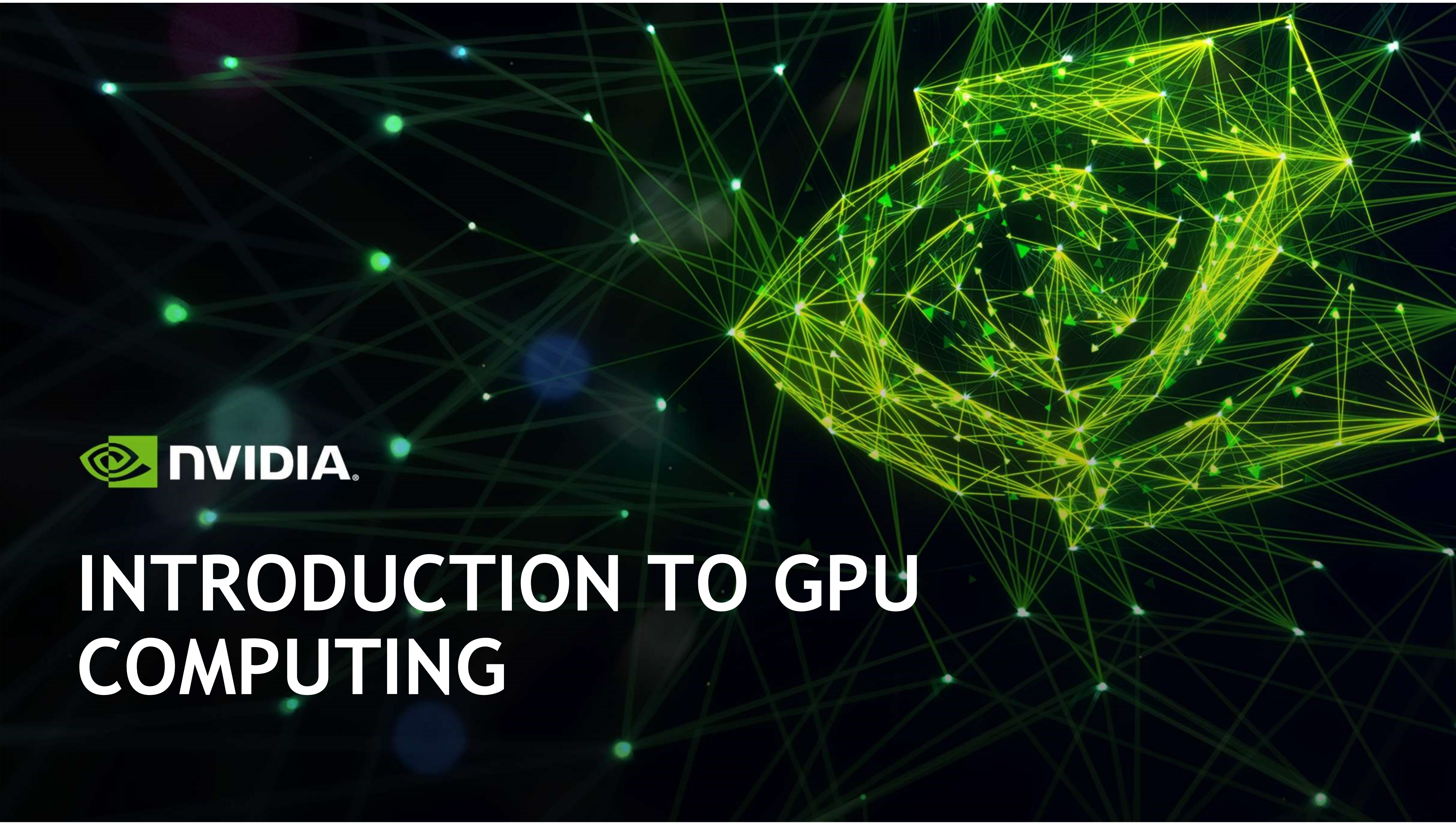
THE CUDA PLATFORM

Paul Graham, Senior Solutions Architect, NVIDIA

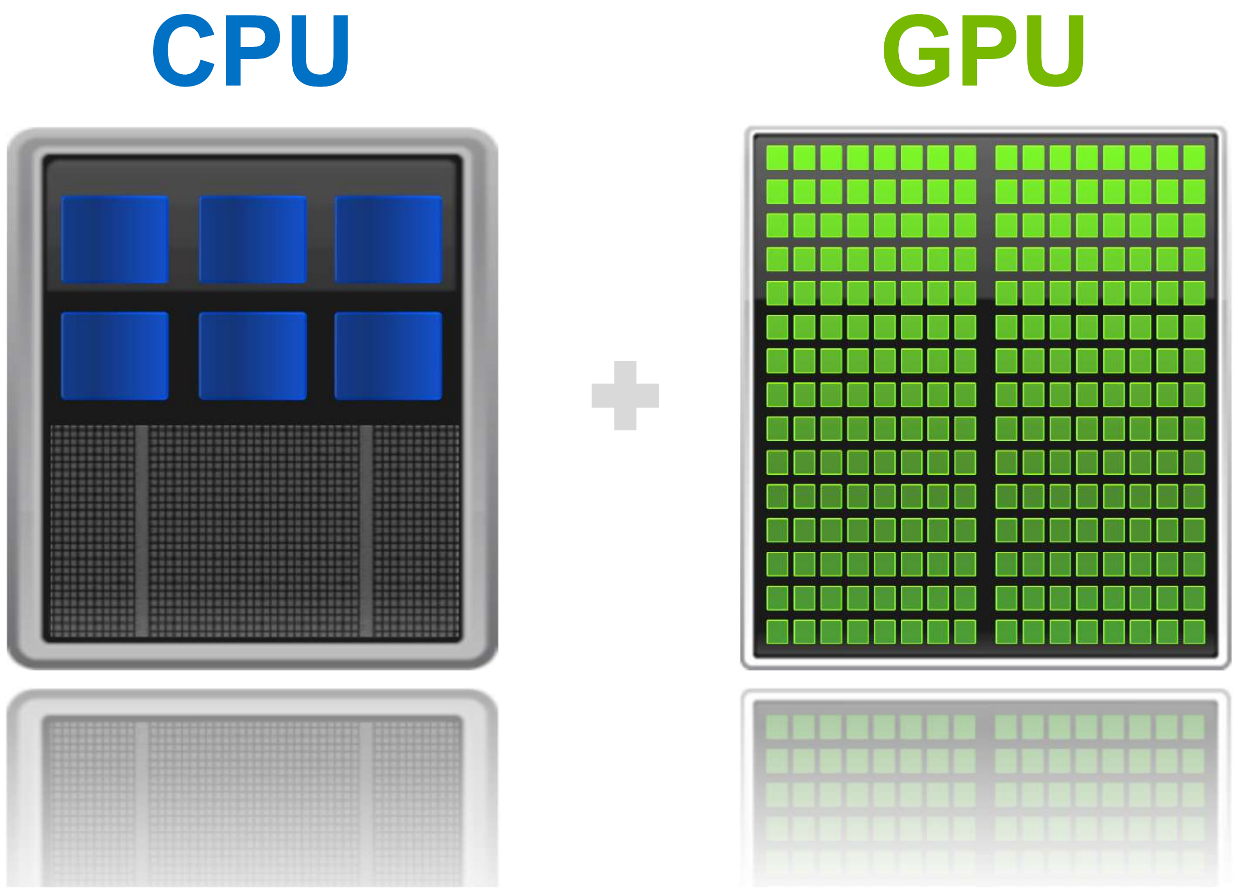
AGENDA

- Introduction to GPU computing
- CUDA platform overview
- Software architecture trends
- CUDA tools and libraries
- Next steps



