# Using Thrust for improving productivity in scientific computing

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Grenoble | images | parole | signal | automatique | laboratoire

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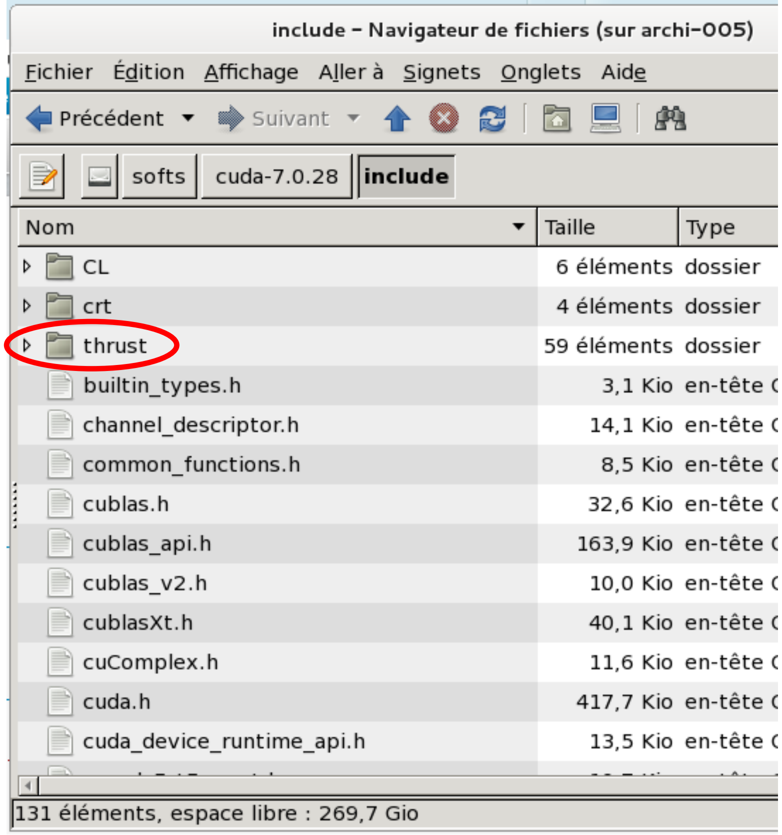
# Plan

- Introduction : Thrust
- 1: The device_vector class
- 2: Thrust, an asynchronous library
- 3: Thrust versatility : CPU/GPU
- 4: Convex optimization using Thrust
- 5: Gradient descent for signal processing
- Interesting links
- Conclusion

# What is Thrust ?

- A template library
- Not a binary
- Part of Cuda Toolkit


include – Navigateur de fichiers (sur archi-005)
Fichier Édition Affichage Aller à Signets Onglets Aide
Précédent
Suivant
softs
cuda-7.0.28
include

| Nom | Taille | Type |
|---|---|---|
| CL | 6 éléments | dossier |
| crt | 4 éléments | dossier |
| thrust | 59 éléments | dossier |
| builtin_types.h | 3,1 Kio | en-tête |
| channel_descriptor.h | 14,1 Kio | en-tête |
| common_functions.h | 8,5 Kio | en-tête |
| cublas.h | 32,6 Kio | en-tête |
| cublas_api.h | 163,9 Kio | en-tête |
| cublas_v2.h | 10,0 Kio | en-tête |
| cublasXt.h | 40,1 Kio | en-tête |
| cuComplex.h | 11,6 Kio | en-tête |
| cuda.h | 417,7 Kio | en-tête |
| cuda_device_runtime_api.h | 13,5 Kio | en-tête |

131 éléments, espace libre : 269,7 Gio

# Compiling : Don’t be Afraid !

```
notargth@archi-005:~/Projets/Cuda_Thrust_Introduction/build$ make install
[ 20%] Built target HostDeviceVector
[ 40%] Built target DeviceBackend
[ 60%] Built target AsynchronousLaunch
[ 80%] Built target MultiGpuThrust
[100%] Building NVCC (Device) object ThrustVectorWrappingCublas/CMakeFiles/ThrustVectorWrappingCublas.dir/ThrustVectorWrappingCublas_generated_main.cu.o
/softs/cuda-7.0.28/include/thrust/detail/internal_functional.h(322): error: expression must be a modifiable lvalue
          detected during:
            instantiation of "thrust::detail::enable_if_non_const_reference_or_tuple_of_iterator_references<thrust::tuple_element<1, Tuple>::type>::type thrust::detail::unary_transform_functor<UnaryFunction>::operator()(Tuple) [with UnaryFunction=thrust::identity<float>,
Tuple=thrust::detail::tuple_of_iterator_references<float &, const float &, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type>]"
/softs/cuda-7.0.28/include/thrust/detail/function.h(60): here
            instantiation of "Result thrust::detail::wrapped_function<Function, Result>::operator()(const Argument &) const [with Function=thrust::detail::unary_transform_functor<thrust::identity<float>>, Result=void,
Argument=thrust::detail::tuple_of_iterator_references<thrust::device_reference<float>, thrust::device_reference<const float>, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type>]"
/softs/cuda-7.0.28/include/thrust/system/cuda/detail/for_each.inl(57): here
            instantiation of "void thrust::system::cuda::detail::for_each_n_detail::for_each_kernel::operator()(thrust::system::cuda::detail::bulk_::parallel_group<thrust::system::cuda::detail::bulk_::concurrent_group<thrust::system::cuda::detail::bulk_::agent<1UL>, 0UL>, 0UL> &, Iterator,
Function, Size) [with Iterator=thrust::zip_iterator<thrust::tuple<thrust::device_ptr<float>, thrust::device_ptr<const float>, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type>>,
Function=thrust::detail::wrapped_function<thrust::detail::unary_transform_functor<thrust::identity<float>>, void>, Size=unsigned int]"
/softs/cuda-7.0.28/include/thrust/system/cuda/detail/bulk/detail/apply_from_tuple.hpp(71): here
            instantiation of "void thrust::system::cuda::detail::bulk_::detail::apply_from_tuple(Function, const thrust::tuple<Arg1, Arg2, Arg3, Arg4, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type> &) [with
Function=thrust::system::cuda::detail::for_each_n_detail::for_each_kernel, Arg1=thrust::system::cuda::detail::bulk_::parallel_group<thrust::system::cuda::detail::bulk_::concurrent_group<thrust::system::cuda::detail::bulk_::agent<1UL>, 0UL>, 0UL> &,
Arg2=thrust::zip_iterator<thrust::tuple<thrust::device_ptr<float>, thrust::device_ptr<const float>, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type>>,
Arg3=thrust::detail::wrapped_function<thrust::detail::unary_transform_functor<thrust::identity<float>>, void>, Arg4=unsigned int]"
/softs/cuda-7.0.28/include/thrust/system/cuda/detail/bulk/detail/closure.hpp(50): here
            instantiation of "void thrust::system::cuda::detail::bulk_::detail::closure<Function, Tuple>::operator()() [with Function=thrust::system::cuda::detail::for_each_n_detail::for_each_kernel,
Tuple=thrust::tuple<thrust::system::cuda::detail::bulk_::parallel_group<thrust::system::cuda::detail::bulk_::concurrent_group<thrust::system::cuda::detail::bulk_::agent<1UL>, 0UL>, 0UL> &, thrust::zip_iterator<thrust::tuple<thrust::device_ptr<float>, thrust::device_ptr<const float>,
thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type>>, thrust::detail::wrapped_function<thrust::detail::unary_transform_functor<thrust::identity<float>>, void>, unsigned int, thrust::null_type,
thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type>]"
/softs/cuda-7.0.28/include/thrust/system/cuda/detail/bulk/detail/cuda_task.hpp(58): here
            [ 33 instantiation contexts not shown ]
            instantiation of "OutputIterator thrust::adjacent_difference(const thrust::detail::execution_policy_base<DerivedPolicy> &, InputIterator, InputIterator, OutputIterator, BinaryFunction) [with DerivedPolicy=thrust::system::cuda::detail::tag,
InputIterator=thrust::detail::normal_iterator<thrust::device_ptr<float>>, OutputIterator=thrust::detail::normal_iterator<thrust::device_ptr<const float>>, BinaryFunction=thrust::minus<float>]"
/softs/cuda-7.0.28/include/thrust/system/detail/generic/adjacent_difference.inl(44): here
            instantiation of "OutputIterator thrust::system::detail::generic::adjacent_difference(thrust::execution_policy<DerivedPolicy> &, InputIterator, InputIterator, OutputIterator) [with DerivedPolicy=thrust::system::cuda::detail::tag,
InputIterator=thrust::detail::normal_iterator<thrust::device_ptr<float>>, OutputIterator=thrust::detail::normal_iterator<thrust::device_ptr<const float>>]"
/softs/cuda-7.0.28/include/thrust/detail/adjacent_difference.inl(39): here
            instantiation of "OutputIterator thrust::adjacent_difference(const thrust::detail::execution_policy_base<DerivedPolicy> &, InputIterator, InputIterator, OutputIterator) [with DerivedPolicy=thrust::system::cuda::detail::tag,
InputIterator=thrust::detail::normal_iterator<thrust::device_ptr<float>>, OutputIterator=thrust::detail::normal_iterator<thrust::device_ptr<const float>>]"
/softs/cuda-7.0.28/include/thrust/detail/adjacent_difference.inl(68): here
            instantiation of "OutputIterator thrust::adjacent_difference(InputIterator, InputIterator, OutputIterator) [with InputIterator=thrust::detail::normal_iterator<thrust::device_ptr<float>>, OutputIterator=thrust::detail::normal_iterator<thrust::device_ptr<const float>>]"
/home/notargth/Projets/Cuda_Thrust_Introduction/ThrustVectorWrappingCublas/ThrustWrapper.cu.h(126): here
            instantiation of "void ThrustVectorWrapper<T>::FiniteForwardDifference(const ThrustVectorWrapper<T> &) [with T=float]"
/home/notargth/Projets/Cuda_Thrust_Introduction/ThrustVectorWrappingCublas/Optimisation.cu.h(162): here


/softs/cuda-7.0.28/include/thrust/system/cuda/detail/assign_value.h(91): error: expression must be a modifiable lvalue
          detected during:
            instantiation of "void thrust::system::cuda::detail::assign_value(thrust::system::cuda::detail::execution_policy<DerivedPolicy> &, Pointer1, Pointer2) [with DerivedPolicy=thrust::system::cuda::detail::tag, Pointer1=thrust::device_ptr<const float>, Pointer2=thrust::device_ptr<float>]"
/softs/cuda-7.0.28/include/thrust/detail/reference.inl(171): here
            instantiation of "void thrust::reference<Element, Pointer, Derived>::strip_const_assign_value(const System &, OtherPointer) [with Element=const float, Pointer=thrust::device_ptr<const float>, Derived=thrust::device_reference<const float>, System=thrust::device_system_tag,
OtherPointer=thrust::device_ptr<float>]"
/softs/cuda-7.0.28/include/thrust/detail/reference.inl(139): here
            instantiation of "void thrust::reference<Element, Pointer, Derived>::assign_from(System1 *, System2 *, OtherPointer) [with Element=const float, Pointer=thrust::device_ptr<const float>, Derived=thrust::device_reference<const float>, System1=thrust::device_system_tag,
System2=thrust::device_system_tag, OtherPointer=thrust::device_ptr<float>]"
/softs/cuda-7.0.28/include/thrust/detail/reference.inl(158): here
            instantiation of "void thrust::reference<Element, Pointer, Derived>::assign_from(OtherPointer) [with Element=const float, Pointer=thrust::device_ptr<const float>, Derived=thrust::device_reference<const float>, OtherPointer=thrust::device_ptr<float>]"
/softs/cuda-7.0.28/include/thrust/detail/reference.inl(86): here
            instantiation of "thrust::reference<Element, Pointer, Derived>::derived_type &thrust::reference<Element, Pointer, Derived>::operator=(const thrust::reference<OtherElement, OtherPointer, OtherDerived> &) [with Element=const float, Pointer=thrust::device_ptr<const float>,
Derived=thrust::device_reference<const float>, OtherElement=float, OtherPointer=thrust::device_ptr<float>, OtherDerived=thrust::device_reference<float>]"
/softs/cuda-7.0.28/include/thrust/detail/device_reference.inl(34): here
            [ 10 instantiation contexts not shown ]
            instantiation of "OutputIterator thrust::adjacent_difference(const thrust::detail::execution_policy_base<DerivedPolicy> &, InputIterator, InputIterator, OutputIterator, BinaryFunction) [with DerivedPolicy=thrust::system::cuda::detail::tag,
```

