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- Stay tuned with NVIDIA webinars: http://www.nvidia.com/object/cuda_signup_alerts.html
- Refer to OpenCV Yahoo! Groups
- OpenCV.org: http://answers.opencv.org/questions/

USING NVIDIA GPUS WITH OPENCV FOR ACCELERATED HIGH PERFORMANCE COMPUTER VISION

Anatoly Baksheev, Itseez Inc.

Outline

- Getting and building OpenCV with CUDA
- GPU module API
- Overlapping operations
- Using GPU module with your CUDA code
- Questions & Answers

What is OpenCV

- Popular Computer Vision library
  - 6M downloads
  - BSD license
  - 1000s CV functions for solving various problems
  - Various optimizations
    - **OpenCV GPU** module contains **CUDA** acceleration
    - Intel TBB, IPP, SSE, ARM NEON & GLSL (Tegra)

Getting OpenCV

- Source Forge
  - http://sourceforge.net/projects/opencvlibrary/
    - Source package for each release (**recommended**)
    - OpenCV GPU Demo Pack binaries
    - (Precompiled OpenCV binaries with CUDA support)

- Git repository (modified daily)
  - **`git clone`** `git://github.com/Itseez/opencv.git` (GitHub mirror)
  - **`git checkout -b 2.4 origin/2.4`**

- Two branches
  - **2.4** with binary compatibility between releases (tagged as 2.4.x)
  - **master** (coming OpenCV 3.0 with algorithms API changes, **separate webinar**)

NVIDIA.

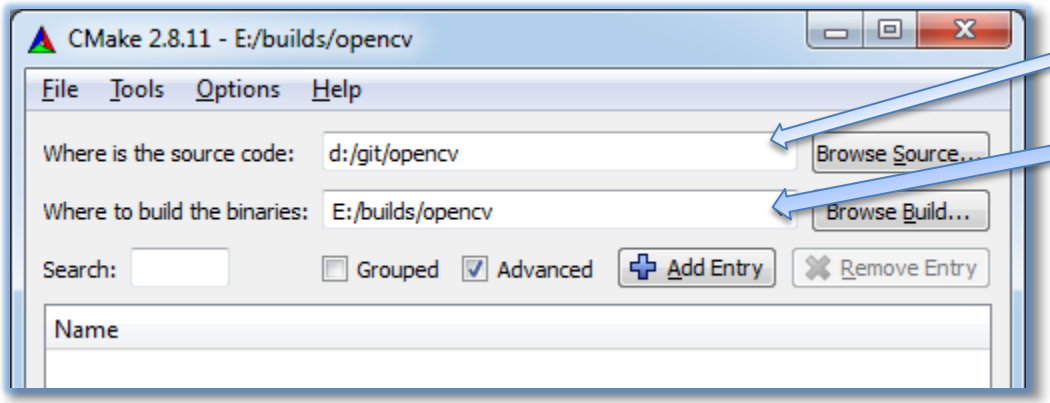
itseez

Building OpenCV with GPU support

- Prerequisites
  - OpenCV sources
  - CMake 2.8.8 (http://www.cmake.org/)
    - CMake-GUI
  - NVIDIA Display Driver
  - NVIDIA GPU Computing Toolkit (for CUDA)
    - https://developer.nvidia.com/cuda-toolkit
  - And your favorite IDE/compiler