INTRODUCTION TO GPU COMPUTING

Add GPUs: Accelerate Applications



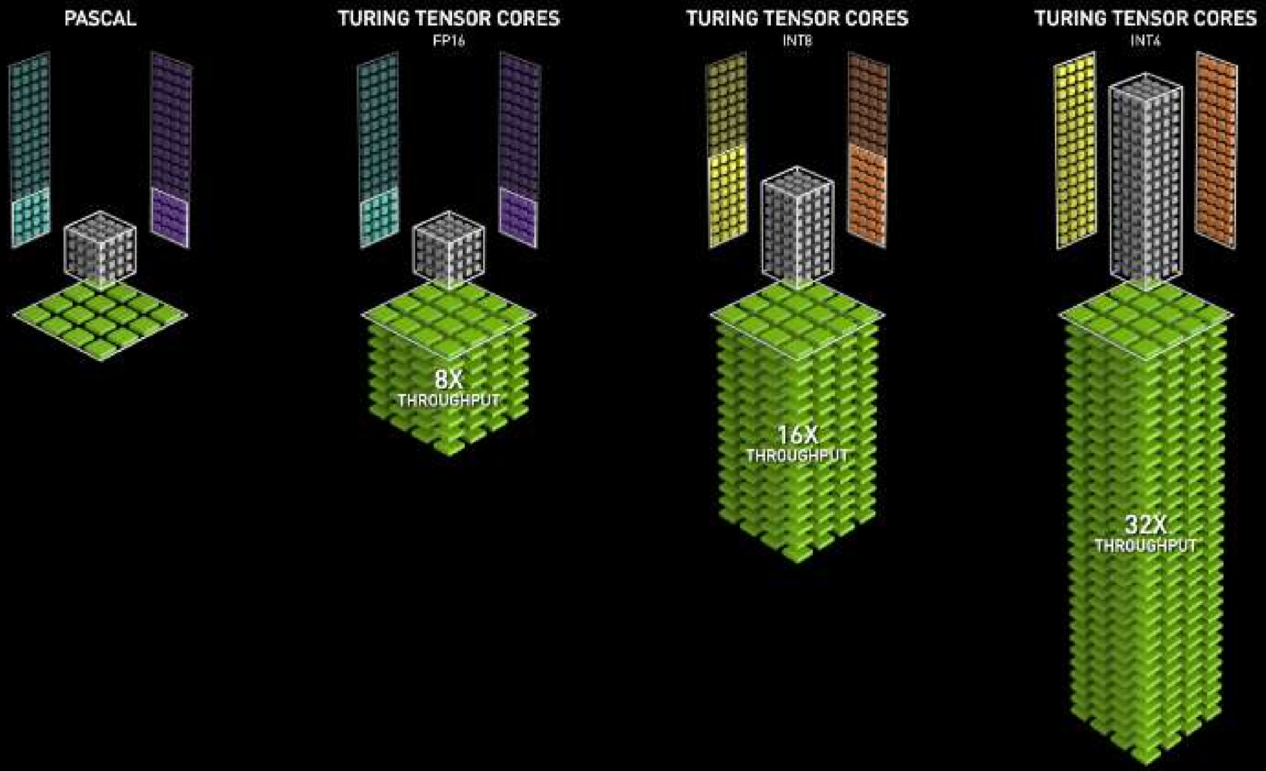
TESLA V100 TENSOR CORE GPU

World's Most Powerful Data Center GPU

5,120 CUDA cores
640 NEW Tensor cores
7.8 FP64 TFLOPS | 15.7 FP32 TFLOPS | 125 Tensor TFLOPS
32 GB HBM2 @ 900GB/s | 300GB/s NVLink

NEW TURING TENSOR CORE

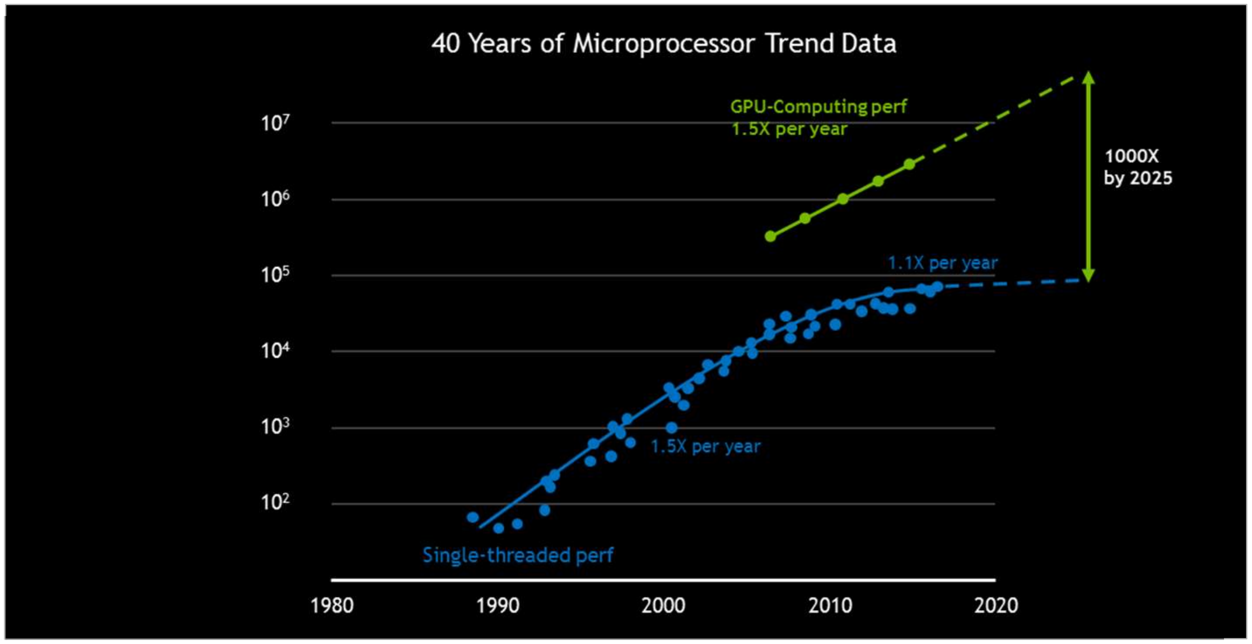
MULTI-PRECISION FOR AI TRAINING AND INFERENCE
65 TFLOPS FP16 | 130 TeraOPS INT8 | 260 TeraOPS INT4



GPU COMPUTING AT THE HEART OF AI

New Advancements Leapfrog Moore's Law

Performance Beyond Moore's Law



Big Bang of Modern AI

55
55
11
11
55
224
11
11
224
55
Stride
of 4
3

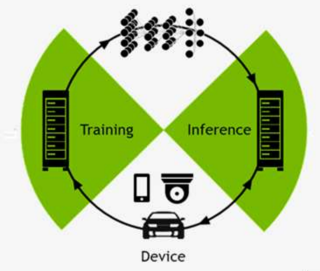
MOST ADOPTED PLATFORM FOR ACCELERATING AI

8 MLPerf 0.6 Training Records

MLPerf

	Benchmark	Record
At Scale Record	Object Detection (Heavy Weight) Mask R-CNN	18.47 Mins
At Scale Record	Translation (Recurrent) GNMT	1.8 Mins
At Scale Record	Reinforcement Learning (MiniGo)	13.57 Mins
Per Accelerator Record	Object Detection (Heavy Weight) Mask R-CNN	25.39 Hrs
Per Accelerator Record	Object Detection (Light Weight) SSD	3.04 Hrs
Per Accelerator Record	Translation (Recurrent) GNMT	2.63 Hrs
Per Accelerator Record	Translation (Non-recurrent)Transformer	2.61 Hrs
Per Accelerator Record	Reinforcement Learning (MiniGo)	3.65 Hrs