# Compiling : Don’t be Afraid !

```
InputIterator=thrust::detail::normal_iterator<thrust::device_ptr<float>>, OutputIterator=thrust::detail::normal_iterator<thrust::device_ptr<const float>>, BinaryFunction=thrust::minus<float>]"
/softs/cuda-7.0.28/include/thrust/system/detail/generic/adjacent_difference.inl(44): here
            instantiation of "OutputIterator thrust::system::detail::generic::adjacent_difference(thrust::execution_policy<DerivedPolicy> &, InputIterator, InputIterator, OutputIterator) [with DerivedPolicy=thrust::system::cuda::detail::tag,
InputIterator=thrust::detail::normal_iterator<thrust::device_ptr<float>>, OutputIterator=thrust::detail::normal_iterator<thrust::device_ptr<const float>>]"
/softs/cuda-7.0.28/include/thrust/detail/adjacent_difference.inl(39): here
            instantiation of "OutputIterator thrust::adjacent_difference(const thrust::detail::execution_policy_base<DerivedPolicy> &, InputIterator, InputIterator, OutputIterator) [with DerivedPolicy=thrust::system::cuda::detail::tag,
InputIterator=thrust::detail::normal_iterator<thrust::device_ptr<float>>, OutputIterator=thrust::detail::normal_iterator<thrust::device_ptr<const float>>]"
/softs/cuda-7.0.28/include/thrust/detail/adjacent_difference.inl(68): here
            instantiation of "OutputIterator thrust::adjacent_difference(InputIterator, InputIterator, OutputIterator) [with InputIterator=thrust::detail::normal_iterator<thrust::device_ptr<float>>, OutputIterator=thrust::detail::normal_iterator<thrust::device_ptr<const float>>]"
/home/notargth/Projets/Cuda_Thrust_Introduction/ThrustVectorWrappingCublas/ThrustWrapper.cu.h(126): here
            instantiation of "void ThrustVectorWrapper<T>::FiniteForwardDifference(const ThrustVectorWrapper<T> &) [with T=float]"
/home/notargth/Projets/Cuda_Thrust_Introduction/ThrustVectorWrappingCublas/Optimisation.cu.h(162): here


/softs/cuda-7.0.28/include/thrust/system/cuda/detail/trivial_copy.inl(108): error: a value of type "const float *" cannot be used to initialize an entity of type "void *"
          detected during:
            instantiation of "void thrust::system::cuda::detail::trivial_copy_n(thrust::system::cuda::detail::cross_system<System1, System2> &, RandomAccessIterator1, Size, RandomAccessIterator2) [with System1=thrust::host_system_tag, System2=thrust::system::cuda::detail::tag,
RandomAccessIterator1=const float *, Size=std::ptrdiff_t, RandomAccessIterator2=thrust::device_ptr<const float>]"
/softs/cuda-7.0.28/include/thrust/system/cuda/detail/copy_cross_system.inl(151): here
            instantiation of "RandomAccessIterator2 thrust::system::cuda::detail::copy_cross_system(thrust::system::cuda::detail::cross_system<System1, System2>, RandomAccessIterator1, RandomAccessIterator1, RandomAccessIterator2, thrust::random_access_traversal_tag,
thrust::random_access_traversal_tag, thrust::detail::true_type) [with System1=thrust::host_system_tag, System2=thrust::system::cuda::detail::tag, RandomAccessIterator1=const float *, RandomAccessIterator2=thrust::device_ptr<const float>]"
/softs/cuda-7.0.28/include/thrust/system/cuda/detail/copy_cross_system.inl(245): here
            instantiation of "RandomAccessIterator2 thrust::system::cuda::detail::copy_cross_system(thrust::system::cuda::detail::cross_system<System1, System2>, RandomAccessIterator1, RandomAccessIterator1, RandomAccessIterator2, thrust::random_access_traversal_tag,
thrust::random_access_traversal_tag) [with System1=thrust::host_system_tag, System2=thrust::system::cuda::detail::tag, RandomAccessIterator1=const float *, RandomAccessIterator2=thrust::device_ptr<const float>]"
/softs/cuda-7.0.28/include/thrust/system/cuda/detail/copy_cross_system.inl(279): here
            instantiation of "OutputIterator thrust::system::cuda::detail::copy_cross_system(thrust::system::cuda::detail::cross_system<System1, System2>, InputIterator, InputIterator, OutputIterator) [with System1=thrust::host_system_tag, System2=thrust::system::cuda::detail::tag,
InputIterator=const float *, OutputIterator=thrust::device_ptr<const float>]"
/softs/cuda-7.0.28/include/thrust/system/cuda/detail/copy.inl(54): here
            instantiation of "OutputIterator thrust::system::cuda::detail::copy(thrust::system::cuda::detail::cross_system<System1, System2>, InputIterator, InputIterator, OutputIterator) [with System1=thrust::host_system_tag, System2=thrust::system::cuda::detail::tag,
InputIterator=const float *, OutputIterator=thrust::device_ptr<const float>]"
/softs/cuda-7.0.28/include/thrust/detail/copy.inl(37): here
            [ 16 instantiation contexts not shown ]
            instantiation of "OutputIterator thrust::adjacent_difference(const thrust::detail::execution_policy_base<DerivedPolicy> &, InputIterator, InputIterator, OutputIterator, BinaryFunction) [with DerivedPolicy=thrust::system::cuda::detail::tag,
InputIterator=thrust::detail::normal_iterator<thrust::device_ptr<float>>, OutputIterator=thrust::detail::normal_iterator<thrust::device_ptr<const float>>, BinaryFunction=thrust::minus<float>]"
/softs/cuda-7.0.28/include/thrust/system/detail/generic/adjacent_difference.inl(44): here
            instantiation of "OutputIterator thrust::system::detail::generic::adjacent_difference(thrust::execution_policy<DerivedPolicy> &, InputIterator, InputIterator, OutputIterator) [with DerivedPolicy=thrust::system::cuda::detail::tag,
InputIterator=thrust::detail::normal_iterator<thrust::device_ptr<float>>, OutputIterator=thrust::detail::normal_iterator<thrust::device_ptr<const float>>]"
/softs/cuda-7.0.28/include/thrust/detail/adjacent_difference.inl(39): here
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InputIterator=thrust::detail::normal_iterator<thrust::device_ptr<float>>, OutputIterator=thrust::detail::normal_iterator<thrust::device_ptr<const float>>]"
/softs/cuda-7.0.28/include/thrust/detail/adjacent_difference.inl(68): here
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/home/notargth/Projets/Cuda_Thrust_Introduction/ThrustVectorWrappingCublas/ThrustWrapper.cu.h(126): here
            instantiation of "void ThrustVectorWrapper<T>::FiniteForwardDifference(const ThrustVectorWrapper<T> &) [with T=float]"
/home/notargth/Projets/Cuda_Thrust_Introduction/ThrustVectorWrappingCublas/Optimisation.cu.h(162): here


/softs/cuda-7.0.28/include/thrust/detail/internal_functional.h(322): error: expression must be a modifiable lvalue
          detected during:
            instantiation of "thrust::detail::enable_if_non_const_reference_or_tuple_of_iterator_references<thrust::tuple_element<1, Tuple>::type>::type thrust::detail::unary_transform_functor<UnaryFunction>::operator()(Tuple) [with UnaryFunction=thrust::identity<float>,
Tuple=thrust::detail::tuple_of_iterator_references<const float &, const float &, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type>]"
/softs/cuda-7.0.28/include/thrust/detail/function.h(60): here
            instantiation of "Result thrust::detail::wrapped_function<Function, Result>::operator()(const Argument &) const [with Function=thrust::detail::unary_transform_functor<thrust::identity<float>>, Result=void, Argument=thrust::detail::tuple_of_iterator_references<const float &,
thrust::device_reference<const float>, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type>]"
/softs/cuda-7.0.28/include/thrust/system/cuda/detail/for_each.inl(57): here
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Iterator, Function, Size) [with Iterator=thrust::zip_iterator<thrust::tuple<const float *, thrust::device_ptr<const float>, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type>>,
Function=thrust::detail::wrapped_function<thrust::detail::unary_transform_functor<thrust::identity<float>>, void>, Size=unsigned int]"
/softs/cuda-7.0.28/include/thrust/system/cuda/detail/bulk/detail/apply_from_tuple.hpp(71): here
            instantiation of "void thrust::system::cuda::detail::bulk_::detail::apply_from_tuple(Function, const thrust::tuple<Arg1, Arg2, Arg3, Arg4, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type> &) [with
Function=thrust::system::cuda::detail::for_each_n_detail::for_each_kernel, Arg1=thrust::system::cuda::detail::bulk_::parallel_group<thrust::system::cuda::detail::bulk_::concurrent_group<thrust::system::cuda::detail::bulk_::agent<1UL>, 0UL>, 0UL> &,
Arg2=thrust::zip_iterator<thrust::tuple<const float *, thrust::device_ptr<const float>, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type>>,
Arg3=thrust::detail::wrapped_function<thrust::detail::unary_transform_functor<thrust::identity<float>>, void>, Arg4=unsigned int]"
/softs/cuda-7.0.28/include/thrust/system/cuda/detail/bulk/detail/closure.hpp(50): here
            instantiation of "void thrust::system::cuda::detail::bulk_::detail::closure<Function, Tuple>::operator()() [with Function=thrust::system::cuda::detail::for_each_n_detail::for_each_kernel,
Tuple=thrust::tuple<thrust::system::cuda::detail::bulk_::parallel_group<thrust::system::cuda::detail::bulk_::concurrent_group<thrust::system::cuda::detail::bulk_::agent<1UL>, 0UL>, 0UL> &, thrust::zip_iterator<thrust::tuple<const float *, thrust::device_ptr<const float>,
thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type>>, thrust::detail::wrapped_function<thrust::detail::unary_transform_functor<thrust::identity<float>>, void>, unsigned int, thrust::null_type,
thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type, thrust::null_type>]"
/softs/cuda-7.0.28/include/thrust/system/cuda/detail/bulk/detail/cuda_task.hpp(58): here
```

# Compiling : Don’t be Afraid !

```
        [ 34 instantiation contexts not shown ]
        instantiation of "OutputIterator thrust::adjacent_difference(const thrust::detail::execution_policy_base<DerivedPolicy> &, InputIterator, InputIterator, OutputIterator, BinaryFunction) [with DerivedPolicy=thrust::system::cuda::detail::tag,
InputIterator=thrust::detail::normal_iterator<thrust::device_ptr<float>>, OutputIterator=thrust::detail::normal_iterator<thrust::device_ptr<const float>>, BinaryFunction=thrust::minus<float>]"
/softs/cuda-7.0.28/include/thrust/system/detail/generic/adjacent_difference.inl(44): here
        instantiation of "OutputIterator thrust::system::detail::generic::adjacent_difference(thrust::execution_policy<DerivedPolicy> &, InputIterator, InputIterator, OutputIterator) [with DerivedPolicy=thrust::system::cuda::detail::tag,
InputIterator=thrust::detail::normal_iterator<thrust::device_ptr<float>>, OutputIterator=thrust::detail::normal_iterator<thrust::device_ptr<const float>>]"
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       detected during:
        instantiation of "void thrust::system::cuda::detail::assign_value(thrust::system::cuda::detail::execution_policy<DerivedPolicy> &, Pointer1, Pointer2) [with DerivedPolicy=thrust::system::cuda::detail::tag, Pointer1=thrust::device_ptr<const float>, Pointer2=const float *]"
(179): here
        instantiation of "void thrust::system::cuda::detail::assign_value(thrust::system::cuda::detail::cross_system<System1, System2> &, Pointer1, Pointer2) [with System1=thrust::system::cuda::detail::tag, System2=thrust::host_system_tag, Pointer1=thrust::device_ptr<const float>,
Pointer2=const float *]"
/softs/cuda-7.0.28/include/thrust/detail/reference.inl(171): here
        instantiation of "void thrust::reference<Element, Pointer, Derived>::strip_const_assign_value(const System &, OtherPointer) [with Element=const float, Pointer=thrust::device_ptr<const float>, Derived=thrust::device_reference<const float>,
System=thrust::system::cuda::detail::cross_system<thrust::system::cuda::detail::tag, thrust::host_system_tag>, OtherPointer=const float *]"
/softs/cuda-7.0.28/include/thrust/detail/reference.inl(139): here
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System2=thrust::host_system_tag, OtherPointer=const float *]"
/softs/cuda-7.0.28/include/thrust/detail/reference.inl(158): here
        instantiation of "void thrust::reference<Element, Pointer, Derived>::assign_from(OtherPointer) [with Element=const float, Pointer=thrust::device_ptr<const float>, Derived=thrust::device_reference<const float>, OtherPointer=const float *]"
/softs/cuda-7.0.28/include/thrust/detail/reference.inl(65): here
        [ 11 instantiation contexts not shown ]
        instantiation of "OutputIterator thrust::adjacent_difference(const thrust::detail::execution_policy_base<DerivedPolicy> &, InputIterator, InputIterator, OutputIterator, BinaryFunction) [with DerivedPolicy=thrust::system::cuda::detail::tag,
InputIterator=thrust::detail::normal_iterator<thrust::device_ptr<float>>, OutputIterator=thrust::detail::normal_iterator<thrust::device_ptr<const float>>, BinaryFunction=thrust::minus<float>]"
/softs/cuda-7.0.28/include/thrust/system/detail/generic/adjacent_difference.inl(44): here
        instantiation of "OutputIterator thrust::system::detail::generic::adjacent_difference(thrust::execution_policy<DerivedPolicy> &, InputIterator, InputIterator, OutputIterator) [with DerivedPolicy=thrust::system::cuda::detail::tag,
InputIterator=thrust::detail::normal_iterator<thrust::device_ptr<float>>, OutputIterator=thrust::detail::normal_iterator<thrust::device_ptr<const float>>]"
/softs/cuda-7.0.28/include/thrust/detail/adjacent_difference.inl(39): here
        instantiation of "OutputIterator thrust::adjacent_difference(const thrust::detail::execution_policy_base<DerivedPolicy> &, InputIterator, InputIterator, OutputIterator) [with DerivedPolicy=thrust::system::cuda::detail::tag, InputIterator=thrust::detail::normal_iterator<thrust::device_ptr<float>>,
OutputIterator=thrust::detail::normal_iterator<thrust::device_ptr<const float>>]"
/softs/cuda-7.0.28/include/thrust/detail/adjacent_difference.inl(68): here
        instantiation of "OutputIterator thrust::adjacent_difference(InputIterator, InputIterator, OutputIterator) [with InputIterator=thrust::detail::normal_iterator<thrust::device_ptr<float>>, OutputIterator=thrust::detail::normal_iterator<thrust::device_ptr<const float>>]"
/home/notargth/Projets/Cuda_Thrust_Introduction/ThrustVectorWrappingCublas/ThrustWrapper.cu.h(126): here
        instantiation of "void ThrustVectorWrapper<T>::FiniteForwardDifference(const ThrustVectorWrapper<T> &) [with T=float]"
/home/notargth/Projets/Cuda_Thrust_Introduction/ThrustVectorWrappingCublas/Optimisation.cu.h(162): here


5 errors detected in the compilation of "/tmp/tmpxft_000007bd_00000000-7_main.cpp1.ii".
CMake Error at ThrustVectorWrappingCublas_generated_main.cu.o.cmake:264 (message):
  Error generating file
  /home/notargth/Projets/Cuda_Thrust_Introduction/build/ThrustVectorWrappingCublas/CMakeFiles/ThrustVectorWrappingCublas.dir//./ThrustVectorWrappingCublas_generated_main.cu.o



make[2]: *** [ThrustVectorWrappingCublas/CMakeFiles/ThrustVectorWrappingCublas.dir/ThrustVectorWrappingCublas_generated_main.cu.o] Erreur 1
make[1]: *** [ThrustVectorWrappingCublas/CMakeFiles/ThrustVectorWrappingCublas.dir/all] Erreur 2
make: *** [all] Erreur 2
```

