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# Computer Vision on the GPU with OpenCV

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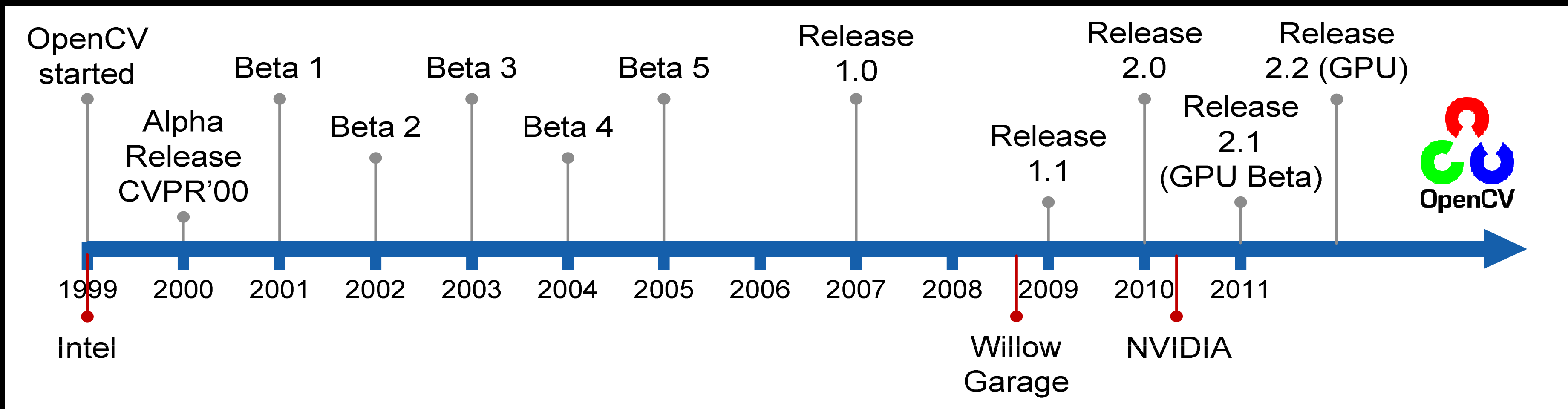
itseez

NVIDIA.

# Outline

- Introduction into OpenCV
- OpenCV GPU module
- Face Detection on GPU
- Pedestrian detection on GPU

# OpenCV History

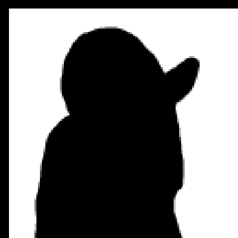



- Original goal:
  - Accelerate the field by lowering the bar to computer vision
  - Find compelling uses for the increasing MIPS out in the market
- Staffing:
  - Climbed in 1999 to average 7 first couple of years
  - Little development from 2002 – 2008
  - Willow entered in 2008 to accelerate development, NVIDIA joined in 2010
  - 8 full time professional developers, 3 of them dedicated to GPU

# OpenCV Functionality Overview

*Image processing*


General Image Processing


Segmentation

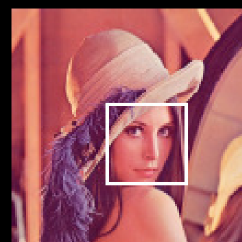
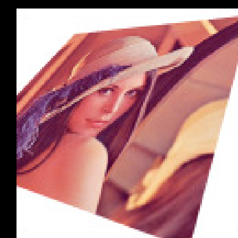
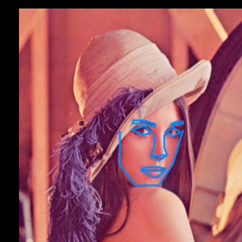
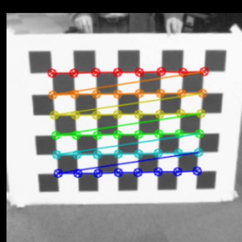

Machine Learning, Detection

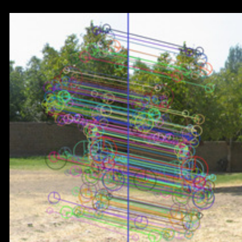

Image Pyramids

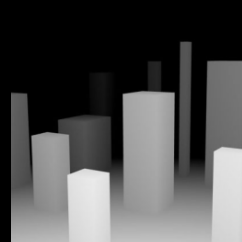

Transforms

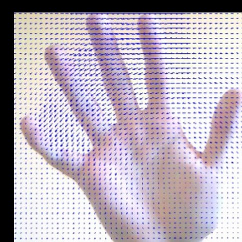

Fitting

*Video, Stereo, and 3D*


Camera Calibration


Features


Depth Maps


Optical Flow


Inpainting


Tracking

# OpenCV Architecture and Development

Languages:
- C
- C++
- Python
- CUDA

Technologies:
- CUDA
- SSE
- MPU
- TBB

3rd party libs:
- Eigen
- IPP
- Jasper
- JPEG, PNG
- OpenEXR
- OpenNI
- QT
- TBB
- VideoInput