RECORD-SETTING PERFORAMNCE



Chainer TensorRT AWS SageMaker

mxnet ONNX GCP ML Engine

PYTORCH python™ AzureML

TensorFlow RAPIDS

END-TO-END SOFTWARE STACK

Alibaba Cloud aliyun.com aws Google Cloud

IBM Cloud Microsoft Azure Tencent Cloud

Cloud Services

Atos CRAY DELL

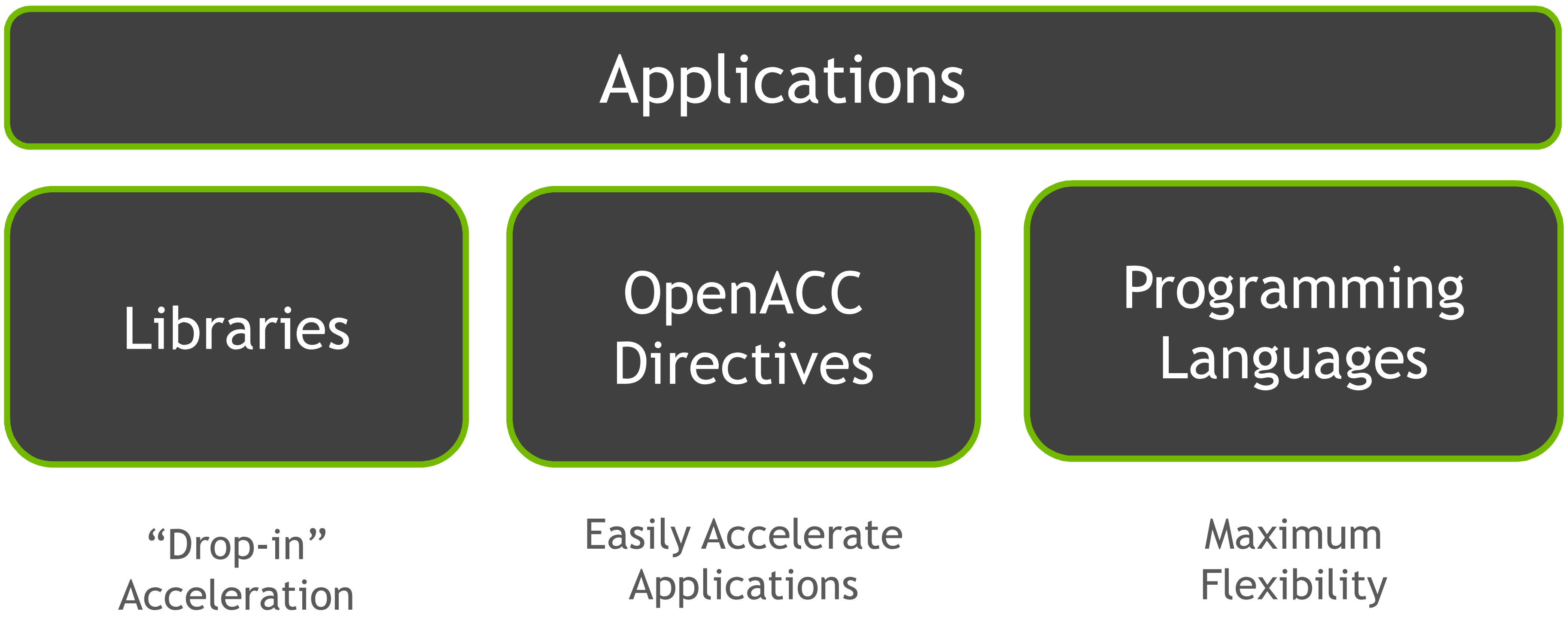
FUJITSU Hewlett Packard Enterprise IBM

inspur Lenovo SUPERMICRO

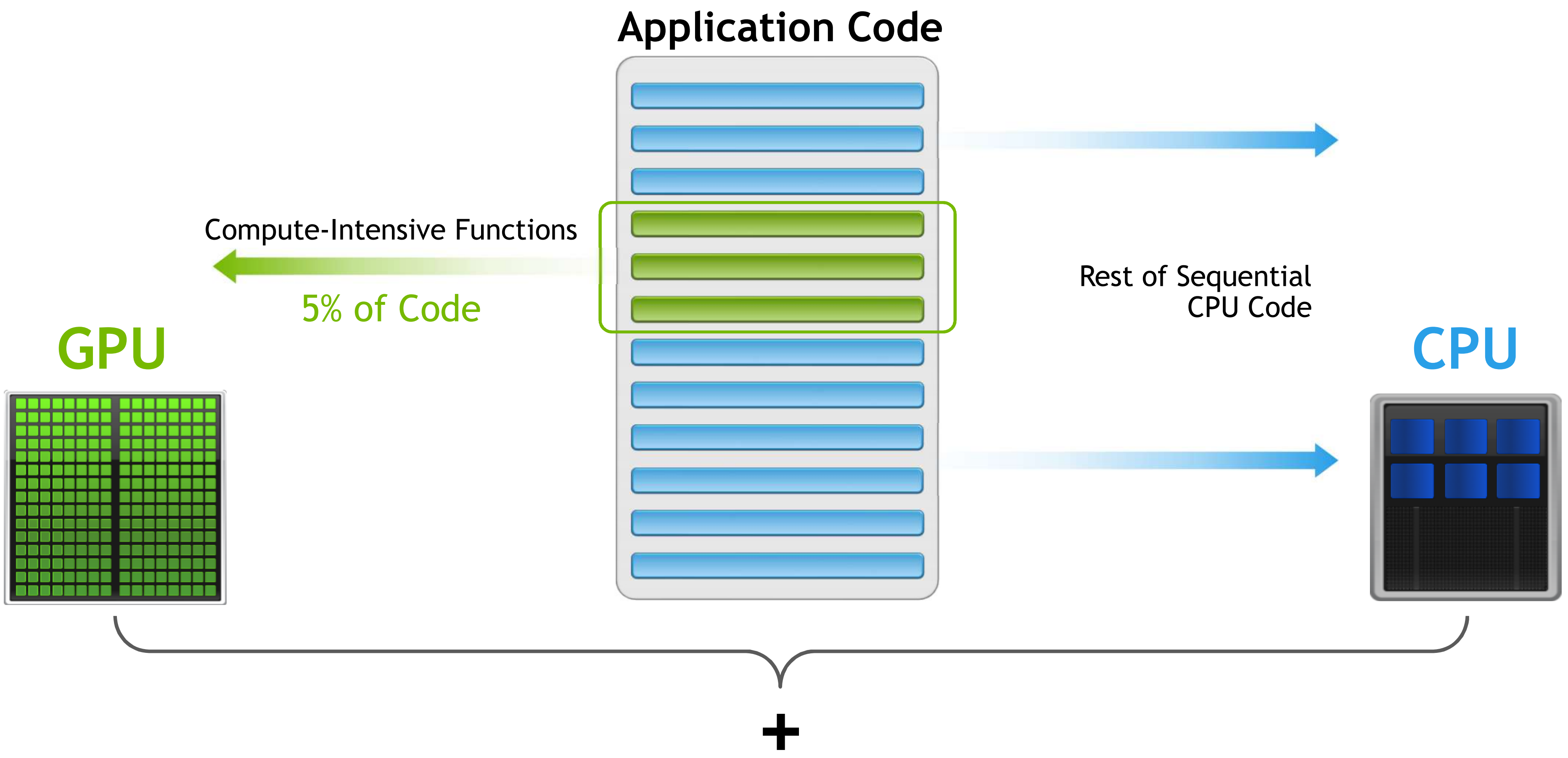
Systems

AVAILABLE EVERYWHERE

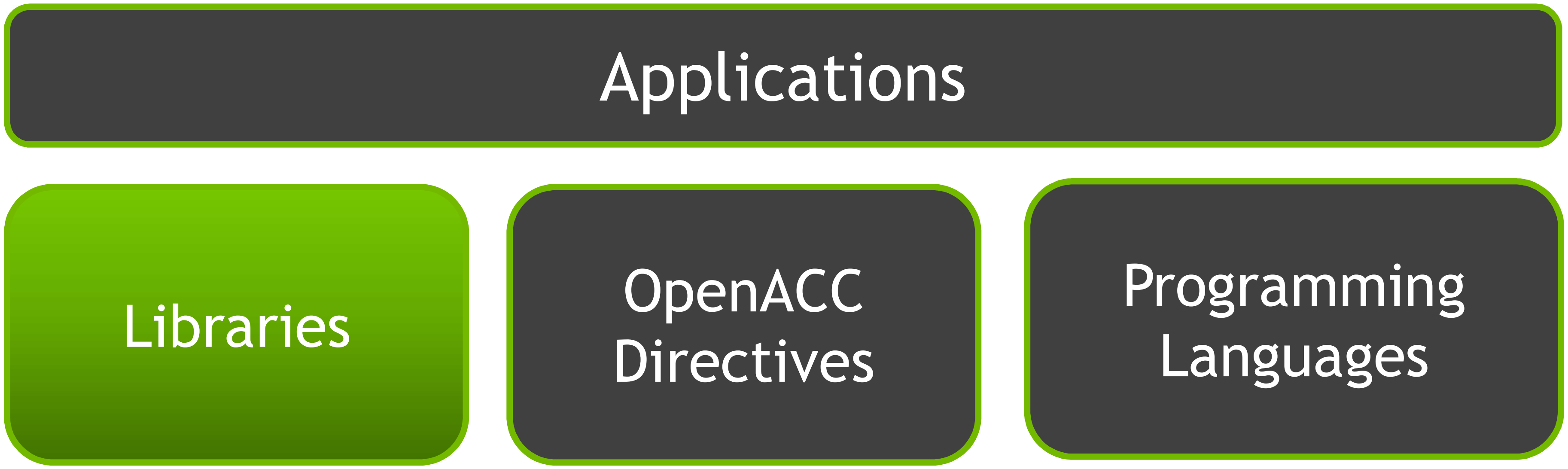
3 WAYS TO ACCELERATE APPLICATIONS



SMALL CHANGES, BIG SPEED-UP



3 WAYS TO ACCELERATE APPLICATIONS



"Drop-in" Acceleration

Easily Accelerate Applications

Maximum Flexibility

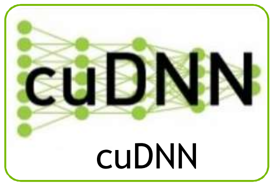
LIBRARIES: EASY, HIGH-QUALITY ACCELERATION

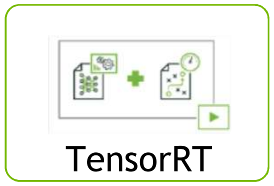
EASE OF USE	Using libraries enables GPU acceleration without in-depth knowledge of GPU programming
“DROP-IN”	Many GPU-accelerated libraries follow standard APIs, thus enabling acceleration with minimal code changes
QUALITY	Libraries offer high-quality implementations of functions encountered in a broad range of applications
PERFORMANCE	NVIDIA libraries are tuned by experts

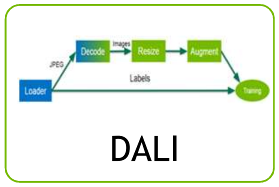
GPU ACCELERATED LIBRARIES

“Drop-in” Acceleration for Your Applications

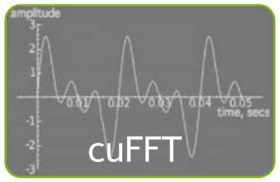
DEEP LEARNING

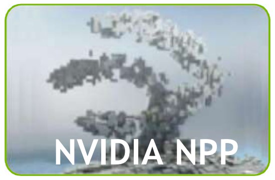




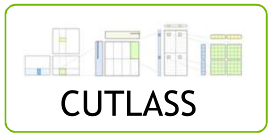


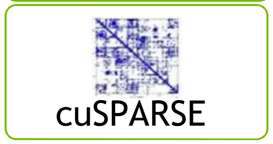
SIGNAL & IMAGE PROCESSING

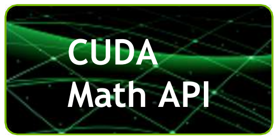




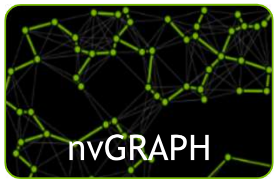
LINEAR ALGEBRA

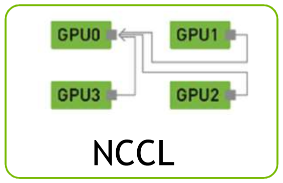






PARALLEL ALGORITHMS





3 STEPS TO CUDA-ACCELERATED APPLICATION