# 1: device_vector class

# 1: device_vector class

- What it is:
  - A « container »
  - Cuda buffer Wrapper
  - Equivalent of std::vector<T>
- What it allows:
  - Equivalent of <algorithm> : fill, generate, reduce, sort, …
  - Automatic allocation/destruction
  - Handle some cuda error
  - Ease host/device copy management.
- What it cannot do:
  - Wrap cuda array, 1D,2D,3D textures nor surfaces
  - Bound checking per se

# 1:Classic usage

Declaration

```
//Thrust Device vectors intend to mimic std::vector class from stl, plus its algorithms
thrust::device_vector<int> deviceVector;
//Also available in host flavour
thrust::host_vector<int> hostVector;
```

Allocation

```
//Allocate vector on device
deviceVector.resize( VEC_SIZE );
//Initialize host vector as size 8 elements, each containing the value 111
hostVector.resize( VEC_SIZE, 111 );
```

Copy To device

```
//Explicit copy to device
thrust::copy( hostVector.begin(), hostVector.end(), deviceVector.begin() );
```

Compute on device

```
//Compute on device, here inclusive scan, for histogram equalization for instance
thrust::inclusive_scan( deviceVector.begin(), deviceVector.end(), deviceVector.begin() );
```

Copy To host

```
//Copy back to host
thrust::copy( deviceVector.begin(), deviceVector.end(), hostVector.begin() );
```

# 1:Better practical expressivity

Declaration
+ Allocation

```
//Declare and initialize device vector in one line
thrust::device_vector<int> deviceVector( VEC_SIZE, 111 );
```

Computation
on device

```
//Compute algorithm
thrust::inclusive_scan( deviceVector.begin(), deviceVector.end(), deviceVector.begin() );
```

Read or write
without explicit
copy

```
//Print results
std::cout << "Version 2, vector contains: ";
for( auto it = deviceVector.begin(); it != deviceVector.end(); it++ )
{
    std::cout << " / " << *it;
    //Dereferencing iterator for reading: can also be done for writing !
}
```

# 1: Compatibility with user allocated memory

Handmade allocation

```
//Raw pointer to device memory
int * raw_ptr;
checkCudaErrors( cudaMalloc((void **) &raw_ptr, VEC_SIZE * sizeof(int) ) );
```

Thrust raw pointer wrapper

```
//Wrap raw pointer with a device_ptr
thrust::device_ptr<int> dev_ptr(raw_ptr);
```

Initializing using thrust utility

```
//Use device_ptr in thrust algorithms
thrust::fill(dev_ptr, dev_ptr + VEC_SIZE, (int) 111);
```

Compute on device

```
//Compute on device, here inclusive scan, for histogram equalization for instance
thrust::inclusive_scan( dev_ptr, dev_ptr + VEC_SIZE, dev_ptr );
```

Wrapper is iconvenient

```
//Print results
std::cout << "Version 3, vector contains: ";
for( int i = 0; i != VEC_SIZE; i++ )
{
    std::cout << " / " << dev_ptr[i];
    //Dereferencing pointer for reading: can also be done for writing !
}
```

# 1:Compatibility with user written kernels

Handwritten
cuda kernel

```
__global__ void naive_sequential_scan( T* ptr )
{
    T val = 0;
    #pragma unroll
    for( auto i = 0; i < SIZE; i++ )
    {
        ptr[i] += val;
         val = ptr[i];
    }
}
```

Declaration
+ Allocation

```
//Declare and initialize device vector in one line
thrust::device_vector<int> deviceVector( VEC_SIZE, 111 );
```

Declare
Synchronization tool

```
//Compute algorithm
cudaStream_t stream;
checkCudaErrors( cudaStreamCreate(&stream) );
```

Launch handwritten
kernel

```
naive_sequential_scan<int,VEC_SIZE><<<1,1,0,stream>>>(
    thrust::raw_pointer_cast(deviceVector.data() ) );
```

Synchronize

```
checkCudaErrors( cudaStreamSynchronize( stream) );
```

# 1:Handle some errors as exceptions

```
try
{
    //Declare and initialize device vector in one line
    thrust::device_vector<int> deviceVector( VEC_SIZE, 111 );


     //Compute algorithm
     std::cout << "Version 5, we are going to catch an exception: ";
     thrust::inclusive_scan( deviceVector.begin(), deviceVector.end(),
                deviceVector.begin() );
}
catch( thrust::system_error &e )
{
    std::cerr << "Thrust mechanism for handling error  : " << e.what() << std::endl;
}
```

Declaration
+ Allocation

Compute on device :
wrong iterator

Classic
catch
block

# 2: Thrust: An asynchronous library

# 2: Thrust: An asynchronous library

- Asynchronous behaviour in cuda
  - The compute / copy paradigm
  - Streams concept in cuda
  - Execution_policy in Thrust

- Asynchronous traps
  - Beware of pageable memory !
  - Data chunk size
  - Problem with default stream ( --default-stream per-thread )
  - Copy engine ressource

# 2: Thrust: An asynchronous library

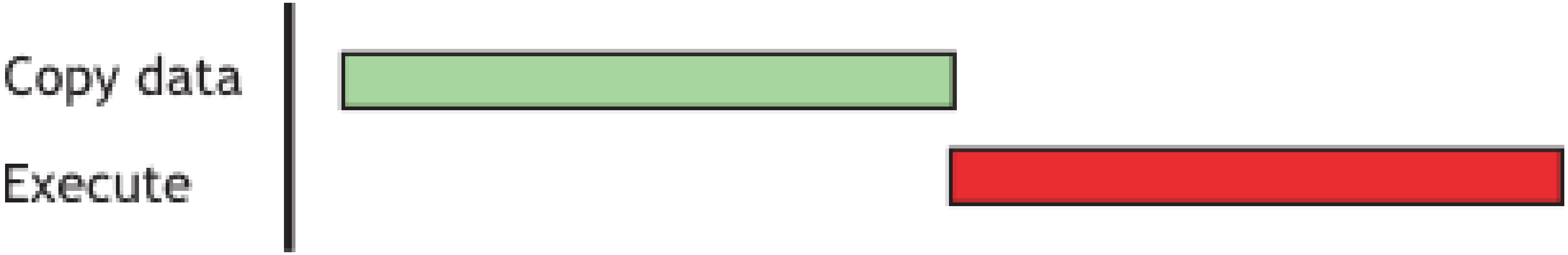
- Execution_policy in Thrust could be
  - thrust::host
  - thrust::device
  - thrust::seq
  - thrust::system::omp::par
  - thrust::system::tbb::par
  - thrust::system::cuda::par( cudaStream_t )

- Looks like C++17 execution_policy_tag
  - std::execution::sequenced_policy
  - std::execution::parallel_policy
  - std::execution::parallel_unsequenced_policy

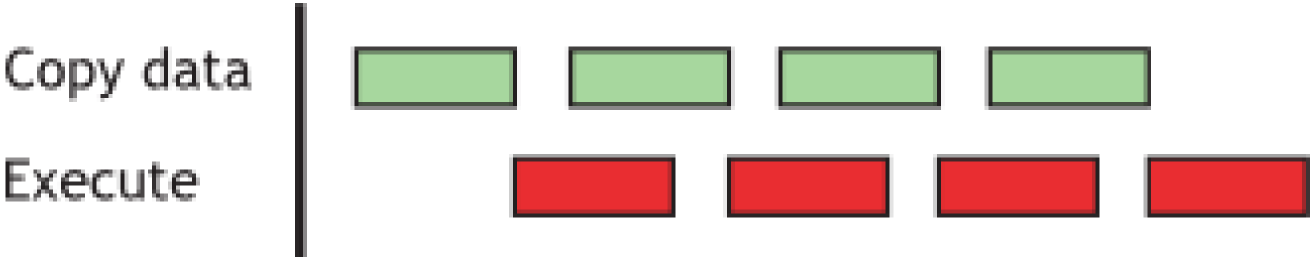
# 2: Thrust: Multiple stream approach

## Achieving Copy / Compute overlapping

Avoid large datasets



Prefere small data chunks



# 2: Thrust: Multiple stream approach V1

Stream vector

```
//Declare  and initialize cuda stream
std::vector<cudaStream_t> vStream(nbOfStrip);
for( auto it = vStream.begin(); it != vStream.end(); it++ )
{
    cudaStreamCreate( &(*it) );
}
```

Only one loop

```
//Now, we would like to perform an alternate scheme copy/compute in a loop using the
copyToDevice/Compute/CopyToHost for each stream scheme:
for( int j=0; j!=nbOfStrip; j++)
{
```

Synchronize

```
    size_t offset = stripSize*j;
    size_t nextOffset = stripSize*(j+1);
    cudaStreamSynchronize(vStream.at(j));
```

Copy to device

```
    cudaMemcpyAsync(thrust::raw_pointer_cast(deviceVector.data())+offset, hostVector+offset,
stripSize*sizeof(float), cudaMemcpyHostToDevice, vStream.at(j));
```

Compute

```
    thrust::transform( thrust::cuda::par.on(vStream.at(j)), deviceVector.begin()+offset,
deviceVector.begin()+nextOffset, deviceVector.begin()+offset, computeFunctor<float>() );
```

Copy to host

```
    cudaMemcpyAsync(hostVector+offset, thrust::raw_pointer_cast(deviceVector.data())+offset,
stripSize*sizeof(float), cudaMemcpyDeviceToHost, vStream.at(j));
}
```

# 2: Thrust: Multiple stream approach V2

Synchronize loop

```
for( int j=0; j!=nbOfStrip; j++)
{
    cudaStreamSynchronize(vStream.at(j));
}
```

Copy to device loop

```
for( int j=0; j!=nbOfStrip; j++)
{
    size_t offset = stripSize*j;
    cudaMemcpyAsync(thrust::raw_pointer_cast(deviceVector.data())+offset,
        hostVector+offset, stripSize*sizeof(float), cudaMemcpyHostToDevice,
        vStream.at(j));
}
```

Compute loop

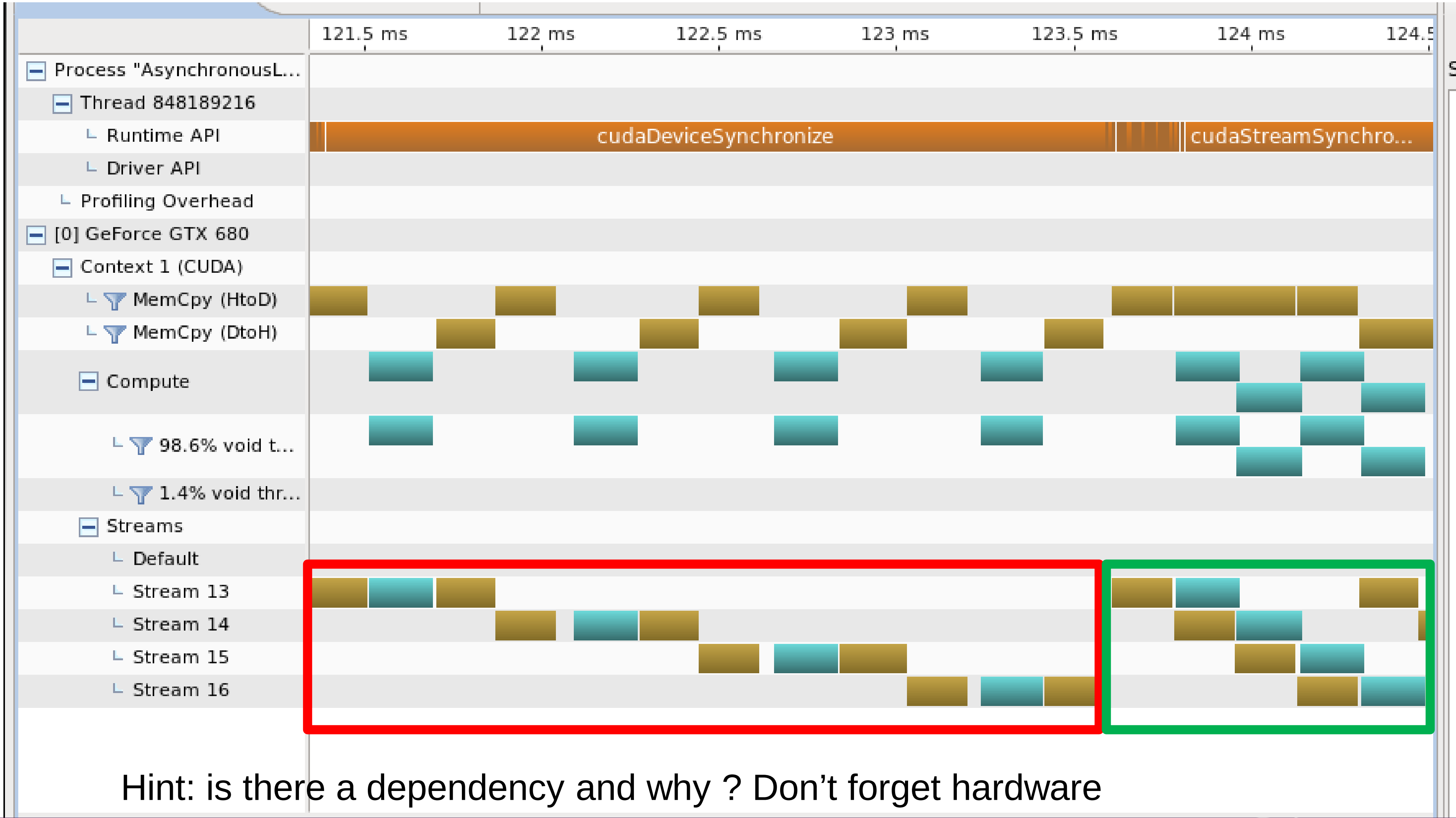
```
for( int j=0; j!=nbOfStrip; j++)
{
    size_t offset = stripSize*j;
    size_t nextOffset = stripSize*(j+1);
    thrust::transform( thrust::cuda::par.on(vStream.at(j)), deviceVector.begin()+offset,
        deviceVector.begin()+nextOffset, deviceVector.begin()+offset,
        computeFunctor<float>() );
}
```