Development:
- Maintainers
- Contributors

QA:
- Buildbot
- Google Tests

Modules:
- Core
- HighGUI
- GPU
- ImgProc
- ML
- ObjDetect
- Video
- Calib3D
- Features2D
- FFMPEG
- FLANN

Target archs:
- X86
- X64
- ARM
- CUDA

Target OS:
- Windows
- Linux
- Mac OS
- Android

# OpenCV License

Based on BSD license

- Free for commercial and research use
- Does not force your code to be open
- You need not contribute back
  - *We hope you will contribute back!*

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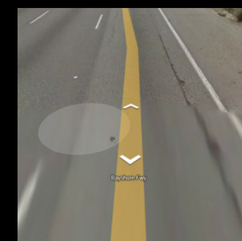
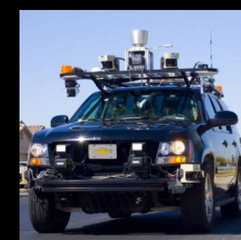
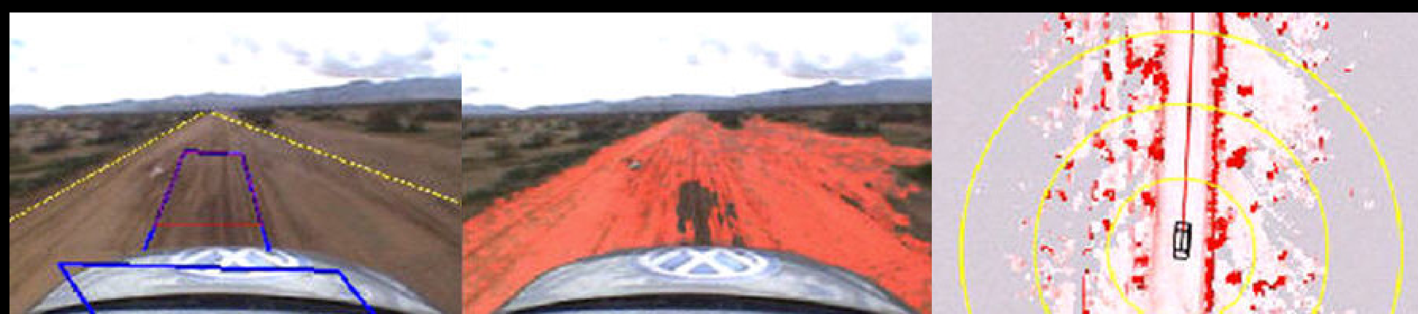
# Projects Using OpenCV

- Google Maps, Google street view, Google Earth
- Academic and Industry Research
- Security systems
- Image retrieval
- Video search
- Machine vision factory production systems
- Structure from motion in movies
- Robotics



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- Introduction into OpenCV
- OpenCV GPU module
- Face Detection on GPU
- Pedestrian detection on GPU

# OpenCV GPU Module

## Motivation:

- Many computer vision tasks are inherently parallel
- GPUs provide cheap computational power

# OpenCV GPU Module

## Goals:

- Provide developers with a convenient computer vision framework on the GPU
- Maintain conceptual consistency with the current CPU functionality
- Achieve the best *performance* with GPUs
  - Efficient kernels tuned for modern architectures
  - Optimized dataflows (asynchronous execution, copy overlaps, zero-copy)

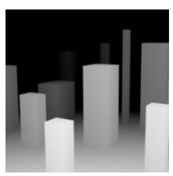
# OpenCV GPU Module Contents

- Image processing building blocks:

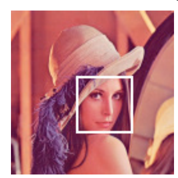
Color conversions | Geometrical transforms | Per-element operations | Integrals, reductions | Template matching | Filtering engine | Feature detectors

- High-level algorithms:

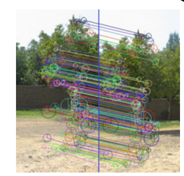
Stereo matching



Face detection

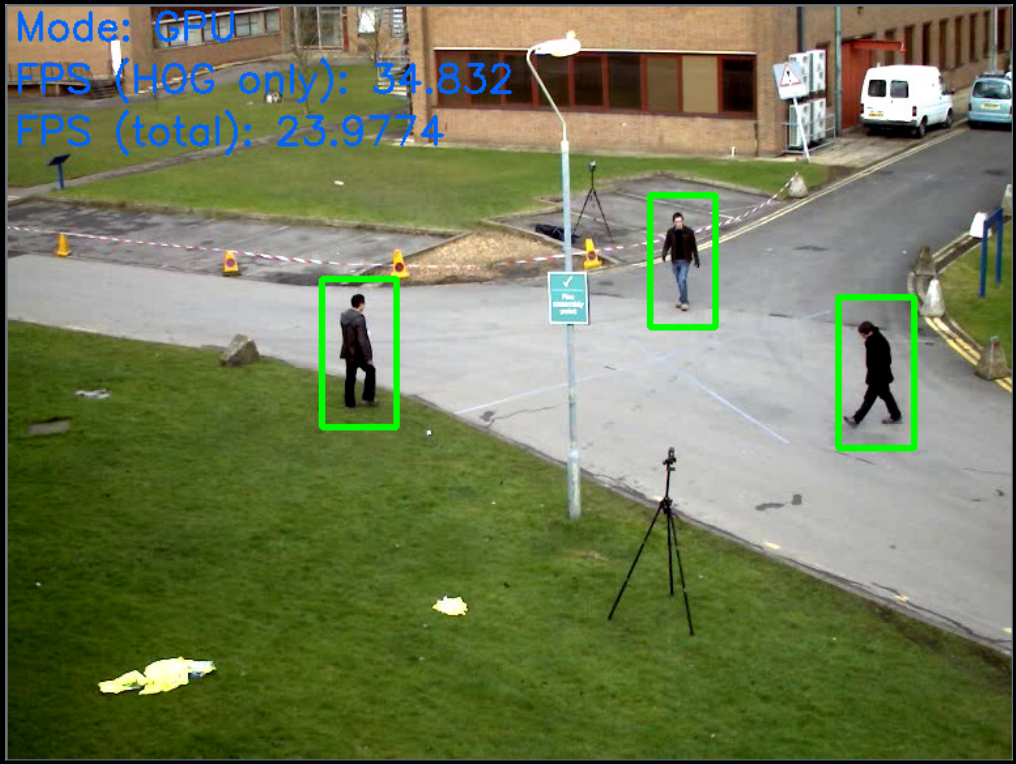


SURF



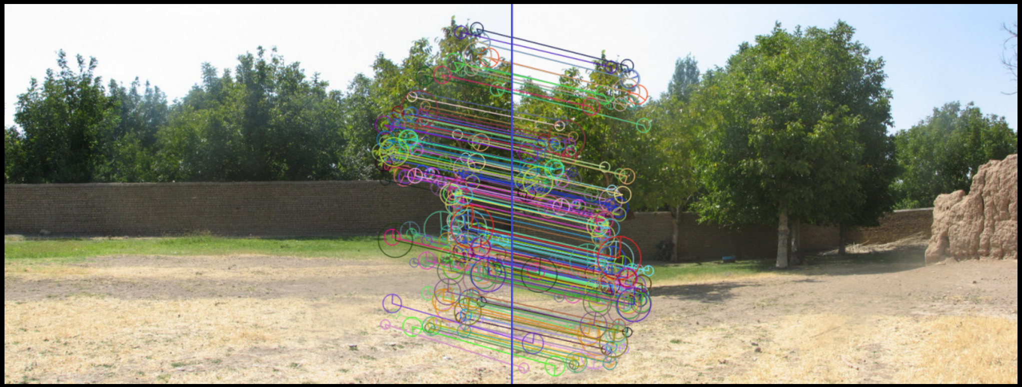
# OpenCV GPU: Histogram of Oriented Gradients

- Used for pedestrian detection
- Speed-up ~ **8×**



# OpenCV GPU: Speeded Up Robust Features

- SURF (12×)
- Bruteforce matcher
  - K-Nearest search (20-30×)
  - In radius search (3-5×)