Step 1: Substitute library calls with equivalent CUDA library calls

```
saxpy ( … ) ► cublasSaxpy ( … )
```

Step 2: Manage data locality

- with CUDA: `cudaMalloc(), cudaMemcpy(), etc.`
- with CUBLAS: `cublasAlloc(), cublasSetVector(), etc.`

Step 3: Rebuild and link the CUDA-accelerated library

```
gcc myobj.o –l cublas
```

DROP-IN ACCELERATION (STEP 1)

```
int N = 1 << 20;








// Perform SAXPY on 1M elements: y[]=a*x[]+y[]
saxpy(N, 2.0, d_x, 1, d_y, 1);
```

DROP-IN ACCELERATION (STEP 1)

```
int N = 1 << 20;








// Perform SAXPY on 1M elements: d_y[]=a*d_x[]+d_y[]
cublasSaxpy(N, 2.0, d_x, 1, d_y, 1);
```

Add “cublas” prefix
and use device variables

DROP-IN ACCELERATION (STEP 2)

```
int N = 1 << 20;
cublasInit();








// Perform SAXPY on 1M elements: d_y[]=a*d_x[]+d_y[]
cublasSaxpy(N, 2.0, d_x, 1, d_y, 1);







cublasShutdown();
```

Initialize cuBLAS

Shut down cuBLAS

DROP-IN ACCELERATION (STEP 2)

```
int N = 1 << 20;
cublasInit();
cublasAlloc(N, sizeof(float), (void**)&d_x);
cublasAlloc(N, sizeof(float), (void**)&d_y);




// Perform SAXPY on 1M elements: d_y[]=a*d_x[]+d_y[]
cublasSaxpy(N, 2.0, d_x, 1, d_y, 1);



cublasFree(d_x);
cublasFree(d_y);
cublasShutdown();
```

Allocate device vectors

Deallocate device vectors

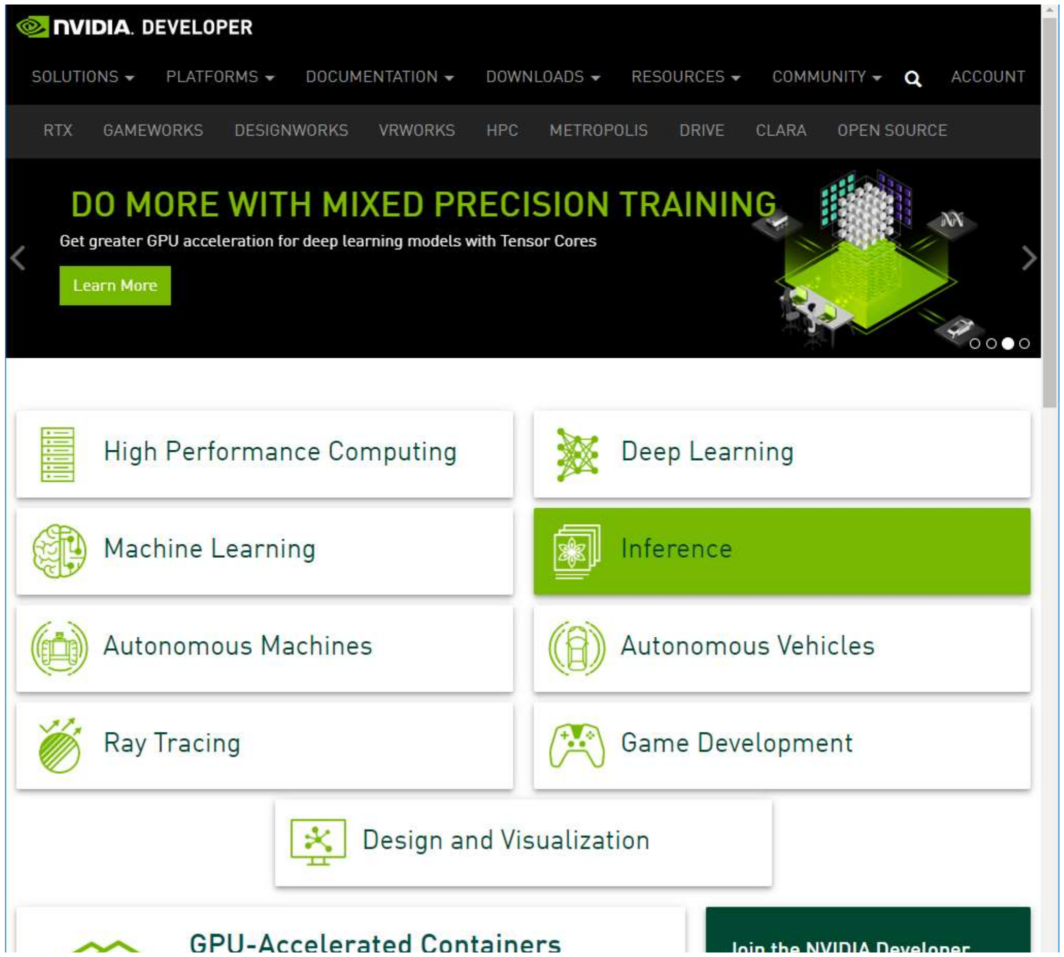
DROP-IN ACCELERATION (STEP 2)

```
int N = 1 << 20;
cublasInit();
cublasAlloc(N, sizeof(float), (void**)&d_x);
cublasAlloc(N, sizeof(float), (void**)&d_y);

cublasSetVector(N, sizeof(x[0]), x, 1, d_x, 1);
cublasSetVector(N, sizeof(y[0]), y, 1, d_y, 1);

// Perform SAXPY on 1M elements: d_y[]=a*d_x[]+d_y[]
cublasSaxpy(N, 2.0, d_x, 1, d_y, 1);

cublasGetVector(N, sizeof(y[0]), d_y, 1, y, 1);

cublasFree(d_x);
cublasFree(d_y);
cublasShutdown();
```