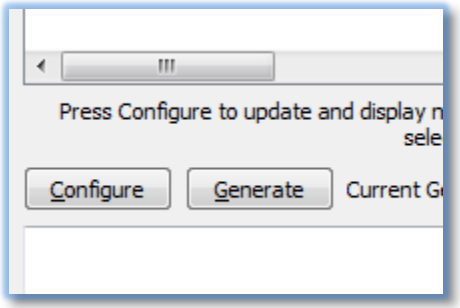
Building OpenCV with GPU support

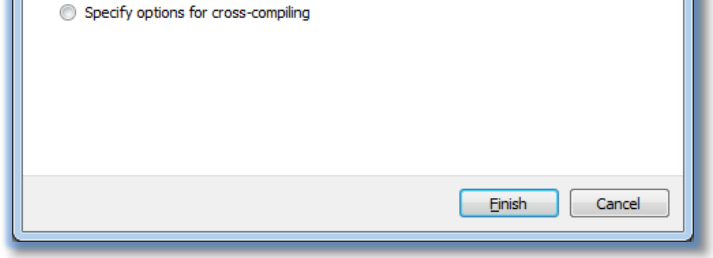
- Build steps (screenshots for Windows 7, Visual Studio)
  - Run CMake GUI and set **source** and **build** directories, press **Configure** and select you compiler to generate project for.



The base folder of OpenCV source code

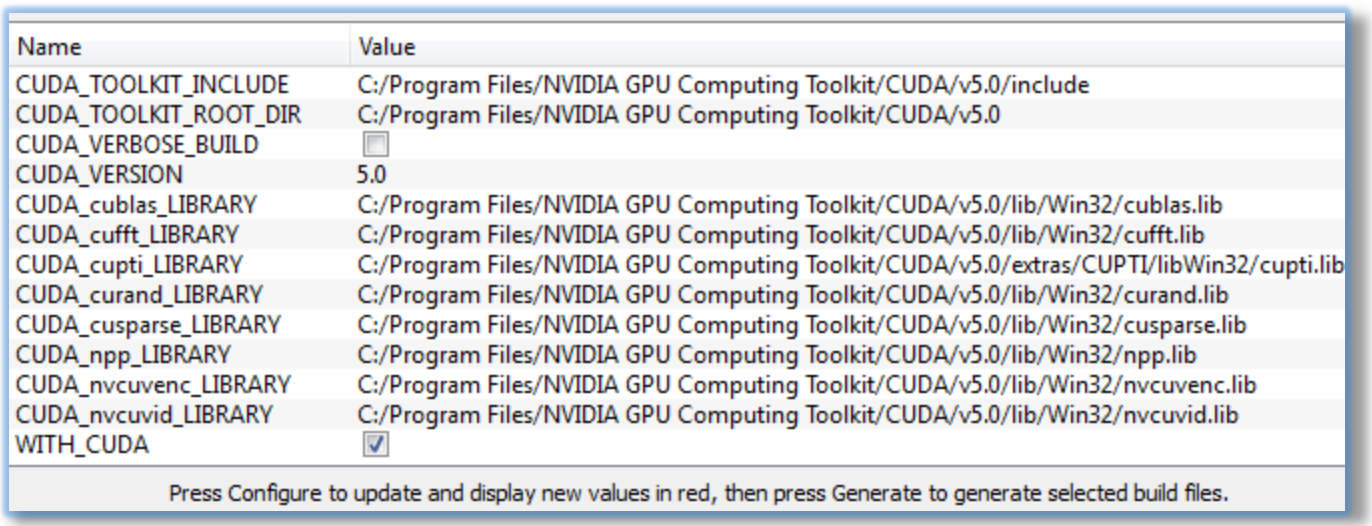
Where to put compiled OpenCV library





Building OpenCV with GPU support

- Build steps
  - Run CMake GUI and set **source** and **build** directories, press **Configure** and select you compiler to generate project for.
  - Enable **WITH_CUDA** flag and ensure that CUDA Toolkit is detected correctly by checking all variables with ‘CUDA_’ prefix.