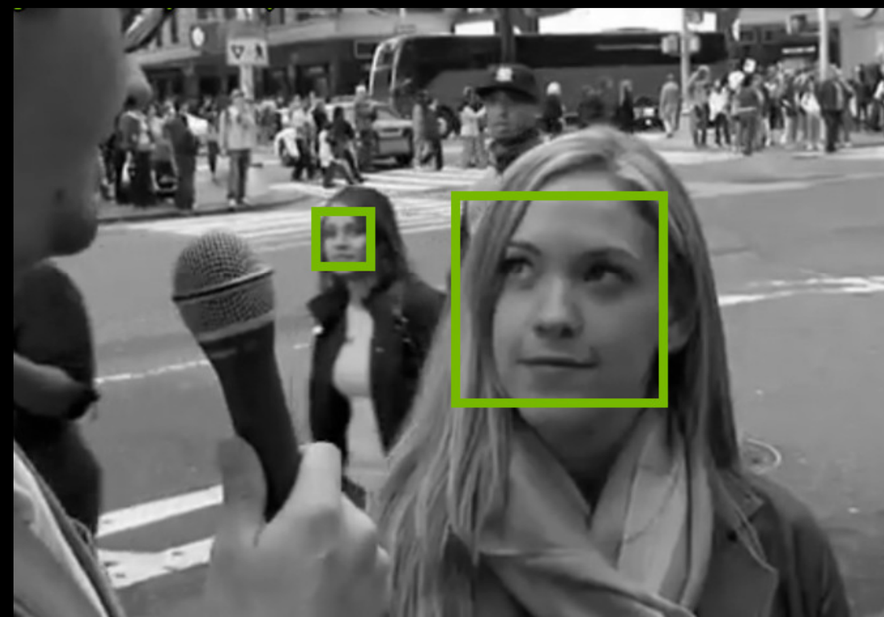


# OpenCV GPU: Stereo Vision

- Stereo Block Matching (7×)
  - Can run Full HD real-time on Dual-GPU
- Hierarchical Dense Stereo
  - Belief Propagation (20×)
  - Constant space BP (50-100×)

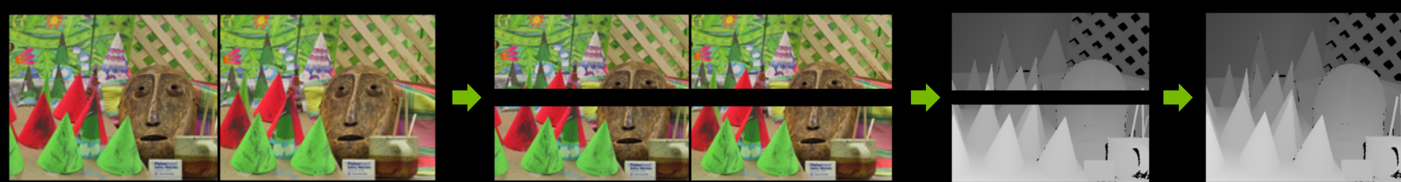
# OpenCV GPU: Viola-Jones Cascade Classifier

- Used for face detection
- Speed-up ~ 6×
- Based on NCV classes (NVIDIA implementation)



# OpenCV with Multiple GPUs

- Algorithms designed with single GPU in mind
- You can split workload manually in slices:
  - Stereo Block Matching (dual-GPU speedup ~ **1.8×**)



  - Multi-scale pedestrian detection: linear speed-up (scale-parallel)

# OpenCV and NPP

- NPP is NVIDIA Performance Primitives library of signal and image processing functions (similar to Intel IPP)
- GPU module uses NPP whenever possible
  - Highly optimized implementations for all supported NVIDIA architectures and OS
  - Part of CUDA Toolkit – no additional dependencies
- NVIDIA will continue adding new primitives
  - Several hundred primitives added every CUDA release
  - If you feel like your function could be a primitive – go ahead and add it to NPP_staging! (part of NCV in OpenCV GPU module)

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# OpenCV GPU Module Usage

- Prerequisites:
  - Get sources from the website http://opencv.willowgarage.com/wiki/InstallGuide
  - CMake
  - NVIDIA Display Driver
  - NVIDIA GPU Computing Toolkit (for CUDA)
- Build OpenCV with CUDA support
- `#include <opencv2/gpu/gpu.hpp>`

# OpenCV GPU Data Structures

- Class GpuMat
  - For storing 2D image in GPU memory, just like class cv::Mat
  - Reference counting
- Class CudaMem
  - For pinned memory support
  - Can be transformed into cv::Mat or cv::gpu::GpuMat
- Class Stream
  - Overloads with extra Stream parameter

```
// class GpuMat
GpuMat(Size size, int type);
GpuMat(const GpuMat& m);
explicit GpuMat (const Mat& m);
GpuMat& operator = (const GpuMat& m);
GpuMat& operator = (const Mat& m);
void upload(const Mat& m);
void upload(const CudaMem& m, Stream& stream);
void download(Mat& m) const;
void download(CudaMem& m, Stream& stream) const;
```

```
// class Stream
bool queryIfComplete();
void waitForCompletion();
void enqueueDownload(const GpuMat& src, Mat& dst);
void enqueueUpload(const Mat& src, GpuMat& dst);
void enqueueCopy(const GpuMat& src, GpuMat& dst);
```