Copy to host loop

```
for( int j=0; j!=nbOfStrip; j++)
{
    size_t offset = stripSize*j;
    cudaMemcpyAsync(hostVector+offset,  thrust::raw_pointer_cast(
        deviceVector.data())+offset, stripSize*sizeof(float),
        cudaMemcpyDeviceToHost, vStream.at(j));
}
```

# 2: Thrust: An asynchronous library

## Who ’s who ?

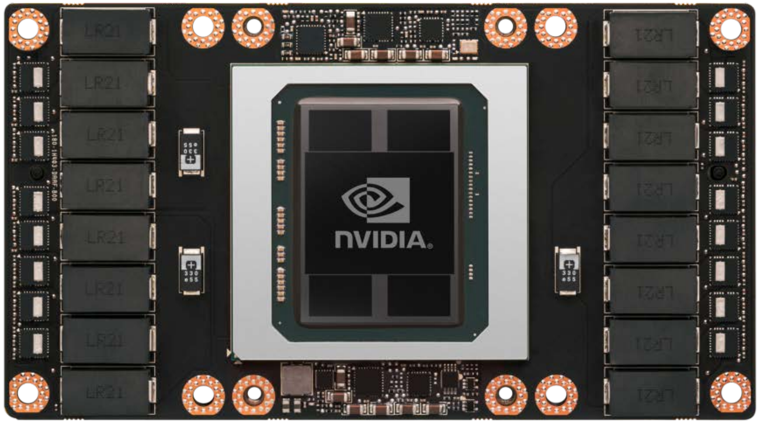


Hint: is there a dependency and why ? Don’t forget hardware

# 3: Thrust versatility : CPU/GPU

# 3: Thrust versatility : CPU/GPU

- Versatility
  - Code once, get multiple implementations
  - Ease GPU speedup calculation



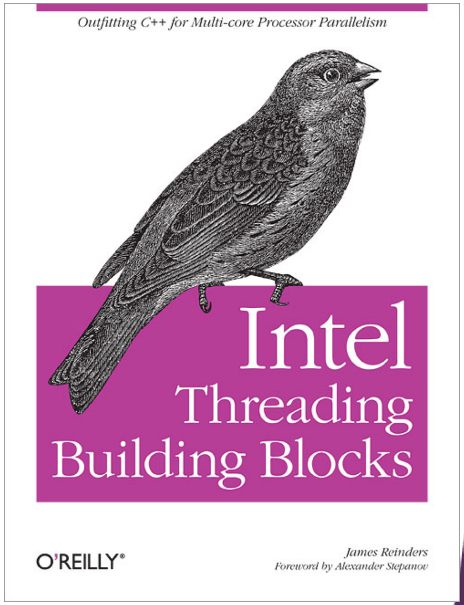
# 3: Thrust versatility : CPU/GPU

- What is OpenMP
  - OpenMulti-Processigng
  - Standard model for parallel programming
  - Mainly pre-processor directive
  - Automatic parallelism paradigm (parallel for, parallel reduction,…)
  - Synchronization primitives and more
- Sample:

```
int main(int argc, char **argv)
{
    int a[100000];

    #pragma omp parallel for
    int i;
    for (i = 0; i < 100000; i++)
        a[i] = 2 * i;

    return 0;
}
```

# 3: Thrust versatility : CPU/GPU

- What is TBB ?
  - Threading Building Blocks
  - C++ Library, portable, OS (GPLv2)
  - Work stealing
- What does it feaures ?
  - Algorithmic skeletons (parallel_while, pipeline,...)
  - Containers (concurrent queue, vector, hash_map)
  - Scalable allocators
  - Advanced synchronization primitives
  - 2D/3D structured iterators (bocked_range)
  - Cache aware policy « affinity_partitioner »


Outfitting C++ for Multi-core Processor Parallelism
Intel Threading Building Blocks
O'REILLY
James Reinders
Foreword by Alexander Stepanov

# 3: Thrust versatility : CPU/GPU

```
#include "tbb/tbb.h"
#include "tbb/blocked_range3d.h"
using namespace tbb;
template <typename T>
class ApplyAssignScalar
{
public:
    void operator( )( const blocked_range3d<size_t,size_t,size_t>& r ) const
    {
         T *const a = m_a;
         const T val = m_val;
         for( size_t k = r.pages().begin(); k != r.pages().end(); ++k )
         {
             for( size_t j = r.rows().begin(); j != r.rows().end(); ++j )
             {
                 for( size_t i = r.cols().begin(); i != r.cols().end(); ++i )
                 {
                     unsigned int addr = getAddr( m_VolSizePx, i, j, k );
                     a[addr] = val ;
                  }
              }
          }
    }
private:
            T *const m_a;
            const size_t m_VolSizePx;
            const T m_val;
};

template <typename T>
void TBBVolume<T>::Assign( T value  )
{
    static tbb::affinity_partitioner ap;
    tbb::parallel_for( m_BlockedRange3D, ApplyAssignScalar<T>( pVolume, VolumeSizePx, value ), ap );
}
```

# 3: Thrust device system

- High level concept

- Multiple possible backends :
  - THRUST_DEVICE_SYSTEM_CUDA
  - THRUST_DEVICE_SYSTEM_OMP
  - THRUST_DEVICE_SYSTEM_TBB

- Compile time decision
  - Using option -DTHRUST_DEVICE_SYSTEM

# 3: Benchmarking backends on sort

CmakeLists.txt

```
###########################################
#          Miscellaneous parallel computing lib        #
###########################################

#Change device execution for fun !
set(THRUST_DEVICE_SYSTEM THRUST_DEVICE_SYSTEM_CUDA)
#set(THRUST_DEVICE_SYSTEM "THRUST_DEVICE_SYSTEM_OMP -Xcompiler -fopenmp" )
#set(THRUST_DEVICE_SYSTEM THRUST_DEVICE_SYSTEM_TBB)

list( APPEND CUDA_NVCC_FLAGS -DTHRUST_DEVICE_SYSTEM=${THRUST_DEVICE_SYSTEM}
```

# 3: Benchmarking backends on sort

## Core code

Start timer

```
//Now measure how many time it take to perform sorting operation
auto begin = std::chrono::high_resolution_clock::now();
```

Compute

```
thrust::sort( deviceVector.begin(), deviceVector.end() );
```

Conditional synchronization point

```
#if THRUST_DEVICE_SYSTEM == THRUST_DEVICE_SYSTEM_CUDA
//Synchronize because of aynchronous behaviour in cuda mode
cudaDeviceSynchronize();
#endif // THRUST_DEVICE_SYSTEM == THRUST_DEVICE_SYSTEM_CUDA
```

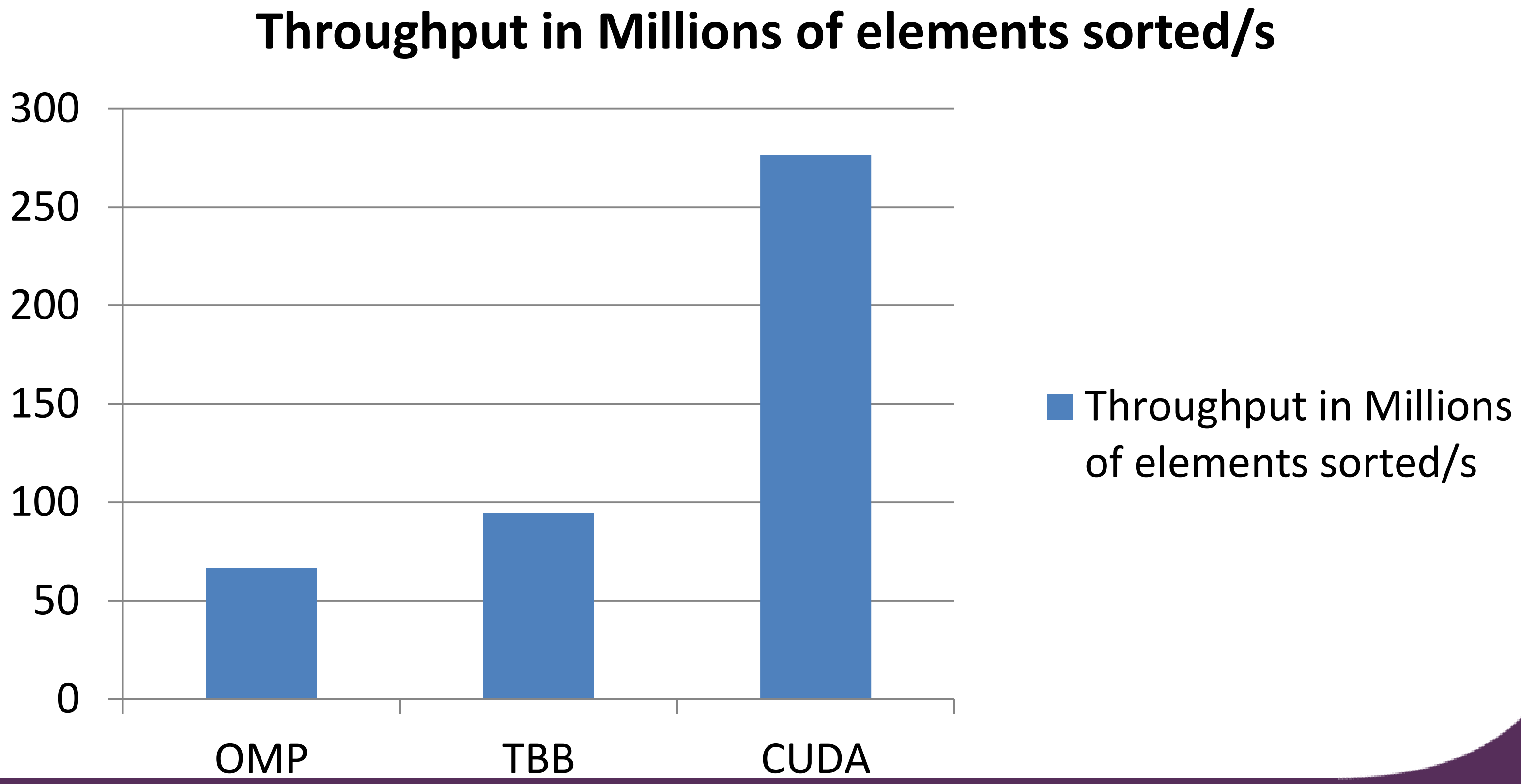
Stop timer

```
auto end = std::chrono::high_resolution_clock::now();
```

# 3: Benchmarking backends on sort

- Results

//OpenMP backend sorted 134’217’728 elements in 2.01271 seconds (66.685 Millions of elements/s )
//TBB backend sorted 134’217’728 elements in 1.42055 seconds (94.4827 Millions of elements/s )
//Cuda backend sorted 134’217’728 elements in 0.485675 seconds (276.353 Millions of elements/s )



# 4: Convex optimization using Thrust and Cublas

# 4: Convex optimization using Thrust and Cublas

- Why convex optimization on GPU ?
  - Unnecessary on small well posed systems
  - Ill-posed problems needs iterative methods
  - Iterative methods are expensive for large systems
  - Large problems needs parallelism

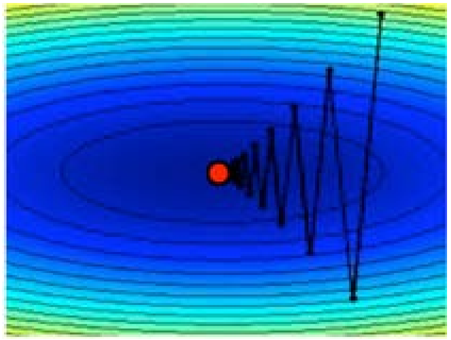
# 4: Convex optimization using Thrust : Steepest descent

- Simple algorithm for a convex differentiable functional
  - Quadratic objectif function: easily differentiable
  - We choose least square problem

$$\min_{x \in \mathbb{R}^d} f(x) = \frac{1}{2} \|AX - B\|^2$$

  - Solved by step, each time going in the opposite sense of the gradient:

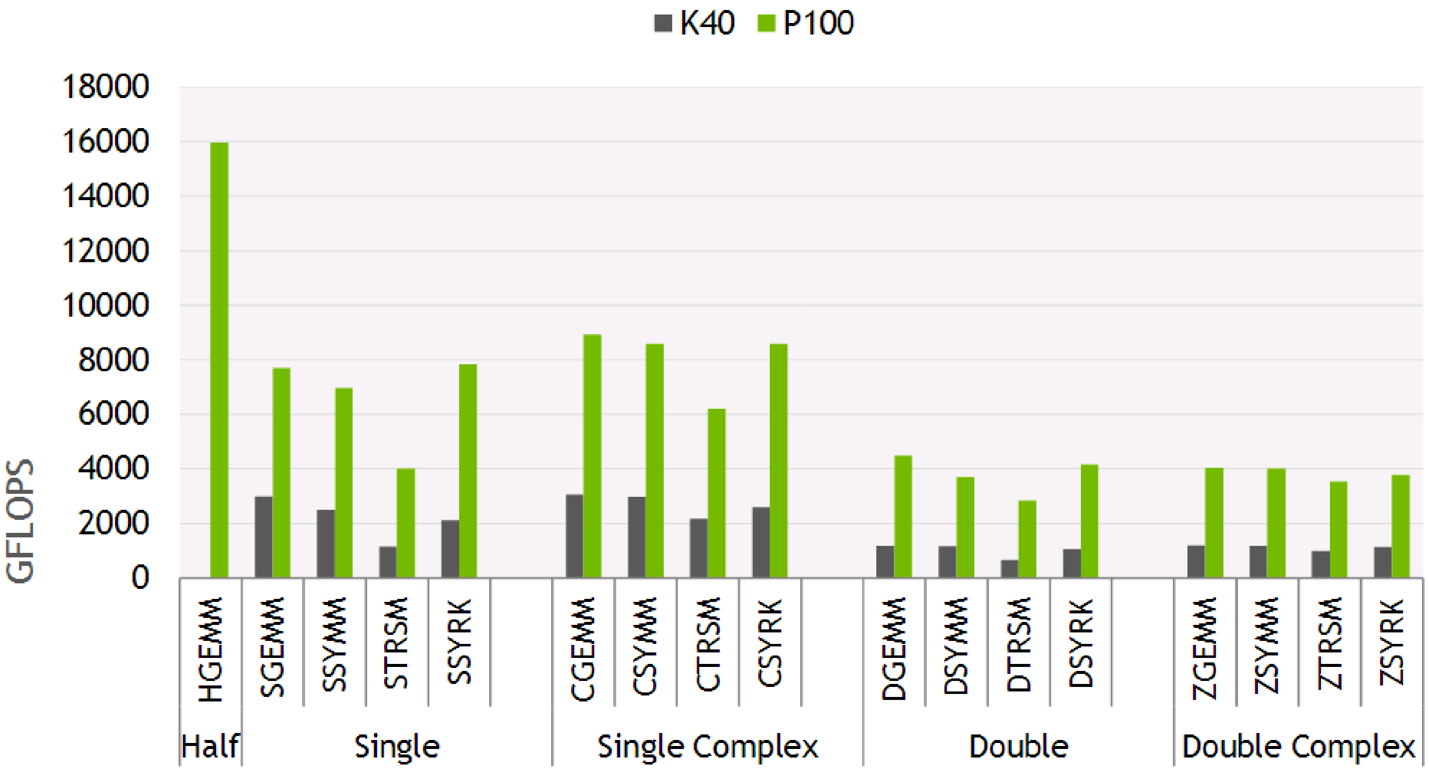
$$\nabla f(x) = A^t AX - A^t B$$



Source: Gabriel Peyré

# 4: Convex optimization using Thrust : What is Cublas ?

- A powerful library (Basic Linear Algebra Subprogram)



cuBLAS, input and output data on device. m=n=k=4096

# 4: Convex optimization using Thrust and Cublas

- Our strategy: Wrap everything inside a higher level interface

Cublas official interface

```
cublasSgemv(handle, transA, m, n, alpha, A, lda, B, ldb, beta, C, ldc)
```

Our wrapper interface

```
void Prod(const ThrustVectorWrapper<T>& Input, ThrustVectorWrapper<T>& Output)
```

Thrust interface

```
thrust::transform( m_deviceVector.begin(), m_deviceVector.end(), in.begin(),
   m_deviceVector.begin(), thrust::plus<T>() );
```

Our wrapper interface

```
void Add( const ThrustVectorWrapper<T>& Input )
```

# 5: Convex optimization using Thrust and Cublas

- Resulting algorithm:

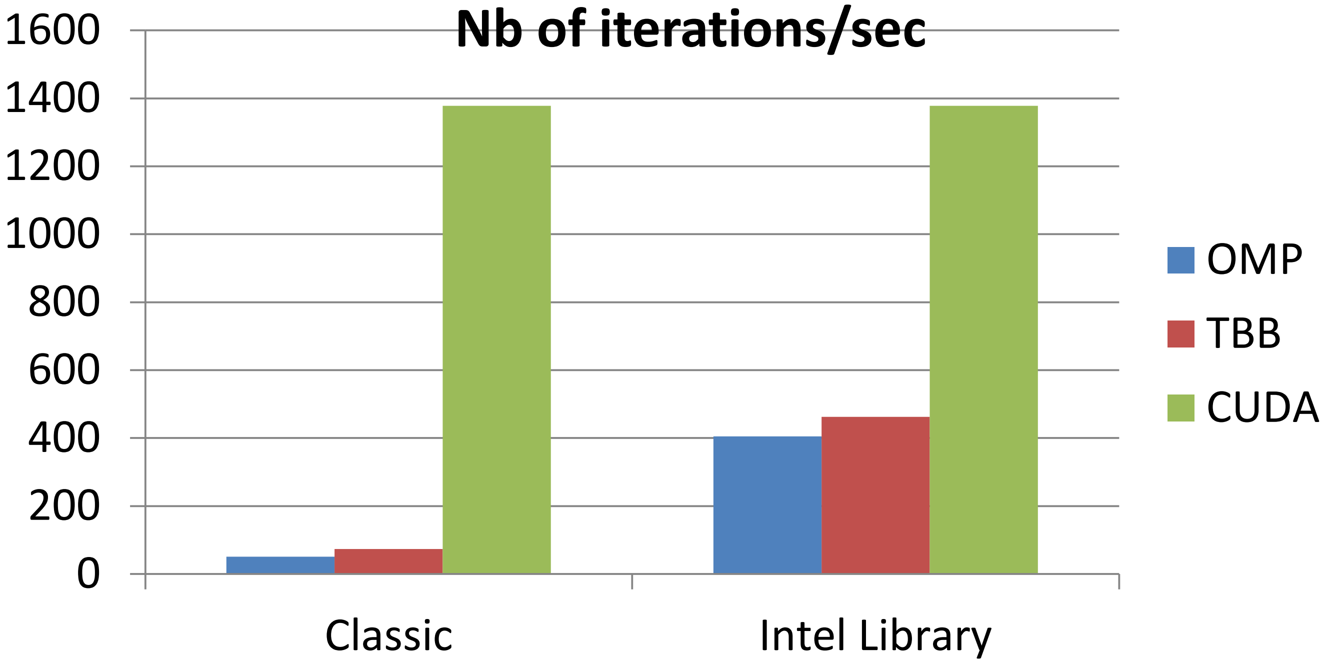
```
while( (niter < nbIteration) && (L2Error > convergenceTol) )
{
    A.Prod( X, Ax );                                   // Ax = A * x
    Ax.Substract( B );                                 // Ax = Ax - b
    A.transProd( Ax, grad );                           // grad = A^t(Ax - B)
    A.Prod( grad, Ag );                                // Ag = A * gradient
    gradstep = grad.GetNorm22()/Ag.GetNorm22();        // Compute gradient step
    X.Saxpy( grad, -gradstep, false );                 // Update solution
    L2Error = Ax.GetNorm22();                          // Compute functional at current step
    niter++;                                           // Ready for next iteration
}
```

Output:

```
./ThrustVectorWrappingCublas
Iteration : 0 over 1000 , L2 error = 653.522
Iteration : 1 over 1000 , L2 error = 164.205
Iteration : 2 over 1000 , L2 error = 82.2171
Iteration : 3 over 1000 , L2 error = 68.4766
Iteration : 4 over 1000 , L2 error = 59.1165
Iteration : 5 over 1000 , L2 error = 52.7413
```

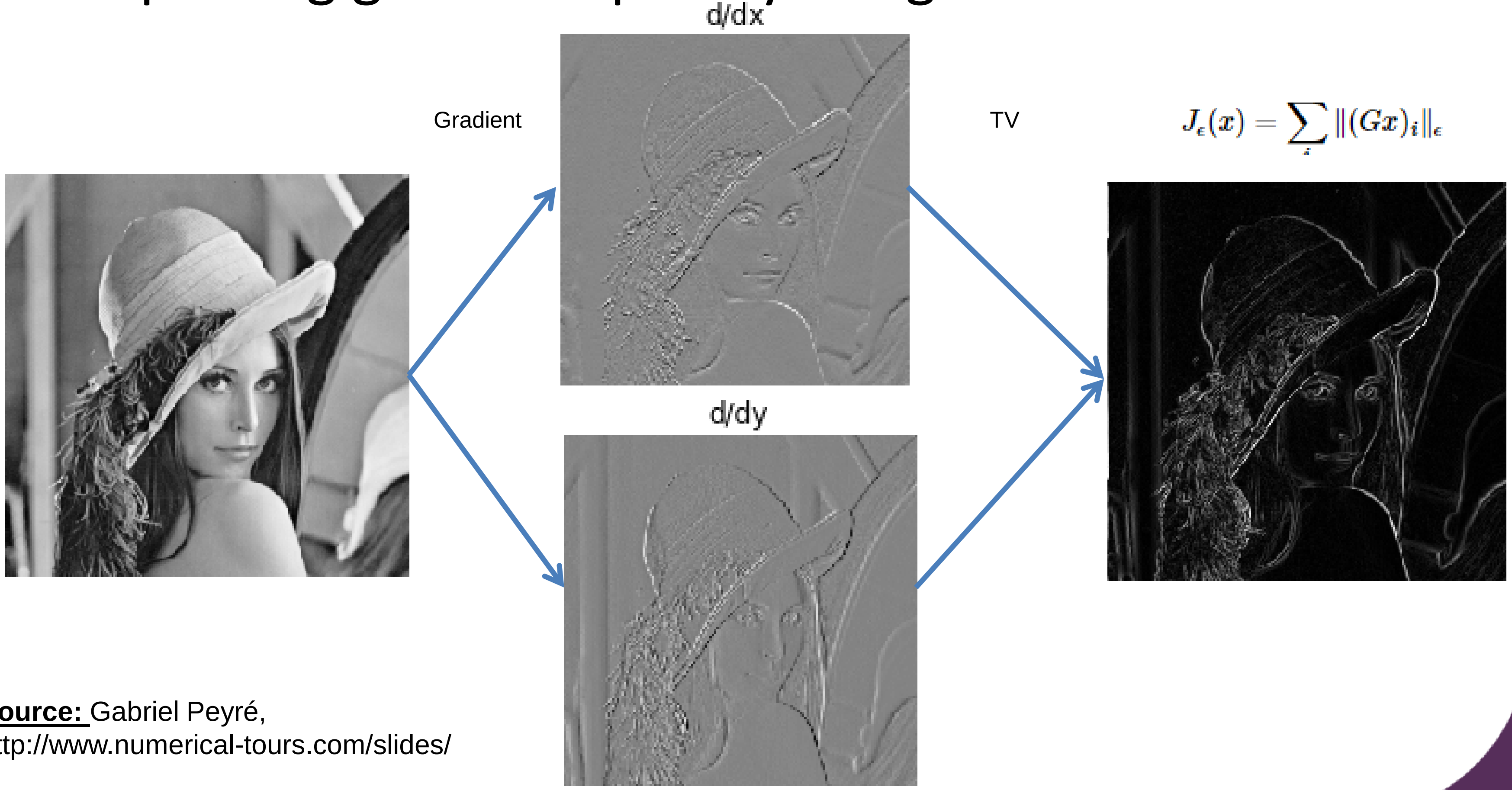
# 4: Convex optimization using Thrust and Cublas : Benchmark

```
//CPU code linked with default gsl_cblas lib and default gcc gomp threading library
//OpenMP backend performed 1000 iterations of gradient descent elements in 19.6776 seconds (50.8192 iterations per seconds )
//TBB backend performed 1000 iterations of gradient descent elements in 13.6715 seconds (73.145 iterations per seconds )

//CPU code Linked with MKL from Intel, and openMP runtime from intel (iomp5 instead of gomp
//OpenMP backend performed 1000 iterations of gradient descent elements in 2.46626 seconds (405.473 iterations per seconds )
//TBB backend performed 1000 iterations of gradient descent elements in 2.163 seconds (462.32 iterations per seconds )

//Cuda Backend
//Cuda backend performed 1000 iterations of gradient descent elements in 0.725926 seconds (1377.55 iterations per seconds
```



# 5: Gradient descent for signal processing

- Exploiting gradient sparsity in signals:



d/dx

d/dy

Gradient

TV

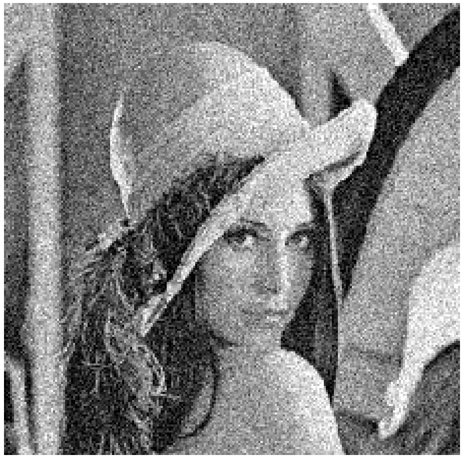
$$J_\epsilon(x) = \sum_i \|(Gx)_i\|_\epsilon$$

**Source:** Gabriel Peyré,
http://www.numerical-tours.com/slides/

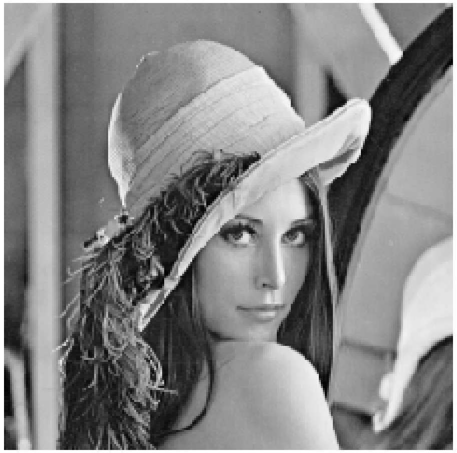
# 5: Gradient descent for signal processing