Transfer data to GPU

Read data back GPU

EXPLORE CUDA LIBRARIES


NVIDIA. DEVELOPER

SOLUTIONS PLATFORMS DOCUMENTATION DOWNLOADS RESOURCES COMMUNITY ACCOUNT

RTX GAMEWORKS DESIGNWORKS VRWORKS HPC METROPOLIS DRIVE CLARA OPEN SOURCE

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Get greater GPU acceleration for deep learning models with Tensor Cores

Learn More

High Performance Computing

Deep Learning

Machine Learning

Inference

Autonomous Machines

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Design and Visualization

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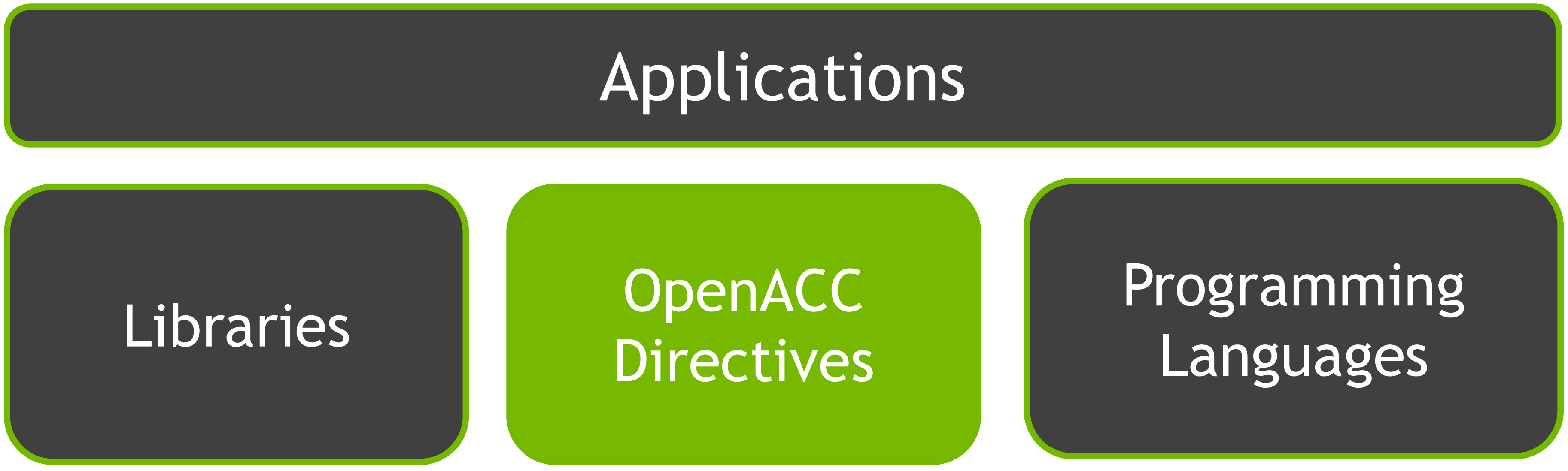
3 WAYS TO ACCELERATE APPLICATIONS



“Drop-in” Acceleration

Easily Accelerate Applications

Maximum Flexibility

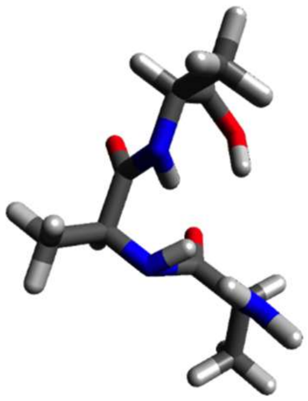
OpenACC is a directives-based programming approach to **parallel computing** designed for **performance** and **portability** on CPUs and GPUs for HPC.

Add Simple Compiler Directive

```
main()
 {
  <serial code>
  #pragma acc kernels
  {
    <parallel code>
  }
}
```

LSDALTON

Large-scale application for calculating high-accuracy molecular energies



"OpenACC makes GPU computing approachable for domain scientists. Initial OpenACC implementation required only minor effort, and more importantly, no modifications of our existing CPU implementation."

Janus Juul Eriksen, PhD Fellow
qLEAP Center for Theoretical Chemistry, Aarhus University

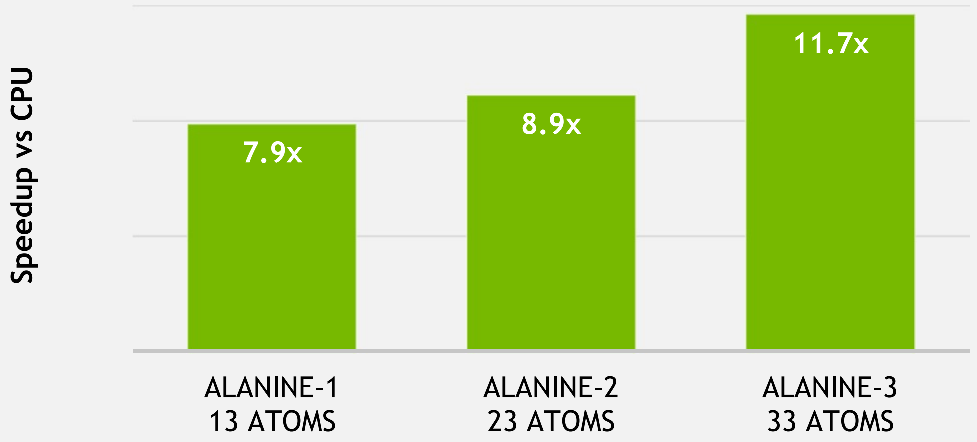
Minimal Effort

Lines of Code Modified	# of Weeks Required	# of Codes to Maintain
<100 Lines	1 Week	1 Source