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# OpenCV GPU Module Example

```
Mat frame;
VideoCapture capture(camera);
cv::HOGDescriptor hog;

hog.setSVMDetector(cv::HOGDescriptor::
         getDefaultPeopleDetectorector());

capture >> frame;



vector<Rect> found;
hog.detectMultiScale(frame, found,
    1.4,  Size(8, 8), Size(0, 0), 1.05, 8);
```

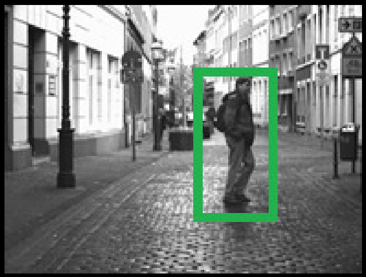
```
Mat frame;
VideoCapture capture(camera);
cv::gpu::HOGDescriptor hog;

hog.setSVMDetector(cv::HOGDescriptor::
         getDefaultPeopleDetectorector());

capture >> frame;

GpuMat gpu_frame;
gpu_frame.upload(frame);

vector<Rect> found;
hog.detectMultiScale(gpu_frame, found,
    1.4, Size(8, 8), Size(0, 0), 1.05, 8);
```



# OpenCV GPU Module Performance

Tesla C2050 (Fermi) vs. Core i5-760 2.8GHz (4 cores, TBB, SSE)


– Average speedup with GPU: 33.98×

What can you get from your computer?

– opencv\samples\gpu\perfomance

– 839 tests for 79 functions

# OpenCV GPU Demo Pack

- Contains demos for high-level GPU algorithms:
  - Face detection (6x)
  - Keypoint detection (12x) / Point matching (20-30x)
  - Pedestrian detection (8x)
  - Image Stitching
  - Optical flow
  - Stereo matching (7x/20x/50x)

http://sourceforge.net/projects/opencvlibrary/

# OpenCV Stitching Module

- Automatic stitching photos taken from the same point
  - Cylindrical, spherical or planar panoramas
  - Multi-band blending technique
  - Smart seam estimation (graph cut based approach)
  - GPU acceleration for the most time-consuming steps

# Auto calibration

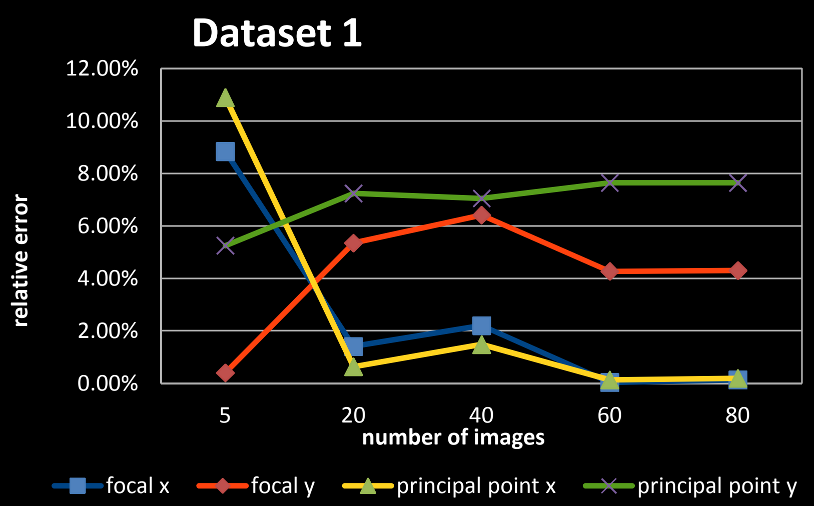
- Rotation camera movement model
  - Requires all photos to be taken from approximately the same position
  - A few tens of images are recommended for accurate work
  - Works without an initial guess of camera intrinsic parameters