Name	Value
CUDA_TOOLKIT_INCLUDE	C:/Program Files/NVIDIA GPU Computing Toolkit/CUDA/v5.0/include
CUDA_TOOLKIT_ROOT_DIR	C:/Program Files/NVIDIA GPU Computing Toolkit/CUDA/v5.0
CUDA_VERBOSE_BUILD	☐
CUDA_VERSION	5.0
CUDA_cublas_LIBRARY	C:/Program Files/NVIDIA GPU Computing Toolkit/CUDA/v5.0/lib/Win32/cublas.lib
CUDA_cufft_LIBRARY	C:/Program Files/NVIDIA GPU Computing Toolkit/CUDA/v5.0/lib/Win32/cufft.lib
CUDA_cupti_LIBRARY	C:/Program Files/NVIDIA GPU Computing Toolkit/CUDA/v5.0/extras/CUPTI/libWin32/cupti.lib
CUDA_curand_LIBRARY	C:/Program Files/NVIDIA GPU Computing Toolkit/CUDA/v5.0/lib/Win32/curand.lib
CUDA_cusparse_LIBRARY	C:/Program Files/NVIDIA GPU Computing Toolkit/CUDA/v5.0/lib/Win32/cusparse.lib
CUDA_npp_LIBRARY	C:/Program Files/NVIDIA GPU Computing Toolkit/CUDA/v5.0/lib/Win32/npp.lib
CUDA_nvcuvenc_LIBRARY	C:/Program Files/NVIDIA GPU Computing Toolkit/CUDA/v5.0/lib/Win32/nvcuvenc.lib
CUDA_nvcuvid_LIBRARY	C:/Program Files/NVIDIA GPU Computing Toolkit/CUDA/v5.0/lib/Win32/nvcuvid.lib
WITH_CUDA	☑

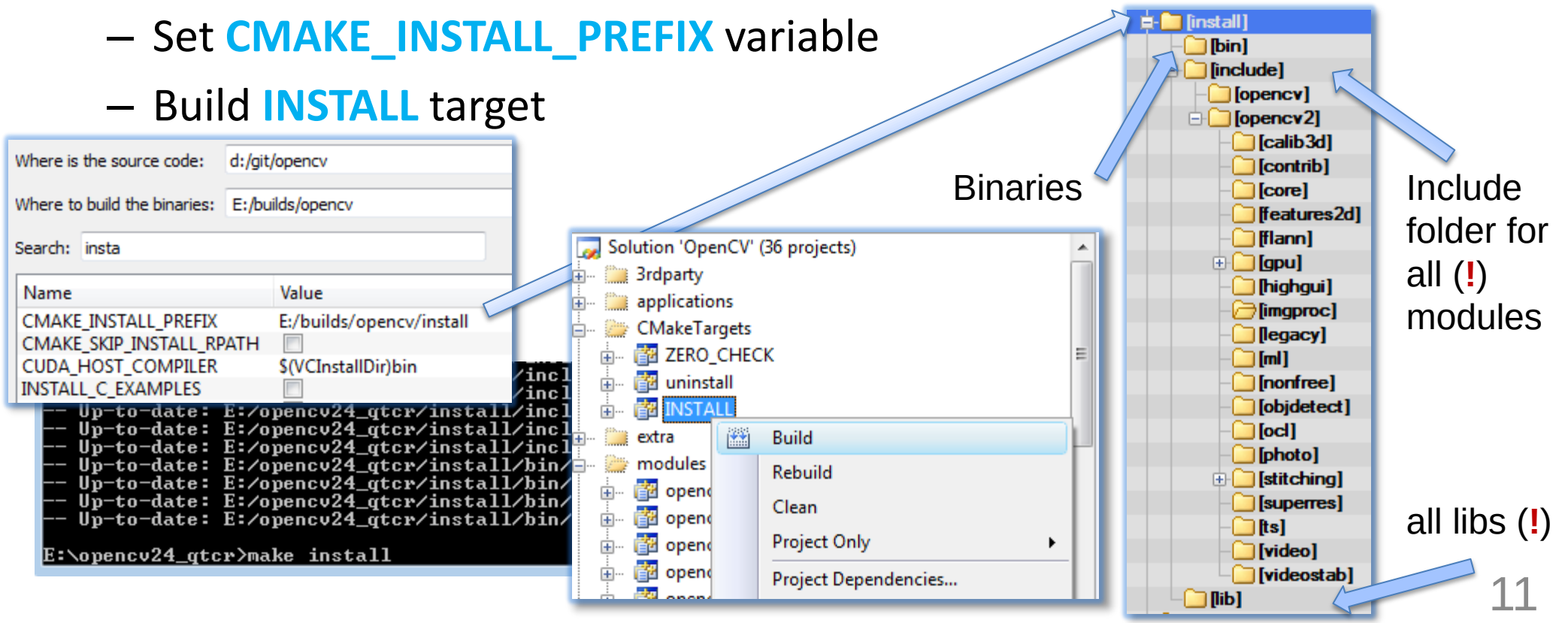
Press Configure to update and display new values in red, then press Generate to generate selected build files.