Big Performance

LS-DALTON CCSD(T) Module

Benchmarked on Titan Supercomputer (AMD CPU vs Tesla K20X)



https://developer.nvidia.com/openacc/success-stories

SINGLE CODE FOR MULTIPLE PLATFORMS

OpenACC - Performance Portable Programming Model for HPC

POWER

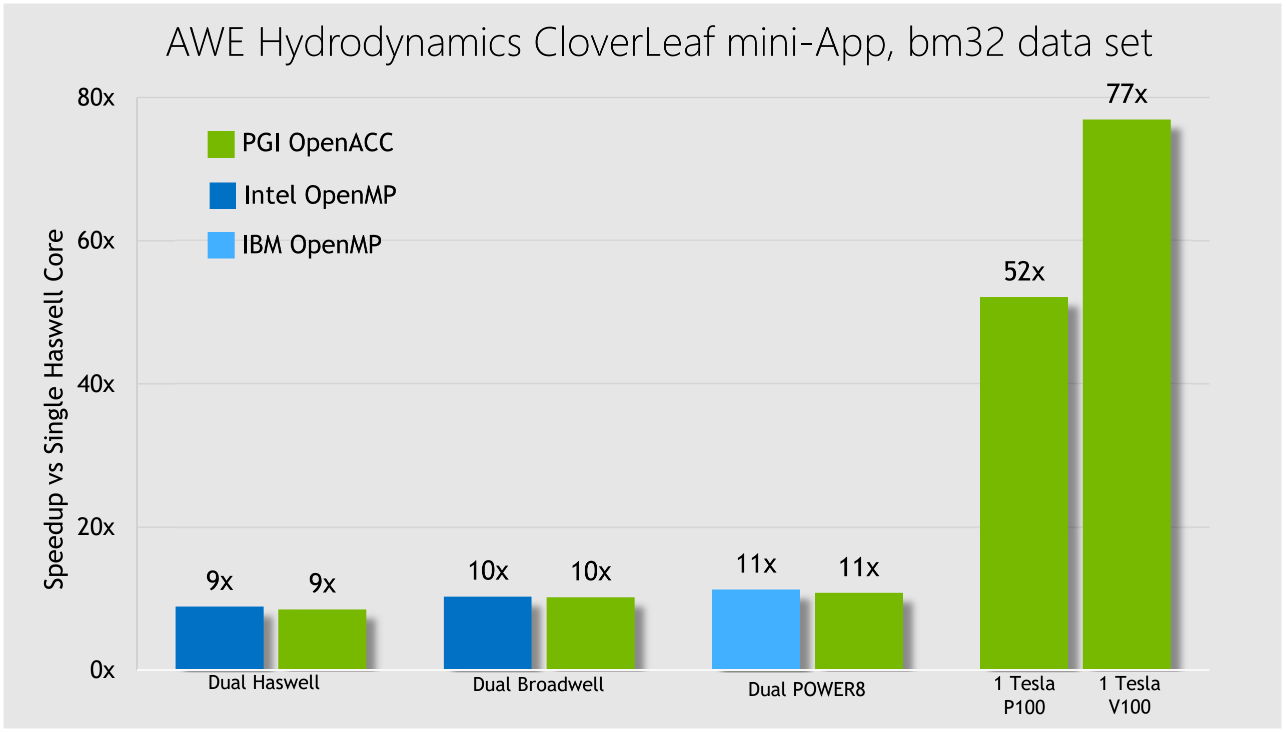
Sunway

x86 CPU

x86 Xeon Phi

NVIDIA GPU

PEZY-SC



Systems: Haswell: 2x16 core Haswell server, four K80s, CentOS 7.2 (perf-hsw10), Broadwell: 2x20 core Broadwell server, eight P100s (dgx1-prd-01), Minsky: POWER8+NVLINK, four P100s, RHEL 7.3 (gsn1).
Compilers: Intel 17.0, IBM XL 13.1.3, PGI 16.10.
Benchmark: CloverLeaf v1.3 downloaded from http://uk-mac.github.io/CloverLeaf the week of November 7 2016; CloverlLeaf_Serial; CloverLeaf_ref (MPI+OpenMP); CloverLeaf_OpenACC (MPI+OpenACC)
Data compiled by PGI November 2016, Volta data collected June 2017

2 BASIC STEPS TO GET STARTED

Step 1:

```
!$acc data copy(util1,util2,util3) copyin(ip,scp2,scp2i)
  !$acc parallel loop
  …
  !$acc end parallel
!$acc end data
```

Step 2:

```
pgf90 -ta=nvidia -Minfo=accel file.f
```

OpenACC DIRECTIVES EXAMPLE

```
!$acc data copy(A,Anew)
 iter=0
 do while ( err > tol .and. iter < iter_max )

  iter = iter +1
  err=0._fp_kind

!$acc kernels
   do j=1,m
    do i=1,n
     Anew(i,j) = .25_fp_kind *( A(i+1,j  ) + A(i-1,j  ) &
                               +A(i  ,j-1) + A(i  ,j+1))
     err = max( err, Anew(i,j)-A(i,j))
    end do
   end do
!$acc end kernels
   IF(mod(iter,100)==0 .or. iter == 1)    print *, iter, err
   A= Anew

 end do
!$acc end data
```

Copy arrays into GPU memory within data region

Parallelize code inside region

Close off parallel region

Close off data region, copy data back

OPENACC FOR EVERYONE

PGI Community Edition Available

	FREE PGI Community Edition	PGI Professional Edition	PGI Enterprise Edition
PROGRAMMING MODELS OpenACC, CUDA Fortran, OpenMP, C/C++/Fortran Compilers and Tools	✓	✓	✓
PLATFORMS X86, OpenPOWER, NVIDIA GPU	✓	✓	✓
UPDATES	1-2 times a year	6-9 times a year	6-9 times a year
SUPPORT	User Forums	PGI Support	PGI Professional Services
LICENSE	Annual	Perpetual	Volume/Site

RESOURCES

FREE Compiler

Success stories

Guides

Tutorials

Videos

Courses

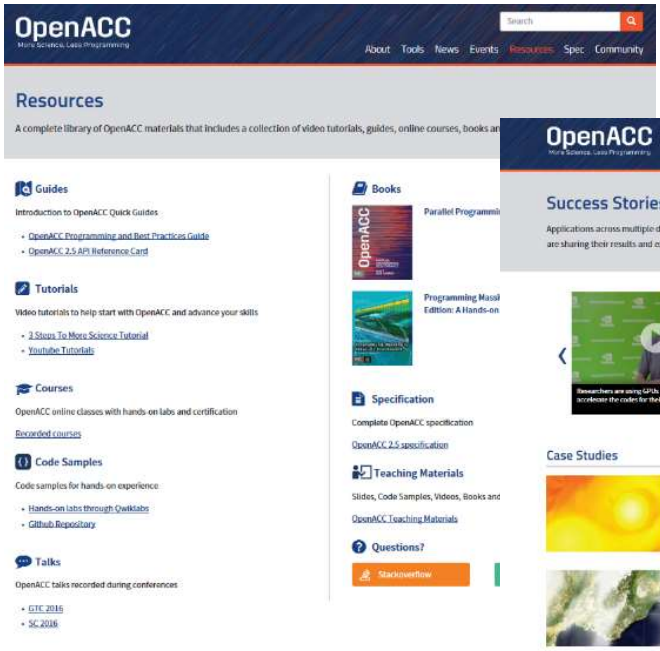
Code Samples

Talks

Books Specification

Teaching Materials

Slack&StackOverflow



OpenACC
More Science, Less Programming

About Tools News Events Resources Spec Community

Resources

A complete library of OpenACC materials that includes a collection of video tutorials, guides, online courses, books an

Guides

Introduction to OpenACC Quick Guides

- OpenACC Programming and Best Practices Guide
- OpenACC 2.5 API Reference Card

Tutorials

Video tutorials to help start with OpenACC and advance your skills

- 3 Steps To More Science Tutorial
- Youtube Tutorials

Courses

OpenACC online classes with hands-on labs and certification

Recorded courses

Code Samples

Code samples for hands-on experience

- Hands-on labs through Qwiklabs
- Github Repository

Talks

OpenACC talks recorded during conferences

- GTC 2016
- SC 2016

Books

Parallel Programmi

Programming Massi
Edition: A Hands-on

Specification

Complete OpenACC specification

OpenACC 2.5 specification

Teaching Materials

Slides, Code Samples, Videos, Books and

OpenACC Teaching Materials

Questions?

Stackoverflow

OpenACC
More Science, Less Programming

About Tools News Events Resources Spec Community

Success Stories

Applications across multiple domains have been accelerated with OpenACC. Scientists and researchers who have been working on these applications are sharing their results and experiences.

Researchers are using GPUs and OpenACC to accelerate the codes for their data-driven simulations

Learn how OpenACC can simplify parallel programming and deliver high performance results

Anne Severt shares how she is using OpenACC to simulate smoke propagation in underground metro stations.

> Watch more OpenACC Videos on YouTube

Case Studies

ASTROPHYSICS
MAESTRO and CASTRO achieved over 4x speedup
Researchers can now run more scientifically interesting simulations by modeling larger nuclear reaction networks in 3D using OpenACC.