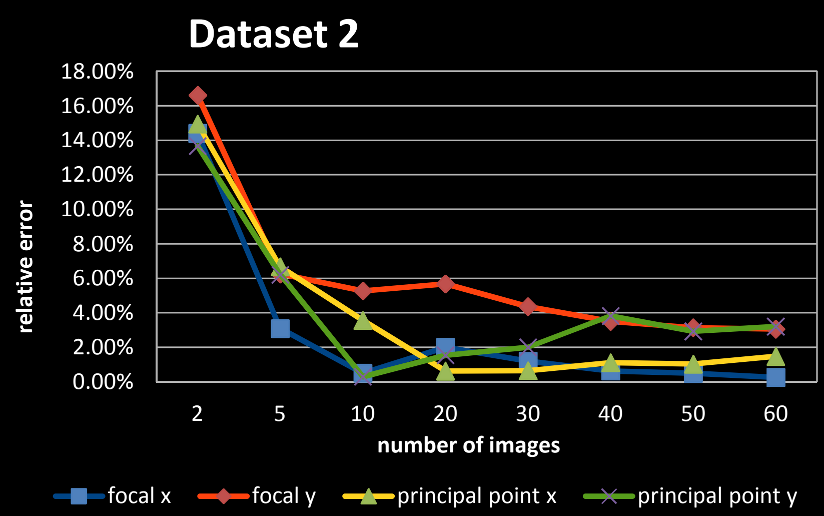
Applications: stitching, augmented reality and many other

# Auto calibration sample images

# Auto calibration

- Relative errors:



# OpenCV Needs Your Feedback!


- Help us set development priorities
  - Which OpenCV functions do you use?
  - Which are the most painful and time-consuming today?

- The more information you can provide about your end application, the better

- Feature request/feedback form on OpenCV Wiki: http://opencv.willowgarage.com/wiki/OpenCV_GPU

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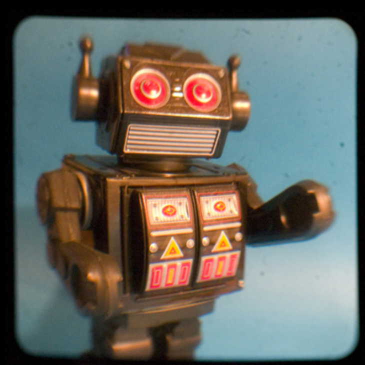
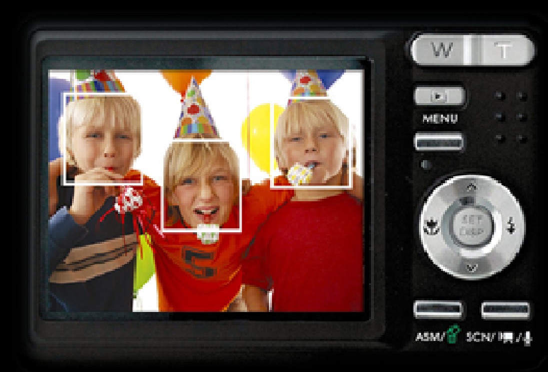
# GPU Face Detection: Motivation

- One of the first Computer Vision problems
- Soul of Human-Computer interaction
- Smart applications in real life