Building OpenCV with GPU support

- Build steps
  - Run CMake GUI and set **source** and **build** directories, press **Configure** and select you compiler to generate project for.
  - Enable **WITH_CUDA** flag and ensure that CUDA Toolkit is detected correctly by checking all variables with ‘CUDA_’ prefix.
  - Press **Configure** and **Generate** to generate a project
    - On Windows, open the Visual Studio solution and click on “Build Solution”.
    - On Linux, run “make” from the build folder.

Installing OpenCV (optional)

- Running OpenCV install scripts is a way to put all headers, libs and binaries to one place for easier use and deployment
  - Set **CMAKE_INSTALL_PREFIX** variable
  - Build **INSTALL** target



Adding OpenCV to your project via CMake

- Create a ‘main.cpp’ file and **CMakeLists.txt** script as below

```
cmake_minimum_required(VERSION 2.8.8)

project(sample_project C CXX)

find_package(OpenCV REQUIRED)
include_directories(${OpenCV_INCLUDE_DIRS})

file(GLOB srcs ./*.cpp ./*.h*)

add_executable(sample_app ${srcs})
target_link_libraries(sample_app ${OpenCV_LIBS})
```

- Use CMake to generate and build the sample. Set **OpenCV_DIR** variable for the project to **build** or **install** OpenCV folder

Name	Value
OpenCV_3RDPARTY_LIB_DIR_DBG	E:/builds/opencv/install/share/OpenCV/3rdparty/lib
OpenCV_3RDPARTY_LIB_DIR_OPT	E:/builds/opencv/install/share/OpenCV/3rdparty/lib
OpenCV_CONFIG_PATH	E:/builds/opencv/install
OpenCV_DIR	E:/builds/opencv/install
OpenCV_LIB_DIR_DBG	E:/builds/opencv/lib
OpenCV_LIB_DIR_OPT	E:/builds/opencv/installlib

Set this. Others
are detected automatically

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- Overlapping operations
- Using GPU module with your CUDA code
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GPU module design considerations

- Key ideas
  - Explicit control of data transfers between CPU and GPU
  - Minimization of the data transfers
  - Completeness
    - Port everything even functions with little speed-up
- Solution
  - Container for GPU memory with upload/download functionality
  - GPU module function take the container as input/output parameters

GpuMat - container for GPU memory

- Class GpuMat – for storing 2D (**pitched**) data on GPU
  - Interface similar to **cv::Mat()**, supports reference counting
  - Its data is not continuous, extra **padding** in the end of each row
  - It contains:
    - **data** - Pointer data beginning in GPU memory
    - **step** - distance **in bytes** is between two consecutive rows
    - **cols, rows** – fields that contain image size
    - Other fields for internal use only


```
GpuMat cloud = ... (get 3-channel float data from a file and copy to GPU)

// compute address of Point at (x, y)
cv::Point3f* pixel_ptr = (cv::Point3f*)(cloud.data + cloud.step * y) + x;

// the same, but simplified
cv::Point3f* pixel_ptr = cloud.ptr<cv::Point3f >(y) + x;
```

Operations with GpuMat

- Allocations (similar to cv::Mat)

```
void GpuMat::GpuMat(const cv::Size& size, int type);
void GpuMat::create(const cv::Size& size, int type);

//Type examples:
    CV_8U - grayscale,
    CV_8UC3 - BGR,
    CV_32FC3 - 3D point
    CV_16U - depth

GpuMat image1(Size(1902,1080), CV_8U);

GpuMat image2;
image2.create(Size(1, 1000), CV_32FC3);
```