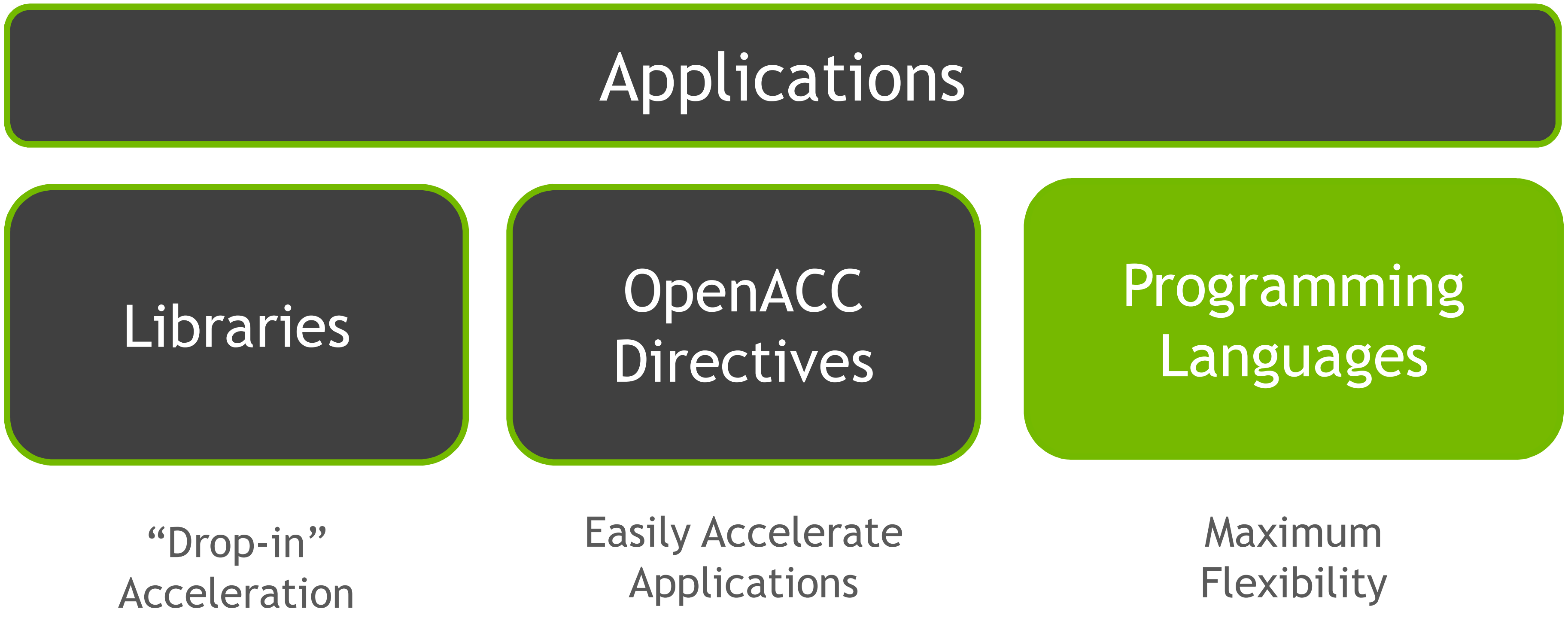
COMPUTATIONAL HYDRODYNAMICS
Performance portability for Cloverleaf
An OpenACC GPU version of CloverLeaf with no code changes runs on a CPU with performance equal to an optimized OpenMP version.

CLIMATE WEATHER OCEAN
More simulations with higher accuracy using COSMO
OpenACC made it efficient to develop for GPU-based hardware while retaining a single source for almost all the COSMO physics code.

COMPUTATIONAL FLUID DYNAMICS
4x speedup for a fully implicit 3D CFD solver
Using OpenACC, the team ported the implicit solver on the GPGPU. OpenACC enabled the translation of mathematical formulations with minimal coding.

Success stories: https://www.openacc.org/success-stories
Resources: https://www.openacc.org/resources
Free Compiler: https://www.pgroup.com/products/community.htm

3 WAYS TO ACCELERATE APPLICATIONS



GPU PROGRAMMING LANGUAGES

Numerical analytics ▷	MATLAB, Mathematica, LabVIEW
Fortran ▷	CUDA Fortran, OpenACC
C, C++ ▷	CUDA C++, OpenACC
Python ▷	CUDA Python, PyCUDA
C# ▷	Altimesh Hybridizer, Alea GPU

CUDA C

```
void saxpy_serial(int n,
                  float a,
                  float *x,
                  float *y)
{

  for (int i = 0; i < n; ++i)
    y[i] = a*x[i] + y[i];
}

// Perform SAXPY on 1M elements
saxpy_serial(4096*256, 2.0, x, y);
```

```
__global__
void saxpy_parallel(int n,
                    float a,
                    float *x,
                    float *y)
{
  int i = blockIdx.x*blockDim.x +
          threadIdx.x;
  if (i < n) y[i] = a*x[i] + y[i];
}

// Perform SAXPY on 1M elements
saxpy_parallel<<<4096,256>>>(n,2.0,x,y);
```

http://developer.nvidia.com/cuda-toolkit

CUDA C++: DEVELOP GENERIC PARALLEL CODE

CUDA C++ features enable sophisticated and flexible applications and middleware

- Class hierarchies
- __device__ methods
- Templates
- Operator overloading
- Functors (function objects)
- Device-side new/delete
- More…

http://developer.nvidia.com/cuda-toolkit

```
template <typename T>
struct Functor {
  __device__ Functor(_a) : a(_a) {}
  __device__ T operator(T x) { return a*x; }
  T a;
}

template <typename T, typename Oper>
__global__ void kernel(T *output, int n) {
  Oper op(3.7);
  output = new T[n]; // dynamic allocation
  int i = blockIdx.x*blockDim.x + threadIdx.x;
  if (i < n)
    output[i] = op(i);  // apply functor
}
```

RAPID PARALLEL C++ DEVELOPMENT

- Resembles C++ STL
- High-level interface
  - Enhances developer productivity
  - Enables performance portability between GPUs and multicore CPUs
- Flexible
  - CUDA, OpenMP, and TBB backends
  - Extensible and customizable
  - Integrates with existing software
- Open source

```
// generate 32M random numbers on host
thrust::host_vector<int> h_vec(32 << 20);
thrust::generate(h_vec.begin(),
                 h_vec.end(),
                 rand);
// transfer data to device (GPU)
thrust::device_vector<int> d_vec = h_vec;
// sort data on device
thrust::sort(d_vec.begin(), d_vec.end());
// transfer data back to host
thrust::copy(d_vec.begin(),
             d_vec.end(),
             h_vec.begin());
```

http://developer.nvidia.com/thrust or http://thrust.googlecode.com

CUDA FORTRAN

- Program GPU using Fortran
  - Key language for HPC
- Simple language extensions
  - Kernel functions
  - Thread / block IDs
  - Device & data management
  - Parallel loop directives
- Familiar syntax
  - Use allocate, deallocate
  - Copy CPU-to-GPU with assignment (=)

http://developer.nvidia.com/cuda-fortran

```
module mymodule contains
  attributes(global) subroutine saxpy(n,a,x,y)
    real :: x(:), y(:), a,
    integer n, i
    attributes(value) :: a, n
    i = threadIdx%x+(blockIdx%x-1)*blockDim%x
    if (i<=n) y(i) = a*x(i) + y(i);
  end subroutine saxpy
end module mymodule

program main
  use cudafor; use mymodule
  real, device :: x_d(2**20), y_d(2**20)
  x_d = 1.0; y_d = 2.0
  call saxpy<<<4096,256>>>(2**20,3.0,x_d,y_d,)
  y = y_d
  write(*,*) 'max error=', maxval(abs(y-5.0))
end program main
```

GET STARTED TODAY

These languages are supported on all CUDA-capable GPUs.

You might already have a CUDA-capable GPU in your laptop or desktop PC!