- Denoising as an optimization problem:

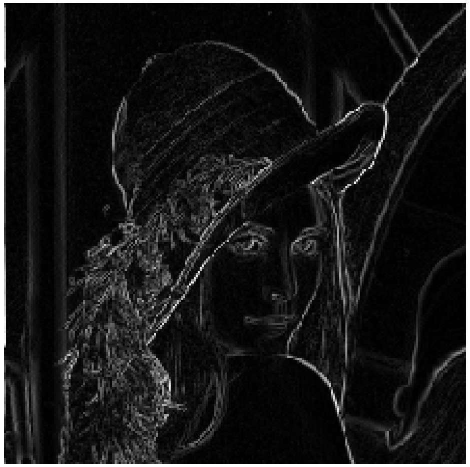
y



x



$J_\epsilon(x) = \sum_i \|(Gx)_i\|_\epsilon$



- Helps crafting our objective function

$$\min_{x \in \mathbb{R}^d} f(x) = \frac{1}{2}\|y - x\|^2 + \lambda J_\epsilon(x)$$

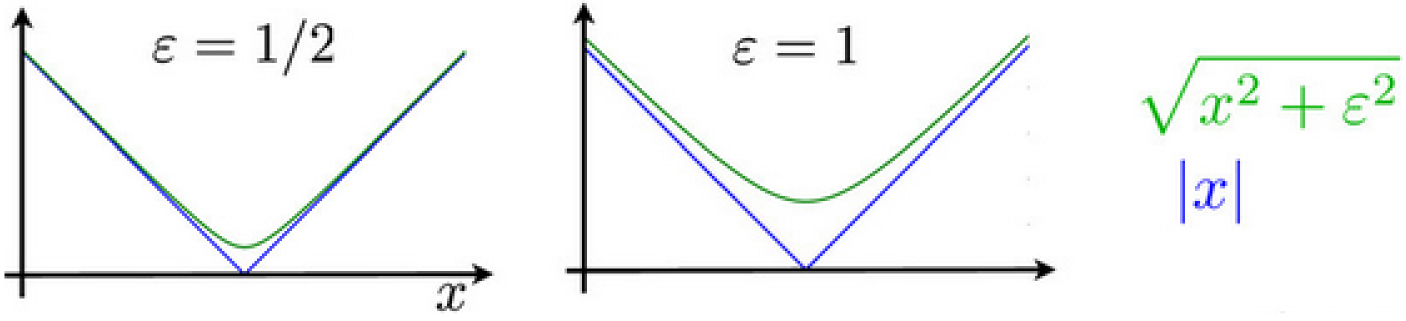
# 5: Gradient descent for signal processing

- Gradient of objective function gives:

$$\nabla f(x) = x - y + \lambda \nabla J_\epsilon(x)$$

- Deriving the Total Variation ?

$$\nabla J_\epsilon(x)_i = -div(u) \quad \text{where} \quad u_i = \frac{(Gx)_i}{||(Gx)_i||_\epsilon}$$



- Ready for the gradient descent ☺

# 5: Gradient descent for signal processing

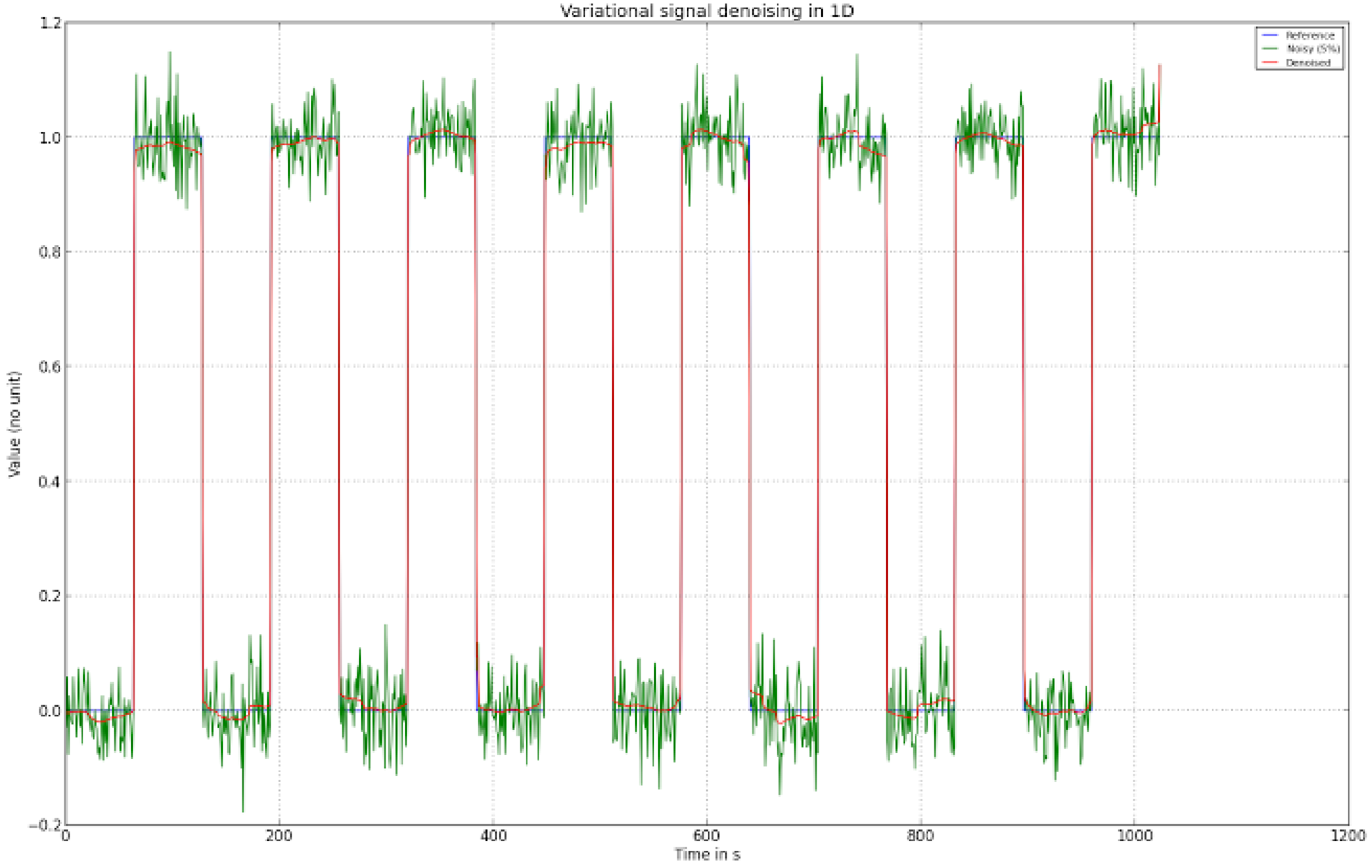
- Algorithm is:

```
while( niter < nbIteration )
{
    grad.Assign( X );                                  // grad = X
    grad.Substract( Y );                               // grad = X – Y
    TvGradientTmp.FiniteForwardDifference( X );        // TvGradient = G(X)
    TvGradientTmp.ApplySmoothedTVGradient(epsilonNorm); // TvGradient = TvGradient / ||TvGradient||e
    TvGradient.FiniteBackwarDifference(TvGradientTmp); // TvGradient = div( TvGradient / ||TvGradient||e )
    grad.Saxpy( TvGradient, -lambda, false );          // grad = X - Y + GradientTV
    X.Saxpy( grad, -stepSize, false );                 // Update solution

    niter++;                                           // Ready for next iteration
}
```

- Helpers from Thrust:

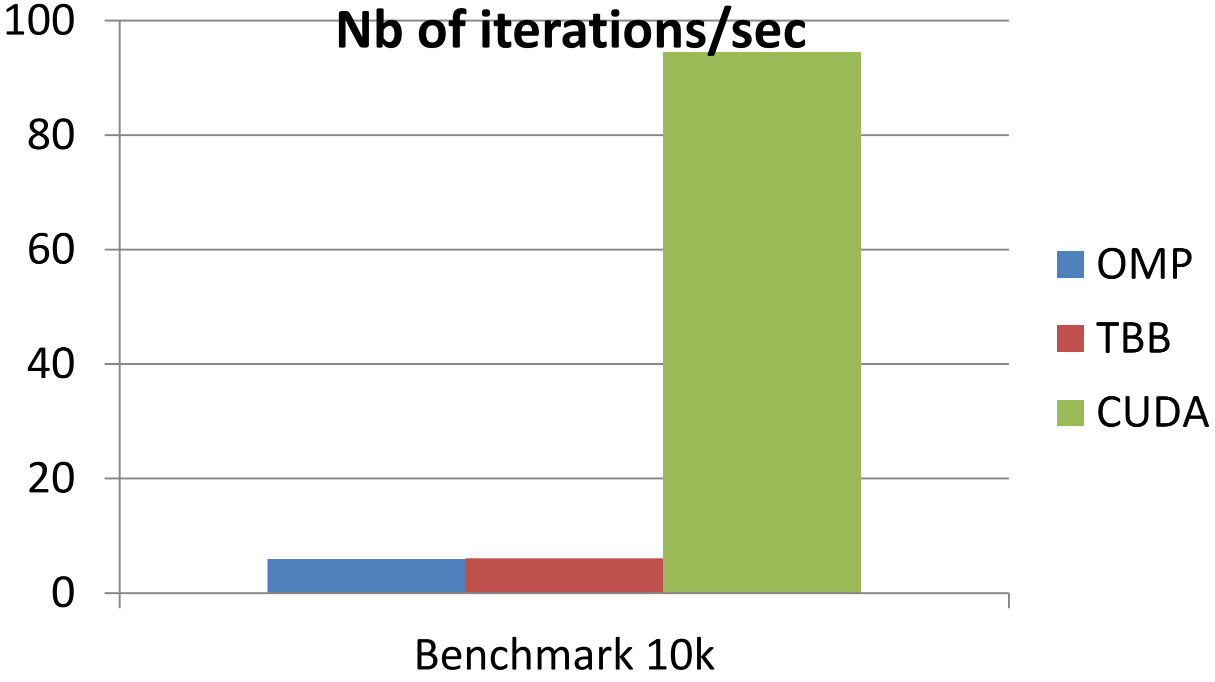
```
thrust::adjacent_difference( in.begin(), in.end(), m_deviceVector.begin());
```

# 5: Gradient descent for signal processing : Results in 1D



# 5: Gradient descent for signal processing : Benchmark

```
//CPU code linked with default gcc gomp threading library
//OpenMP backend performed 10000 iterations of gradient descent over 33’554’432 elements in 1672.89 seconds (5.97768 iterations per seconds )
//TBB backend performed 10000 iterations of gradient descent over 33’554’432 elements in 1648.48 seconds (6.0662 iterations per seconds )
//Cuda Backend
//Cuda backend performed 10000 iterations of gradient descent over 33’554’432 elements in 105.78 seconds (94.5358 iterations per seconds )
```



# Cuda Community and Useful links

- Cuda Official Documentation
  - http://docs.nvidia.com/cuda/cuda-c-programming-guide/
  - http://docs.nvidia.com/cuda/cuda-runtime-api/index.html
- Thrust Official documentation
  - http://thrust.github.io/doc/modules.html
  - https://github.com/thrust/thrust/tree/master/examples
- Nvidia Cuda official forum
  - https://devtalk.nvidia.com/default/board/57/
- Stack Overflow
  - http://stackoverflow.com/search?q=cuda
- Udacity (Best MOOC for Cuda)
  - https://www.udacity.com/wiki/cs344
- Mark Harris (Chief Technologist, GPU Computing at NVIDIA)
  - https://twitter.com/harrism
  - https://twitter.com/GPUComputing
  - https://github.com/harrism
- This tutorial
  - https://github.com/gnthibault/Cuda_Thrust_Introduction
  - https://github.com/gnthibault/daintSkeleton

# Conclusion

- Thrust allows:
  - Saving coding time
  - Clearer code
  - Intensive parameter exploration
  - Portability : CPU/GPU

- Take Home message
  - Think parallel
  - Don’t reinvent the wheel : use libraries
  - Use wrappers

# Example: functional paradigm using thrust

$$\frac{1}{4\sqrt{2}} \times \begin{pmatrix} 1 & 0 & 0 & -1 & 0 & -1 & -1 & 0 \\ 0 & 1 & 1 & 0 & 1 & 0 & 0 & -1 \\ 1 & 0 & 0 & -1 & 0 & 1 & 1 & 0 \\ 0 & 1 & 1 & 0 & -1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 & 0 & -1 & 1 & 0 \\ 0 & 1 & -1 & 0 & 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 & 0 & 1 & -1 & 0 \\ 0 & 1 & -1 & 0 & -1 & 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} v0Begin & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & v0End \\ v1Begin & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & v1End \\ v2Begin & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & v2End \\ v3Begin & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & v3End \\ v4Begin & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & v4End \\ v5Begin & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & v5End \\ v6Begin & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & v6End \\ v7Begin & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & v7End \end{pmatrix}$$

-Rectangular matrix-matrix multiplication

-Non contiguous rows

-Need for “virtual” SoA

-Change backend when needed

# Example: functional paradigm using thrust

```
//Set up the 8 elements zip iterator
auto DTSubbandIteratorBegin(
  thrust::make_zip_iterator( thrust::make_tuple(
    v0Begin, v1Begin, v2Begin, v3Begin,
    v4Begin, v5Begin, v6Begin, v7Begin) ) );

auto DTSubbandIteratorEnd(
  thrust::make_zip_iterator( thrust::make_tuple(
    v0End, v1End, v2End, v3End,
    v4End, v5End, v6End, v7End ) ) );

//Launch
thrust::for_each( DTSubbandIteratorBegin, DTSubbandIteratorEnd,
  OctantToCplx3D<T>( 1.0/(4.0*std::sqrt(2.)) ) );
```

