::transform

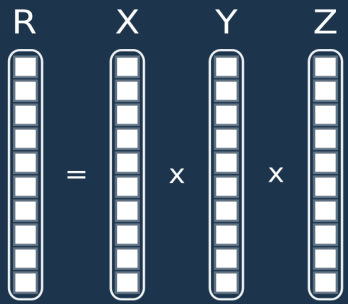
std::views::transform



std::views::transform

```
auto vXY = std::views::transform(std::views::zip(vecX, vecY),
»       »       [](auto tuple){
»       »       »       auto & [x, y] = tuple;
»       »       »       return x*y;
»       »       }
);
std::transform(std::execution::par_unseq,
»       std::begin(vXY), std::end(vXY), std::begin(vecZ),
»       std::begin(vecRes),
»       [](float xy, float z){
»       »       return xy *z;
»       }
);
```

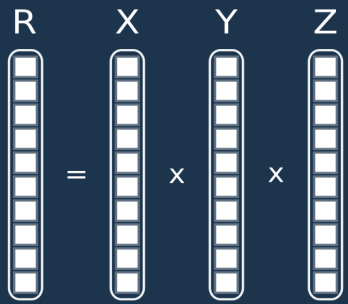
Quadriadic Computation



std::views::transform

```
auto vXY = std::views::transform(std::views::zip(vecX, vecY, vecZ),
»       »       [](auto tuple){
»       »       »       auto & [x, y, z] = tuple;
»       »       »       return x*y*z;
»       »       }
);
std::transform(EXECUTION_POLICY,
»       std::begin(vXY), std::end(vXY),
»       std::begin(vecRes),
»       [](float res){
»       »       return res;
»       }
);
```

Quadriadic Computation

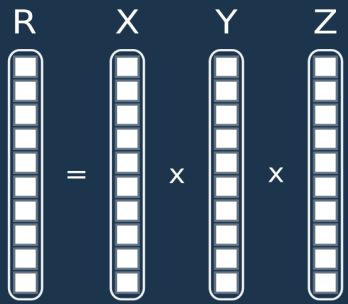


std::views::transform

```
auto vXY = std::views::transform(std::views::zip(vecX, vecY, vecZ),
»       »       [](auto tuple){
»       »       »       auto & [x, y, z] = tuple;
»       »       »       return x*y*z;
»       »       }
);
std::transform(EXECUTION_POLICY,
»       std::begin(vXY), std::end(vXY),
»       std::begin(vecRes),
»       [](float res){
»       »       return res;
»       }
);
```

No extra table needed

Quadriadic Computation



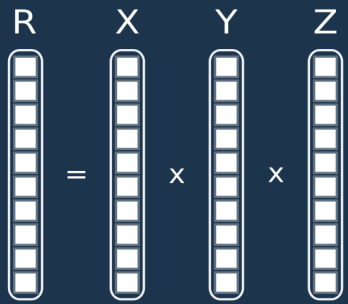
std::views::transform

```
auto vXY = std::views::transform(std::views::zip(vecX, vecY, vecZ),
»       »       [](auto tuple){
»       »       »       auto & [x, y, z] = tuple;
»       »       »       return x*y*z;
»       »       }
);
std::transform(EXECUTION_POLICY,
»       std::begin(vXY), std::end(vXY),
»       std::begin(vecRes),
»       [](float res){
»       »       return res;
»       }
);
```

No extra table needed

Not vectorized yet
because of s**td::views::zip**

Quadriadic Computation



std::views::transform

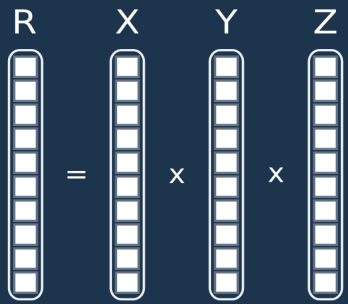
```
auto vXY = std::views::transform(std::views::zip(vecX, vecY, vecZ),
»       »       [](auto tuple){
»       »       »       auto & [x, y, z] = tuple;
»       »       »       return x*y*z;
»       »       }
);
std::transform(EXECUTION_POLICY,
»       std::begin(vXY), std::end(vXY),
»       std::begin(vecRes),
»       [](float res){
»       »       return res;
»       }
);
```

No extra table needed

Use **std::tuple**
Contiguous elements

Not vectorized yet
because of s**td::views::zip**

Quadriadic Computation



std::views::transform

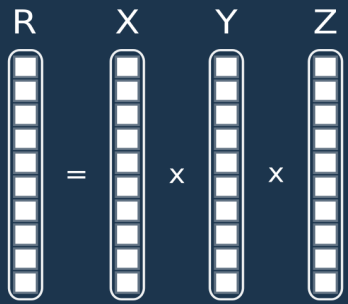
```
auto vXY = std::views::transform(std::views::zip(vecX, vecY, vecZ),
»       »       [](auto tuple){
»       »       »       auto & [x, y, z] = tuple;
»       »       »       return x*y*z;
»       »       }
);
std::transform(EXECUTION_POLICY,
»       std::begin(vXY), std::end(vXY),
»       std::begin(vecRes),
»       [](float res){
»       »       return res;
»       }
);
```

Use **std::tuple**
Contiguous elements

Not vectorized yet
because of s**td::views::zip**

No extra table needed

Quadriadic Computation



Not Vectorisable

std::views::transform

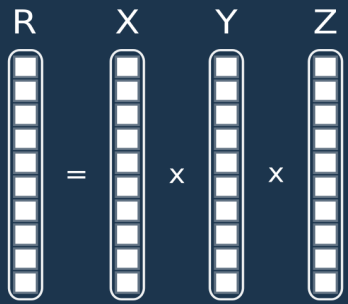
```
auto vXY = std::views::transform(std::views::zip(vecX, vecY, vecZ),
»       »       [](auto tuple){
»       »       »       auto & [x, y, z] = tuple;
»       »       »       return x*y*z;
»       »       }
);
std::transform(EXECUTION_POLICY,
»       std::begin(vXY), std::end(vXY),
»       std::begin(vecRes),
»       [](float res){
»       »       return res;
»       }
);
```

Use **std::tuple**
Contiguous elements

Not vectorized yet
because of s**td::views::zip**

No extra table needed

Quadriadic Computation



Not Vectorisable

Vectorisable

Conclusion

C++ 17 / 20 / 23 algorithms :
- **OK for triadics**

std::view::stransform :
- **Not vectorized yet** because of **std::views::zip**

Allows :
- **Easier vectorization**
- **Computing** on **CPU** and **GPU**

Huge improvement in C++ 26 :
- **Linear Algebra**