- Creating GpuMat **header** for user allocated data

```
void GpuMat::GpuMat(const cv::Size& size, int type, void* data, size_t step);

thrust::device_vector<float> vector(10000);
GpuMat header(Size(vector.size(), 1), CV_32F, &vector[0], vector.size() * sizeof(float));
cv::gpu::threshold(header, header, value, 1000, THRESH_BINARY);
```

Operations with GpuMat

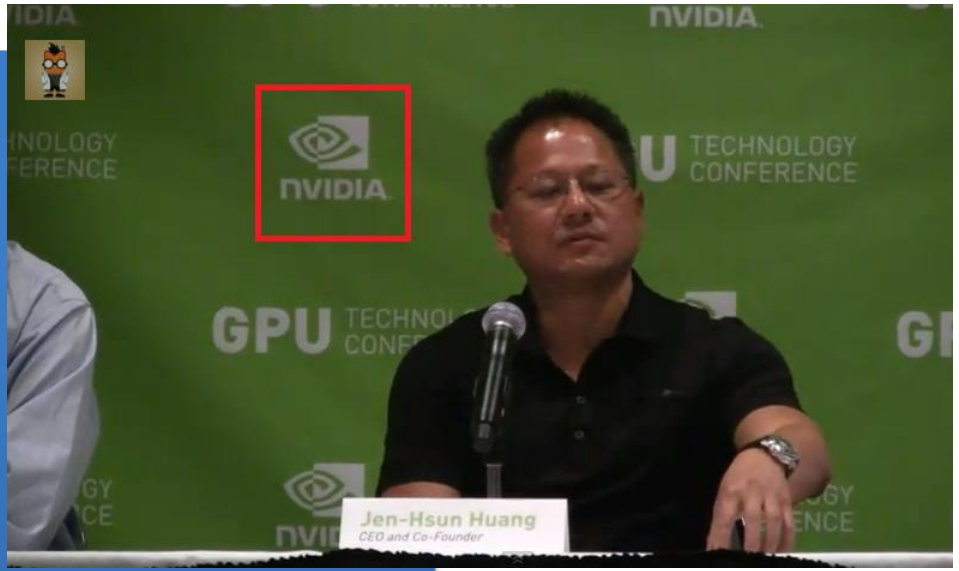
- Copying between CPU-GPU and GPU-GPU

```
void GpuMat::GpuMat(const cv::Mat& host_data);
void GpuMat::upload(const cv::Mat& host_data);

void GpuMat::download(cv::Mat& host_data);
void GpuMat::copyTo(cv::gpu::GpuMat& other);


//Examples
Mat host_image = cv::imload("file.png"); //load image from file

GpuMat device_image1;
device_image1.upload(host_image1);        //allocate memory and upload to GPU

GpuMat device_image2;
device_image1.copyTo(device_image2);     //allocate memory and GPU-GPU copy

device_image2.donwload(host_image);      //download data
```

Template matching

```
#include <opencv2/opencv.hpp>
#include <opencv2/gpu/gpu.hpp>

void process() {
    cv::gpu::setDevice(0);
    cv::VideoCapture capture("video.avi");
    cv::Mat templ_h = cv::imread("nvlogo.png");
    cv::gpu::GpuMat templ_d(templ_h); // upload
    cv::gpu::GpuMat image_d, result;
    cv::Mat image_h;

    for(;;)  {
        capture >> image_h;
        if(image_h.empty())
            break;

        image_d.upload(image_h);
        cv::gpu::matchTemplate(image_d, templ_d, result, cv::TM_CCORR);

        double max_value;
        cv::Point location;
        cv::gpu::minMaxLoc(result, 0, &max_value, 0, &location);
        if (max_value > threshold)
            drawRectangleAndShowImage(location, ...);
    }
}
```

Init CUDA



Template searched

8-20x

* GTX 680 vs. Core i5-760

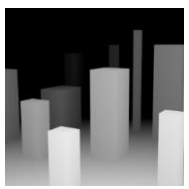
OpenCV GPU Module functionality

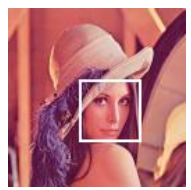
- Image processing building blocks:

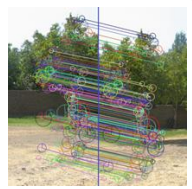
Color conversions | Geometrical transforms | Per-element operations | Integrals, reductions

Template matching | Filtering engine | Feature detectors

- High-level algorithms:

Stereo matching 

Face detection 

SURF 

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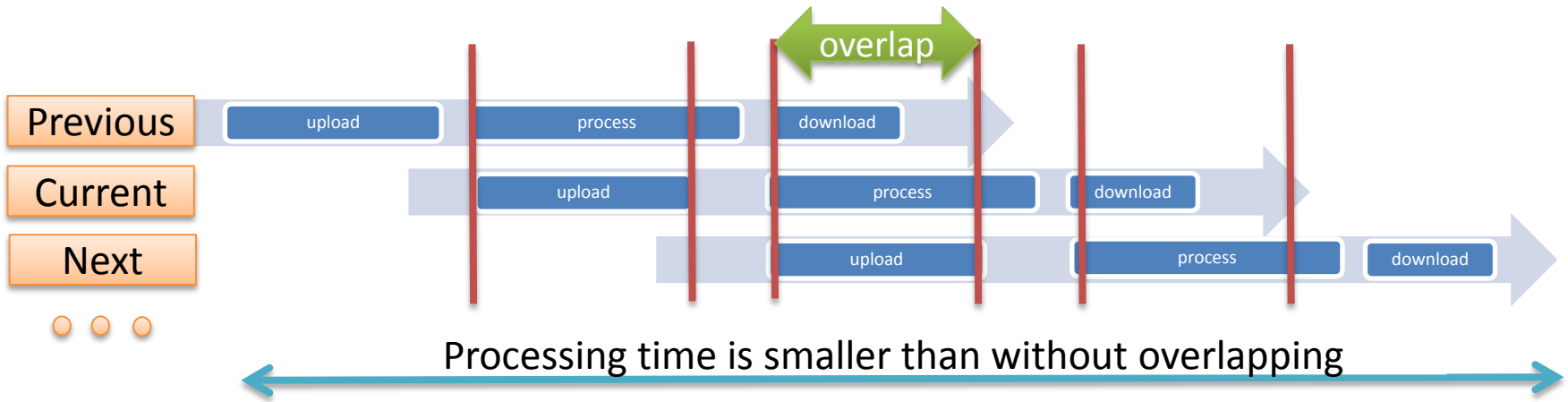
Overlapping operations with CUDA

- Which operations can be run simultaneously?
  - Host and device code execution
  - Data transfer and device code execution
  - Several device code executions
    - Only if GPU is under occupied
    - Must be executed in different streams
    - (won't talk about this)

Overlapping operations with CUDA

- Advantages
  - Allows to use whole computing power of your PC (CPU + GPU)
  - Allows to partly **hide data transfer overheads**
    - Result from previous frame is being downloaded
    - Current is being processed on GPU
    - Next frame is being uploaded



Concurrency in OpenCV GPU

- Class CudaMem
  - Allocates page-locked CPU memory
    - Required for asynchronous data transfers,
    - **2x faster** transfer than regular memory, but limited by available RAM
  - Interface similar to Mat or GpuMat
  - Convertible to Mat, can pass to any CPU function

```
CudaMem page_locked(Size(1920, 1080), CV_32FC3);   //allocate page locked memory
Mat header = page_locked;                          //no copy, just header

VideoCapture cap("video1080p.avi");  // open video stream
for(;;)
{
  cap >> header; //read video frame to the header which actually points to page-locked buffer
  // now can copy the page_locked to GPU in asynchronous fashion
  ...
}
```