# Example: functional paradigm using thrust

```
//matrix multiplication
template<typename T>
struct OctantToCplx3D {
  OctantToCplx3D( T ratio ) : m_ratio( ratio ) {}

  template <class Tuple>
  __host__ __device__
  void operator()(Tuple in) const {
    T T0 = thrust::get<0>(in);
    T T1 = thrust::get<1>(in);
    T T2 = thrust::get<2>(in);
    T T3 = thrust::get<3>(in);
    T T4 = thrust::get<4>(in);
    T T5 = thrust::get<5>(in);
    T T6 = thrust::get<6>(in);
    T T7 = thrust::get<7>(in);

    //Treating Real Part
    thrust::get<0>(in)  = (T0-T3-T5-T6) * m_ratio;
    thrust::get<2>(in)  = (T0-T3+T5+T6) * m_ratio;
    thrust::get<4>(in)  = (T0+T3-T5+T6) * m_ratio;
    thrust::get<6>(in)  = (T0+T3+T5-T6) * m_ratio;

    //Treating Imaginary Part
    thrust::get<1>(in)  = (T1+T2+T4-T7) * m_ratio;
    thrust::get<3>(in)  = (T1+T2-T4+T7) * m_ratio;
    thrust::get<5>(in)  = (T1-T2+T4+T7) * m_ratio;
    thrust::get<7>(in)  = (T1-T2-T4-T7) * m_ratio;
  }
  const T m_ratio;
};
```

# Example: functional paradigm using thrust

Numerical integration with midpoint rule

-sequential paradigm

```
uint64_t nbChunk=1000000;
double gridRes = 1./nbChunck

double lsum=0;
for(uint64_t i=0;i<nbChunk;i++)
{
  double x = (i+0.5)*gridRes;
  lsum += 4./(1.+x*x);
}
pi = lsum*gridRes;
```

# Example: functional paradigm using thrust

Numerical integration with midpoint rule

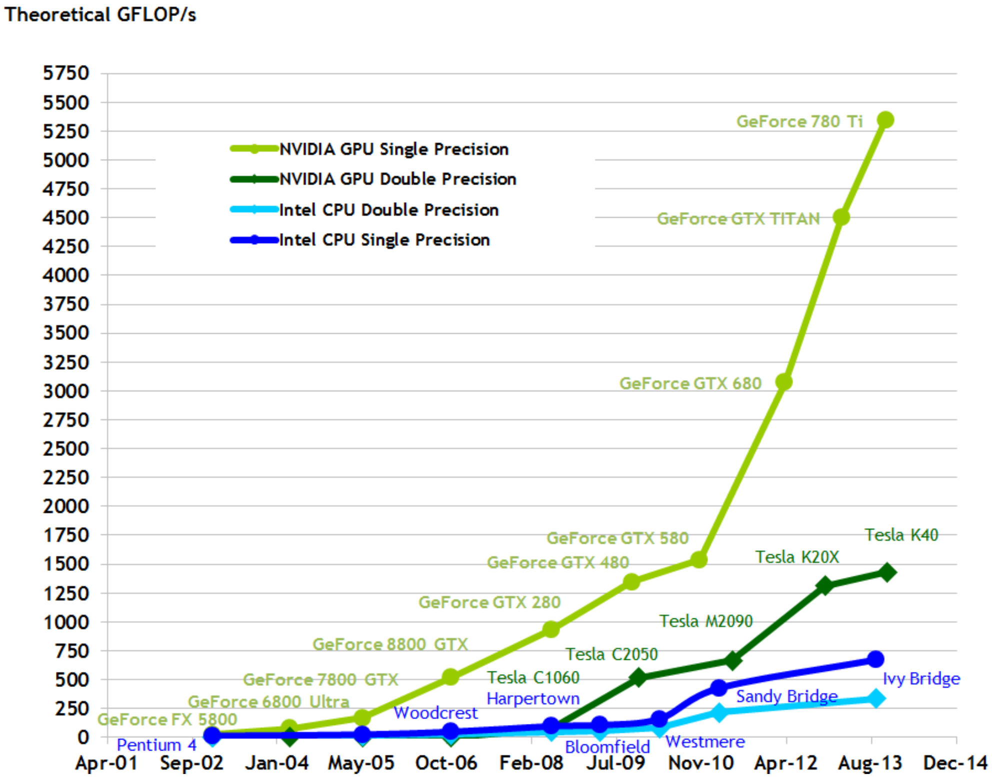
-functional paradigm

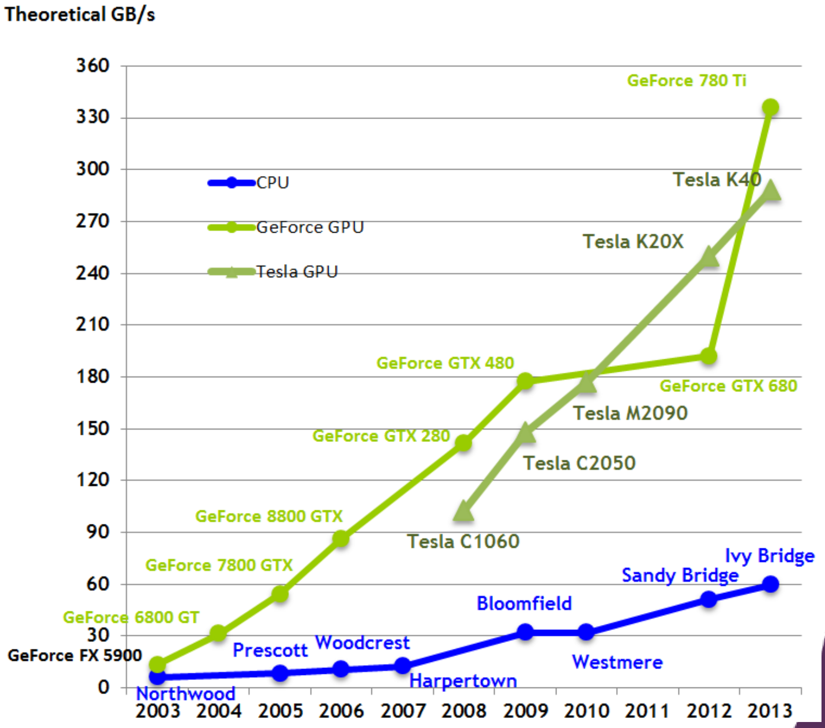
-implicit kernel fusion

```
auto f = [gridRes] __host__ __device__ (uint64_t i)->double {
  double x = (i+0.5)*gridRes;
  return 4./(1.+x*x); };


sum = thrust::reduce(
      thrust::make_transform_iterator(
        thrust::make_counting_iterator<uint64_t>(0), op),
      thrust::make_transform_iterator(
        thrust::make_counting_iterator<uint64_t>(nbChunk), op),
      0.0, thrust::plus<T>() ) * gridRes;
```

# What is Cuda ?

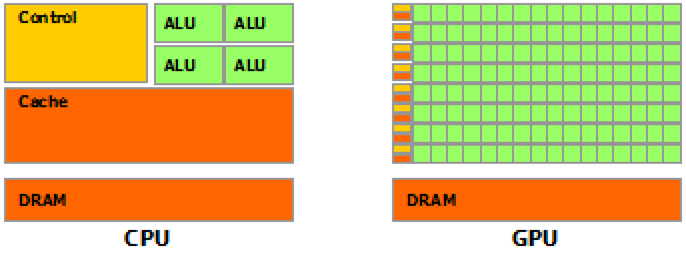
From Graphics Processing to General Purpose Parallel Computing





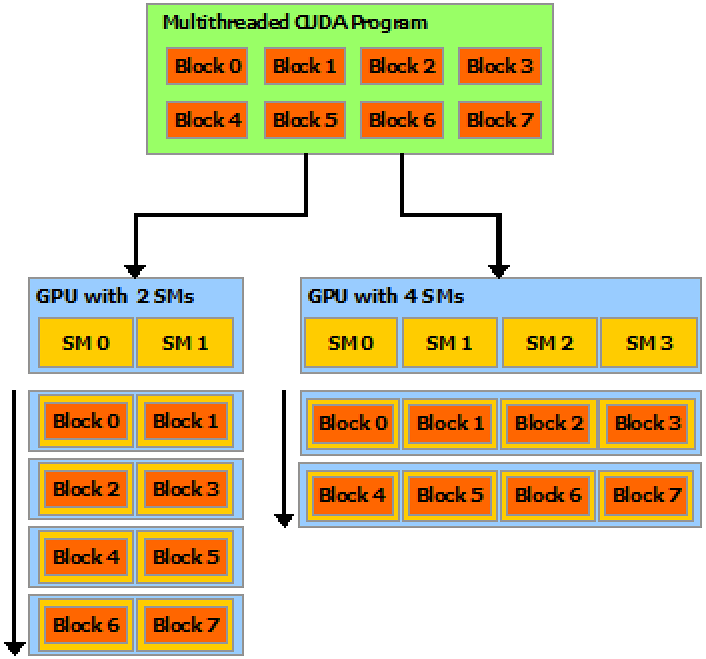
# What is Cuda ?

- A programming model exposing parallelism



*More adapted to control flow management*

*More adapted to massively parallel computing*



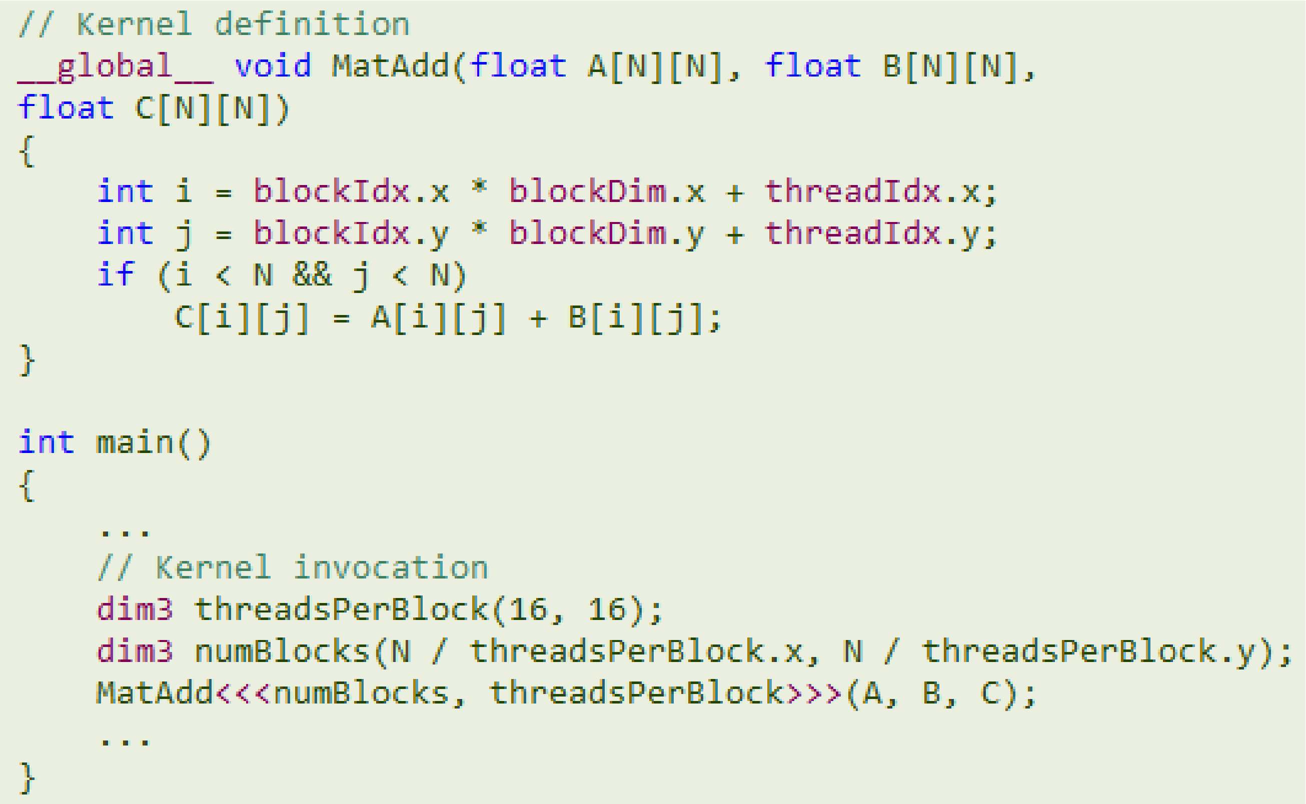
*Handling automatic scalability*

## What is in the cuda SDK ?

- A driver
- An API – with some runtime libraries
- An extension of C/C++
- A compiler (NVCC)
- …. + tools (debugging, profiling…)

# What is Cuda ?

- Exemple of a cuda program



```
// Kernel definition
__global__ void MatAdd(float A[N][N], float B[N][N],
float C[N][N])
{
    int i = blockIdx.x * blockDim.x + threadIdx.x;
    int j = blockIdx.y * blockDim.y + threadIdx.y;
    if (i < N && j < N)
        C[i][j] = A[i][j] + B[i][j];
}

int main()
{
    ...
    // Kernel invocation
    dim3 threadsPerBlock(16, 16);
    dim3 numBlocks(N / threadsPerBlock.x, N / threadsPerBlock.y);
    MatAdd<<<numBlocks, threadsPerBlock>>>(A, B, C);
    ...
}
```