CUDA C/C++
http://developer.nvidia.com/cuda-toolkit

CUDA Python
http://developer.nvidia.com/how-to-cuda-python

Thrust C++ Template Library
http://developer.nvidia.com/thrust

CUDA Fortran
http://developer.nvidia.com/cuda-toolkit

MATLAB
http://www.mathworks.com/discovery/matlab-gpu.html

Mathematica
http://www.wolfram.com/mathematica/new
-in-8/cuda-and-opencl-support/

SIX WAYS TO SAXPY

Programming Languages for GPU Computing

SINGLE PRECISION ALPHA X PLUS Y (SAXPY)

Part of Basic Linear Algebra Subroutines (BLAS) Library

$$z = \alpha x + y$$

x, y, z : vector

α : scalar

GPU SAXPY in multiple languages and libraries

A menagerie* of possibilities, not a tutorial

*technically, a *program chrestomathy*: http://en.wikipedia.org/wiki/Chrestomathy

1

OpenACC COMPILER DIRECTIVES

Parallel C Code

```
void saxpy(int n,
           float a,
           float *x,
           float *y)
{
#pragma acc kernels
  for (int i = 0; i < n; ++i)
    y[i] = a*x[i] + y[i];
}


...
// Perform SAXPY on 1M elements
saxpy(1<<20, 2.0, x, y);
...
```

Parallel Fortran Code

```
subroutine saxpy(n, a, x, y)
  real :: x(:), y(:), a
  integer :: n, i
!$acc kernels
  do i=1,n
    y(i) = a*x(i)+y(i)
  enddo
!$acc end kernels
end subroutine saxpy



...
! Perform SAXPY on 1M elements
call saxpy(2**20, 2.0, x_d, y_d)
...
```

http://developer.nvidia.com/openacc or http://openacc.org

2

cuBLAS LIBRARY

Serial BLAS Code

```
int N = 1<<20;



...

// Use your choice of blas library

// Perform SAXPY on 1M elements
blas_saxpy(N, 2.0, x, 1, y, 1);
```

Parallel cuBLAS Code

```
int N = 1<<20;
cublasInit();
cublasAlloc(N, sizeof(float), (void**)&d_x);
cublasAlloc(N, sizeof(float), (void**)&d_y);
cublasSetVector(N, sizeof(x[0]), x, 1, d_x, 1);
cublasSetVector(N, sizeof(y[0]), y, 1, d_y, 1);

// Perform SAXPY on 1M elements
cublasSaxpy(N, 2.0, d_x, 1, d_y, 1);

cublasGetVector(N, sizeof(y[0]), d_y, 1, y, 1);

cublasShutdown();
```

You can also call cuBLAS from Fortran, C++, Python, and other languages

http://developer.nvidia.com/cublas

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CUDA C

```
void saxpy(int n, float a,
           float *x, float *y)
{
  for (int i = 0; i < n; ++i)
    y[i] = a*x[i] + y[i];
}

int N = 1<<20;



// Perform SAXPY on 1M elements
saxpy(N, 2.0, x, y);
```

```
__global__
void saxpy(int n, float a,
           float *x, float *y)
{
  int i = blockIdx.x*blockDim.x + threadIdx.x;
  if (i < n) y[i] = a*x[i] + y[i];
}

int N = 1<<20;
cudaMemcpy(d_x, x, N, cudaMemcpyHostToDevice);
cudaMemcpy(d_y, y, N, cudaMemcpyHostToDevice);

// Perform SAXPY on 1M elements
saxpy<<<4096,256>>>(N, 2.0, d_x, d_y);

cudaMemcpy(y, d_y, N, cudaMemcpyDeviceToHost);
```

http://developer.nvidia.com/cuda-toolkit

THRUST C++ TEMPLATE LIBRARY

Serial C++ Code
with STL and Boost

```
int N = 1<<20;
std::vector<float> x(N), y(N);

...




// Perform SAXPY on 1M elements
std::transform(x.begin(), x.end(),
               y.begin(), y.end(),
               2.0f * _1 + _2);
```

www.boost.org/libs/lambda

Parallel C++ Code

```
int N = 1<<20;
thrust::host_vector<float> x(N), y(N);

...

thrust::device_vector<float> d_x = x;
thrust::device_vector<float> d_y = y;

// Perform SAXPY on 1M elements
thrust::transform(d_x.begin(), d_x.end(),
                  d_y.begin(),d_y.begin(),
                  2.0f * _1 + _2)
```

http://thrust.github.com

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CUDA FORTRAN

Standard Fortran

```
module mymodule contains
  subroutine saxpy(n, a, x, y)
    real :: x(:), y(:), a
    integer :: n, i
    do i=1,n
      y(i) = a*x(i)+y(i)
    enddo
  end subroutine saxpy
end module mymodule

program main
  use mymodule
  real :: x(2**20), y(2**20)
  x = 1.0, y = 2.0
  ! Perform SAXPY on 1M elements
  call saxpy(2**20, 2.0, x, y)
end program main
```

Parallel Fortran

```
module mymodule contains
  attributes(global) subroutine saxpy(n, a, x, y)
    real :: x(:), y(:), a
    integer :: n, i
    attributes(value) :: a, n
    i = threadIdx%x+(blockIdx%x-1)*blockDim%x
    if (i<=n) y(i) = a*x(i)+y(i)
  end subroutine saxpy
end module mymodule

program main
  use cudafor; use mymodule
  real, device :: x_d(2**20), y_d(2**20)
  x_d = 1.0, y_d = 2.0
  ! Perform SAXPY on 1M elements
  call saxpy<<<4096,256>>>(2**20, 2.0, x_d, y_d)
end program main
```

http://developer.nvidia.com/cuda-fortran

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PYTHON

Standard Python

```
import numpy as np


def saxpy(a, x, y):
  return [a * xi + yi
          for xi, yi in zip(x, y)]

x = np.arange(2**20, dtype=np.float32)
y = np.arange(2**20, dtype=np.float32)



cpu_result = saxpy(2.0, x, y)
```

http://numpy.scipy.org

Numba Parallel Python

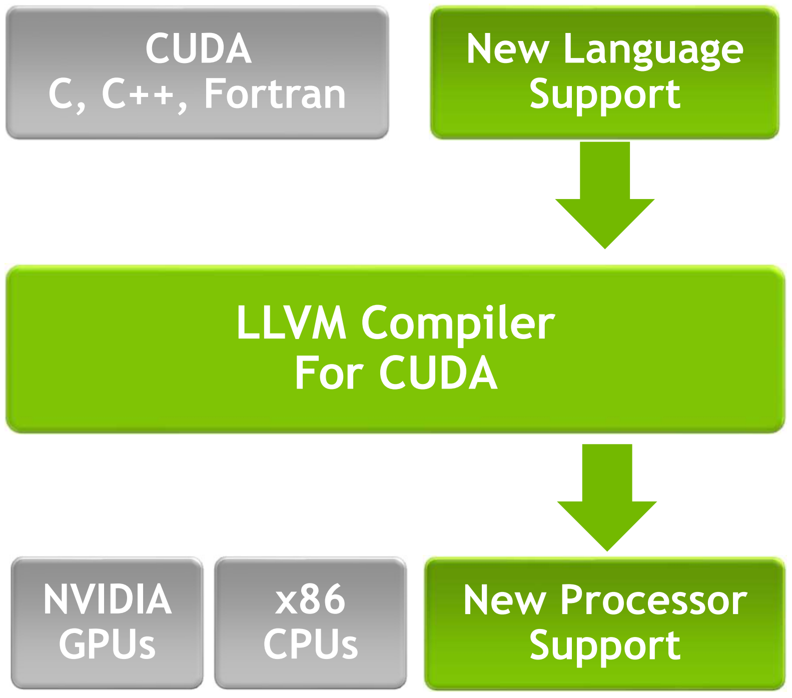
```
import numpy as np
from numba import vectorize

@vectorize(['float32(float32, float32,
float32)'], target='cuda')
def saxpy(a, x, y):
  return a * x + y

N = 1048576

# Initialize arrays
A = np.ones(N, dtype=np.float32)
B = np.ones(A.shape, dtype=A.dtype)
C = np.empty_like(A, dtype=A.dtype)

# Add arrays onGPU
C = saxpy(2.0, X, Y)
```

https://numba.pydata.org

ENABLING ENDLESS WAYS TO SAXPY

- Build front-ends for Java, Python, R, DSLs
- Target other processors like ARM, FPGA, GPUs, x86

CUDA Compiler Contributed to Open Source LLVM



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