Concurrency in OpenCV GPU

- Class Stream (wrapper for cudaStream_t)
  - Represents asynchronous queue of operations
  - Allows querying/waiting operations to complete
  - Enqueue asynchronous data transfers

```
bool Stream::queryIfComplete();
void Stream::waitForCompletion();

void Stream::enqueueDownload(const GpuMat& src, CudaMem& dst);
void Stream::enqueueUpload(const CudaMem& src, GpuMat& dst);
void Stream::enqueueCopy(const GpuMat& src, GpuMat& dst);

typedef void (*StreamCallback)(Stream& stream, int status, void* userData);
void Stream::enqueueHostCallback(StreamCallback callback, void* userData);
```

Concurrency in OpenCV GPU

- Putting device operations into the queue

```
namespace cv {  namespace gpu
{
    void a_opencv_gpu_function(..., Stream& stream = Stream::Null());
}}

// synchronous case
device_image.upload(host_image);                // blocks until upload is done
a_opencv_gpu_function(device_image, output);    // blocks until operation finishes


// asynchronous case
Stream stream;

stream.enqueueUpload(host_image, device_image);         // returns immediately
a_opencv_gpu_function(device_image, output, stream);    // returns immediately
Stream.enqueueDownload(output, ouput_host);             // returns immediately

// CPU resources are available.
// Let's compute on CPU here while GPU does own work.

stream.waitForCompletion();
// output_host is ready!
```

Concurrency in OpenCV GPU

- Current limitation:
  - Unsafe to enqueue the same GPU operation multiple times

```
__constant__ int variable; // constant GPU memory reference
texture<uchar, 2> tex_reference;

cv::gpu::function1(int param, Stream& stream)
{
   cudaMemCopyToSymbol (variable, param); // variable = param
   call_gpu_kernel_that_uses_variable_in_async_fashion(stream)
}

//unsafe
function1(10, stream);
function1(20, stream);
```

- The limitation will be removed in OpenCV 3.x
  - (will re-implement without using constant memory although it may lead to slightly worse performance for small number of kernels)

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Writing your own CUDA code

- GpuMat (can't be passed to cu-file due to nvcc compiler issue, this will be fixed in OpenCV 3.0)
  - **data**, **step**, **cols**, **rows** – can just pass to your code
  - Convertible to **PtrStep<T>**, **PtrStepSz<T>** structures

```
// swap_rb.cpp
#include <opencv2/gpu/stream_accessor.hpp>

void swap_rb_caller(const PtrStepSz<uchar3>& src, PtrStep<uchar3> dst, cudaStream_t stream);


void swap_rb(const GpuMat& src, GpuMat& dst, Stream& stream = Stream::Null())
{
    CV_Assert(src.type() == CV_8UC3);
    dst.create(src.size(), src.type());  // create if not allocated yet
    cudaStream_t s = StreamAccessor::getStream(stream);
    swap_rb_caller(src, dst, s);
}
```

Writing your own CUDA code

```
// swap_rb.cu
#include <opencv2/core/cuda_devptrs.hpp>


__global__ void swap_rb_kernel(const PtrStepSz<uchar3> src, PteStep<uchar3> dst)
{
    int x = threadIdx.x + blockIdx.x * blockDim.x;
    int y = threadIdx.y + blockIdx.y * blockDim.y;

    if (x < src.cols && y < src.rows)
    {
        uchar3 v = src(y, x); // Reads pixel in GPU memory. Valid! We are on GPU!
        dst(y, x) = make_uchar3(v.z, v.y, v.x);
    }
}

void swap_rb_caller(const PtrStepSz<uchar3>& src, PtrStep<uchar3> dst, cudaStream_t stream)
{
   dim3 block(32, 8);
   dim3 grid((src.cols + block.x - 1)/block.x, (src.rows + block.y - 1)/ block.y);

   swap_rb_kernel<<<grid, block, 0, stream>>>(src, dst);

   if (stream == 0)
       cudaDeviceSynchronize();
}
```