# What is Cuda ?

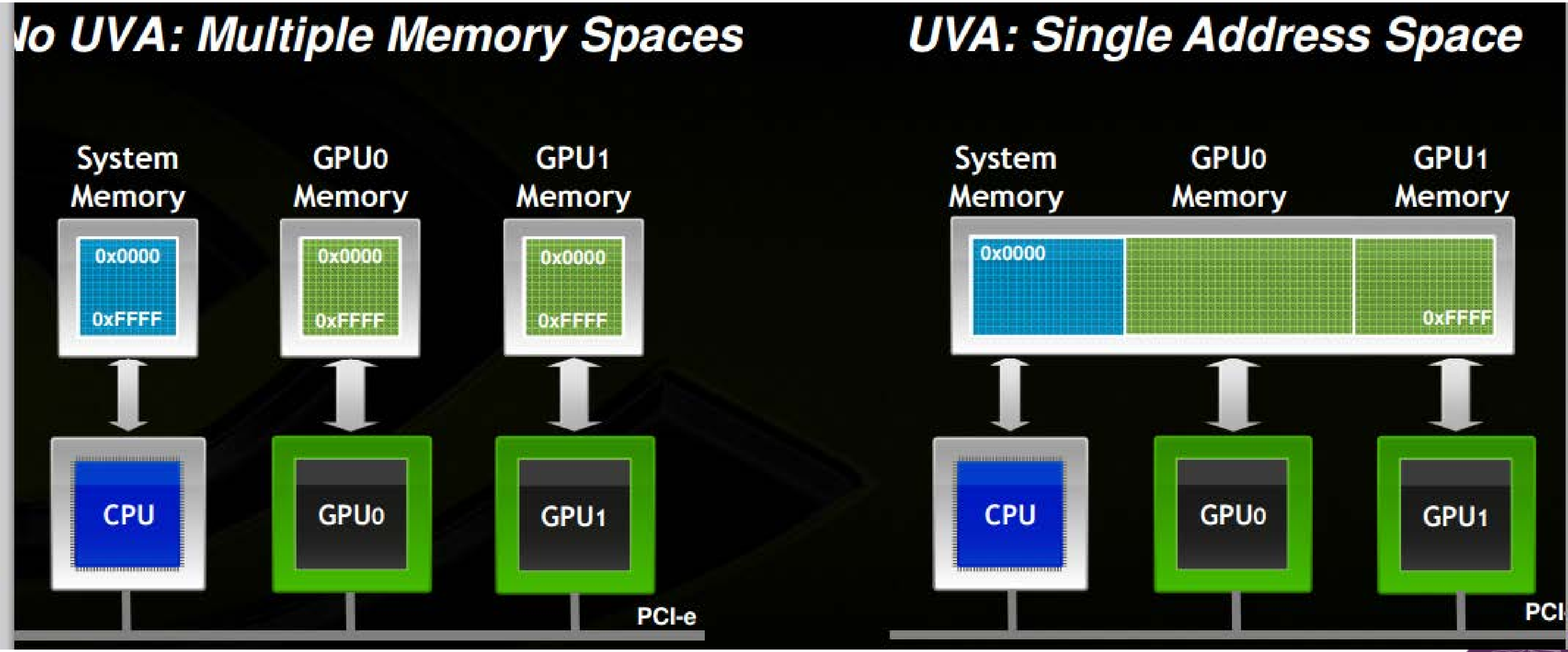
```
#include <stdio.h>
#include <stdlib.h>
#include <math.h>

// CUDA kernel. Each thread takes care of one element of c
__global__ void vecAdd(double *a, double *b, double *c, int n)
{
    // Get our global thread ID
    int id = blockIdx.x*blockDim.x+threadIdx.x;

    // Make sure we do not go out of bounds
    if (id < n)
        c[id] = a[id] + b[id];
}

int main( int argc, char* argv[] )
{
    // Size of vectors
    int n = 100000;

    // Host input vectors
    double *h_a;
    double *h_b;
    //Host output vector
    double *h_c;

    // Device input vectors
    double *d_a;
    double *d_b;
    //Device output vector
    double *d_c;

    // Size, in bytes, of each vector
    size_t bytes = n*sizeof(double);

    // Allocate memory for each vector on host
    h_a = (double*)malloc(bytes);
    h_b = (double*)malloc(bytes);
    h_c = (double*)malloc(bytes);

    // Allocate memory for each vector on GPU
    cudaMalloc(&d_a, bytes);
    cudaMalloc(&d_b, bytes);
    cudaMalloc(&d_c, bytes);

  int i;
    // Initialize vectors on host
    for( i = 0; i < n; i++ ) {
        h_a[i] = sin(i)*sin(i);
        h_b[i] = cos(i)*cos(i);
    }

    // Copy host vectors to device
    cudaMemcpy( d_a, h_a, bytes, cudaMemcpyHostToDevice);
    cudaMemcpy( d_b, h_b, bytes, cudaMemcpyHostToDevice);

    int blockSize, gridSize;

    // Number of threads in each thread block
    blockSize = 1024;

    // Number of thread blocks in grid
    gridSize = (int)ceil((float)n/blockSize);

    // Execute the kernel
    vecAdd<<<gridSize, blockSize>>>(d_a, d_b, d_c, n);

    // Copy array back to host
    cudaMemcpy( h_c, d_c, bytes, cudaMemcpyDeviceToHost );

    // Sum up vector c and print result divided by n, this should equal 1 within error
    double sum = 0;
    for(i=0; i<n; i++)
        sum += h_c[i];
    printf("final result: %f\n", sum/n);

    // Release device memory
    cudaFree(d_a);
    cudaFree(d_b);
    cudaFree(d_c);

    // Release host memory
    free(h_a);
    free(h_b);
    free(h_c);

    return 0;
}
```

# 4: Thrust UVA and Multi GPU

- Why Multi-GPU ?
  - P2P access
  - PCIe 3.0 : effective 8.2 GB/s
  - Huge number of core
  - No need for MPI
  - « Shared memory »

# 4: Thrust UVA and Multi GPU

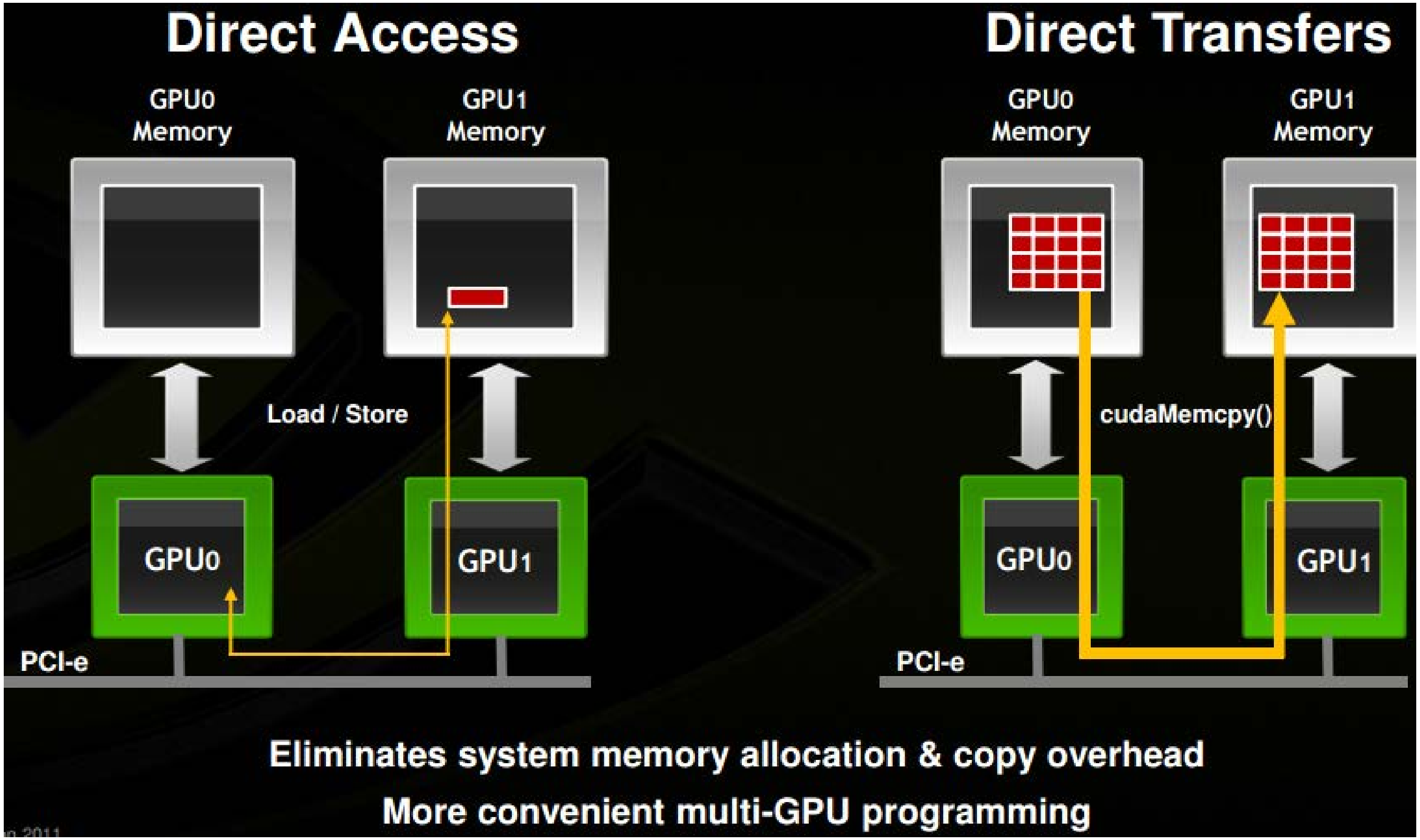
- What is Unified Virtual Addressing ?



Source: http://on-demand.gputechconf.com/gtc-express/2011/presentations/cuda_webinars_GPUDirect_uva.pdf

# 4: Thrust UVA and Multi GPU

- Peer to peer memory access

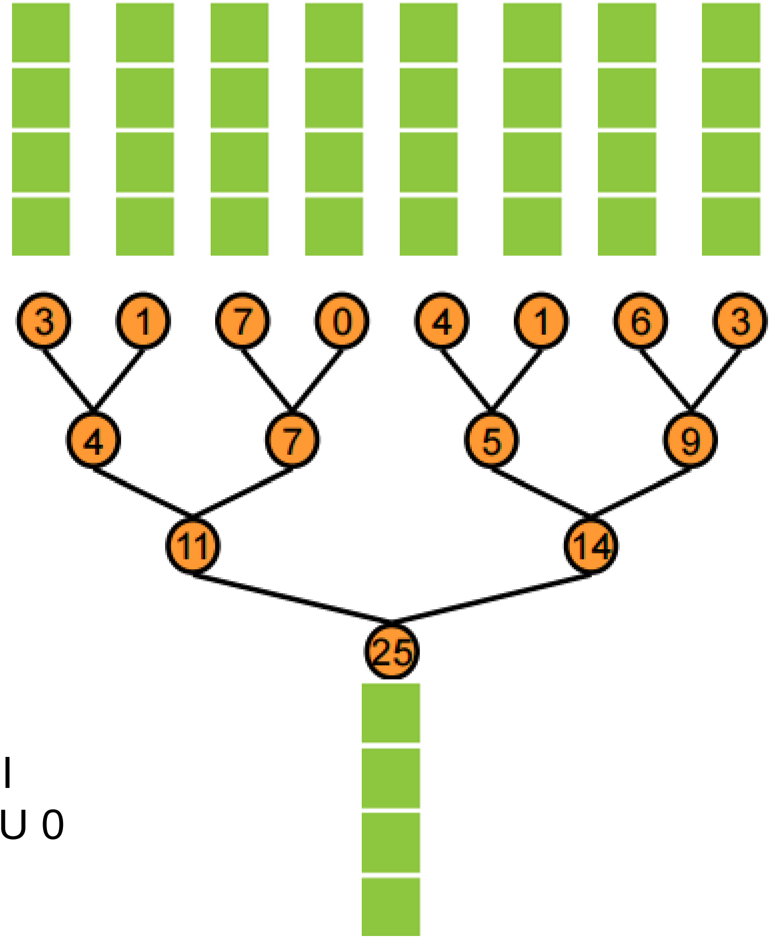


Source: http://on-demand.gputechconf.com/gtc-express/2011/presentations/cuda_webinars_GPUDirect_uva.pdf

# 4: Thrust UVA and Multi GPU

- Peer to peer memory reduction through thrust

**Input**: 8 Gpu, each containing a vector



**Output**: addition of all vectors to one on GPU 0

# 4: Thrust UVA and Multi GPU

- Peer to peer memory reduction through thrust

```
for( int i = 0; i != nb_device; i++ )
{
    //Set device as the current device
    checkCudaErrors( cudaSetDevice( i ) );

    //Initialize memory
    vpDeviceVector.emplace_back(
            std::make_shared<thrust::device_vector<int> >( sizeVector, 111 ) );

    //Enable Peer to Peer access, ie, current device can acces to memory of all superior device IDs
    for( int j = i+1; j < nb_device; j++ )
    {
            checkCudaErrors( cudaDeviceEnablePeerAccess(j, 0) );
    }
}
```

Set current device

Memory is allocated on right device

Grant access to all device having superior IDs

# 4: Thrust UVA and Multi GPU

- Peer to peer memory reduction through thrust

Get upper power of 2

```
// This is where reduction take place
int maxTid = giveReductionSize(nb_device);
while( maxTid != 0 )
{
```

Perform a associative binary operation

```
            //Reduce from high IDs to low ones
            for(int i = 0; i < maxTid; ++i)
            {
                        reduceVector( vpDeviceVector, i, maxTid );
            }
```

Reduction is log2(n) in number of steps

```
            //Half the work is remaining
            maxTid /= 2;
}
```

# 4: Thrust UVA and Multi GPU

- Peer to peer memory reduction through thrust

```
void reduceVector( std::vector<std::shared_ptr<thrust::device_vector<int> > >& v, int tid, int maxTi
{
```

Check bound

```
        if( tid + maxTid <  v.size() )
        {
```

Set current active GPU

```
                //Set current device
                cudaSetDevice( tid );
```

Transparent thrust transformation

```
                // We add vector tid and vector tid+maxTid and put the result into vector tid
                thrust::transform( v.at(tid)->begin(), v.at(tid)->end(), v.at(tid+maxTid)->begin(),
                        v.at(tid)->begin(), thrust::plus<int>() );
        }
}
```