Writing your own CUDA code

- Device layer functions (the set will be extended in OpenCV 3.0)
  - opencv2/gpu/device/*.hpp
  - useful utility code to call from your kernels

```
#define HIST_SIZE 396
#include <opencv2/gpu/device/block.hpp>
__global__ void histogramm_kernel_pass1(const PtrStepSz<float3> cloud, PtrStep<float> ouput) {
    __shared__ float smem[HIST_SIZE];

    Block::fill(smem, smem + HIST_SIZE, 0);
    __syncthreads()

   ... compute histogram using atomics on smem ...

    __syncthreads();
    float sum = Block::reduce_n(smem, HIST_SIZE, plus<float>());
    __syncthreads();

   float* ouput_row = output(blockIdx.y * BLOCK_SIZE + blockIdx.x);
   Block::transform(smem, smem + HIST_SIZE, output_row, divide_by(sum));
}
```

Writing your own CUDA code

- Device layer functions (the set will be ex
  - opencv2/gpu/device/*.hpp
  - useful utility code to call from your

```
template <typename T, class BinOp>
static __device__ __forceinline__
void reduce_n(T* data, unsigned int n, BinOp op)
{
    int ftid = threadIdx.z * blockDim.x * blockDim.y;
    int sft = blockDim.x * blockDim.y * blockDim.z;
    if (sft < n)
    {
        for (unsigned int i = sft + ftid; i < n; i += sft)
            data[ftid] = op(data[ftid], data[i]);
        __syncthreads();
        n = sft;
    }

    while (n > 1)
    {
        unsigned int half = n/2;
        if (ftid < half)
            data[ftid] = op(data[ftid], data[n - ftid - 1]);
        __syncthreads();
        n = n - half;
     }
}
```

```
#define HIST_SIZE 396
#include <opencv2/gpu/device/block.hpp>
__global__ void histogramm_kernel_pass1(const PtrSte
    __shared__ float smem[HIST_SIZE];

    Block::fill(smem, smem + HIST_SIZE, 0);
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   ... compute histogram using atomics on smem ...

    __syncthreads();
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    __syncthreads();

   float* ouput_row = output(blockIdx.y * BLOCK_SIZE + blockIdx.x);
   Block::transform(smem, smem + HIST_SIZE, output_row, divide_by(sum));
}
```
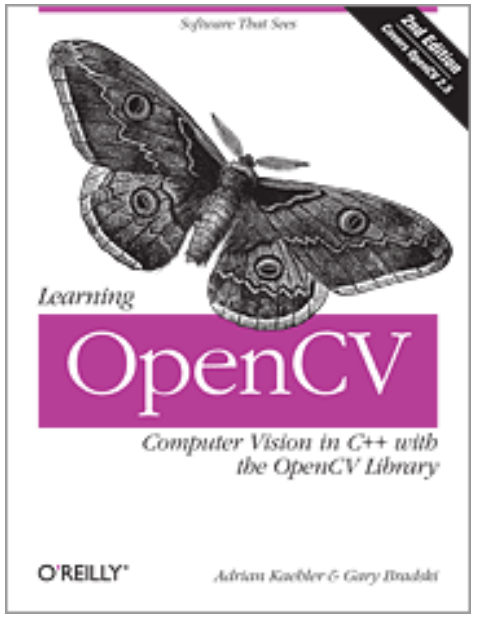

OpenCV resources

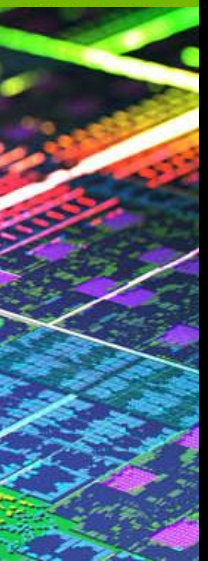
- Main site:
  - http://opencv.org/
- Online documentation (with tutorials)
  - http://docs.opencv.org/
- Question & Answers site
  - http://answers.opencv.org/questions/
- Books
  - http://opencv.org/books.html
- Bug tracker
  - http://code.opencv.org/projects/opencv/issues



"**Learning OpenCV**" 2nd ed.
by G.Bradski, A.Kaehler
with **GPU module** chapter
coming soon!

Questions?

www.opencv.org



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August 13 - GPUs in the Film Visual Effects Pipeline

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- Refer to OpenCV Yahoo! Groups
- OpenCV.org: http://answers.opencv.org/questions/