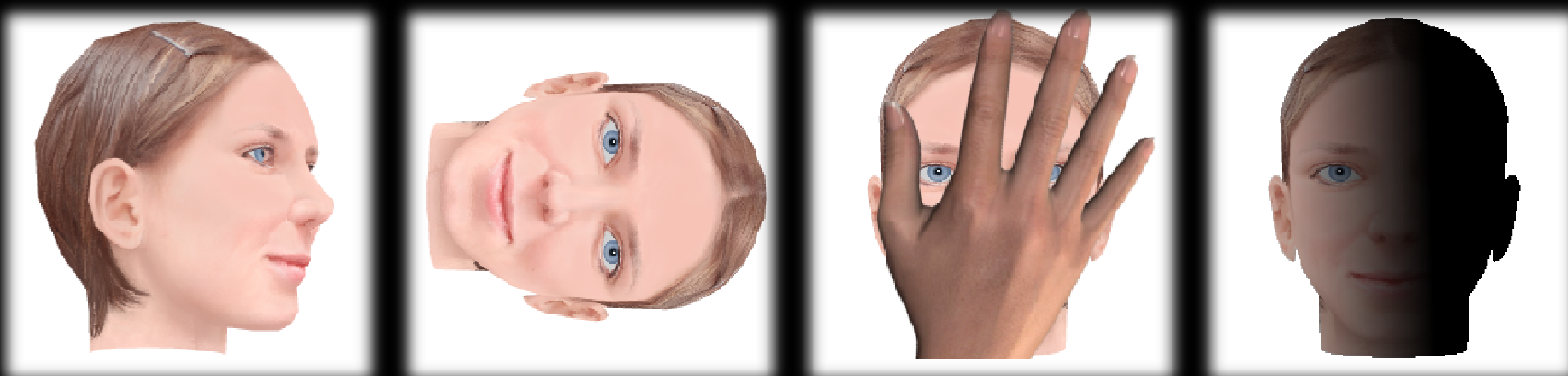




# GPU Face Detection: Problem

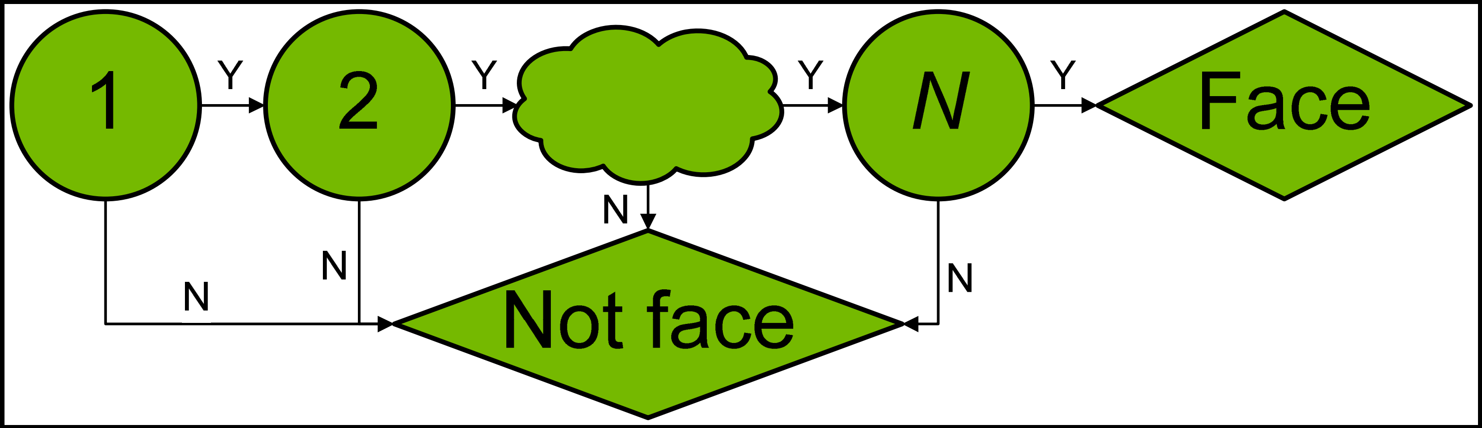
- Locate all upright frontal faces:

- Where face detection does not work:



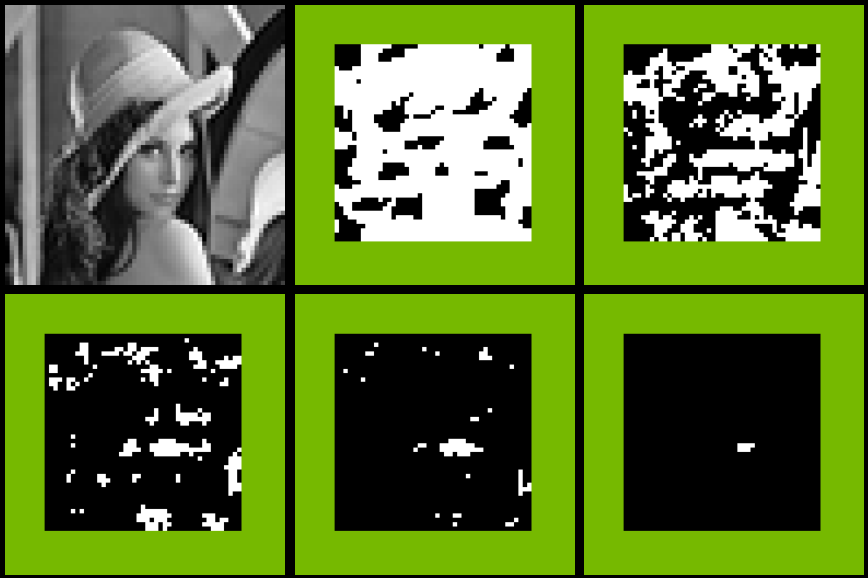
# GPU Face Detection: Approaches

Viola-Jones Haar classifiers framework:




Basic idea: reject most non-face regions on early stages

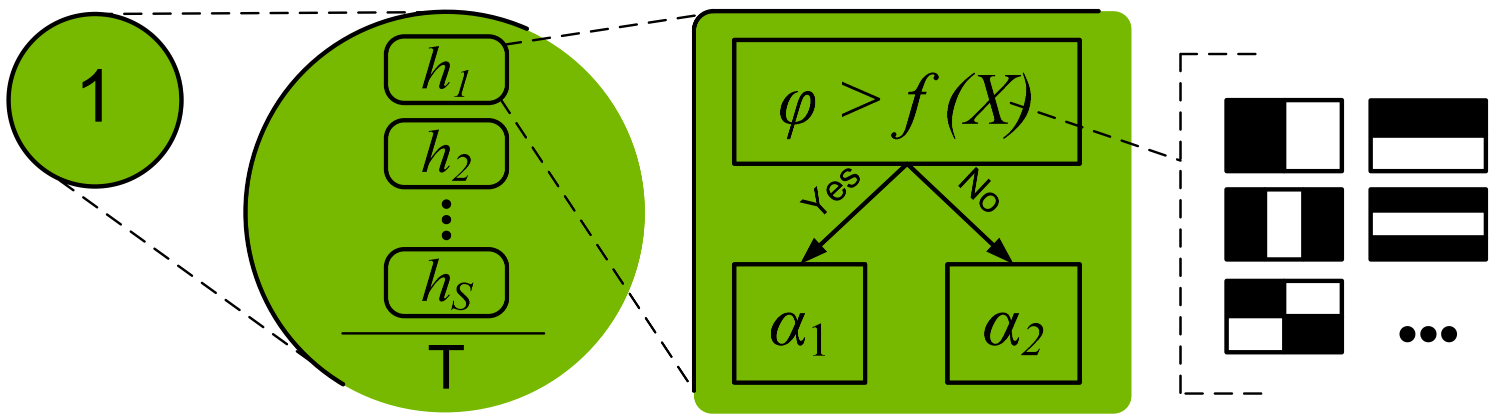
# Classifiers Cascade Explained



- White points represent face windows passed through the 1,2,3,6, and 20 classifier stages
- Time for CUDA to step in! (Parallel windows processing)

# GPU Face Detection: Haar Classifier

Each stage comprises a strong classifier:



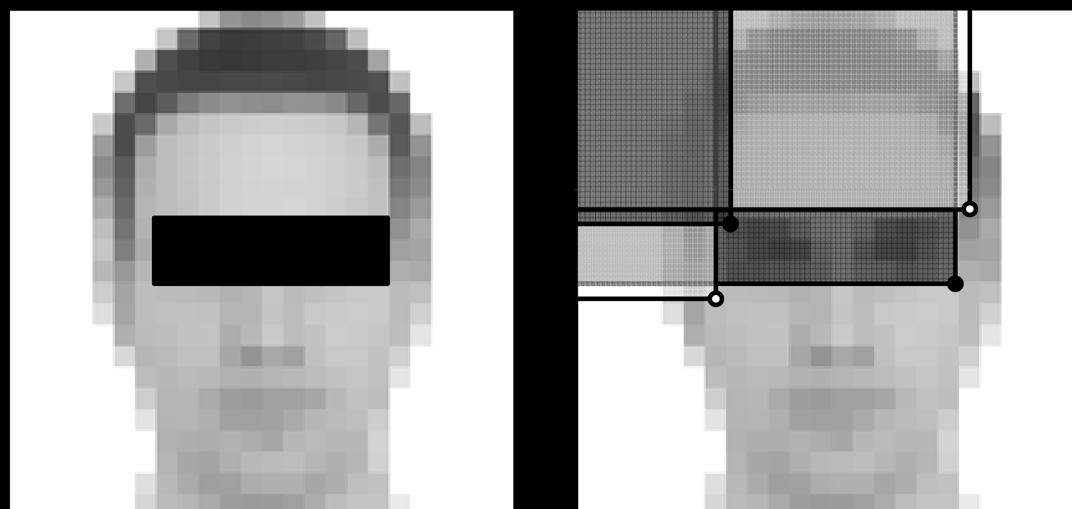

$$H(X) = \begin{cases} 1, & \sum_{i=1}^{K} h_i(X) \geq T \\ 0, & \text{otherwise} \end{cases}$$

# Haar Features Explained

Most representative Haar features for Face Detection

# Integral Image Explained

- Each Integral Image "pixel" contains the sum of all pixels of the original image to the left and top



- Calculation of sum of pixels in a rectangle can be done in 4 accesses to the integral image

# Integral Images with CUDA

Algorithm:

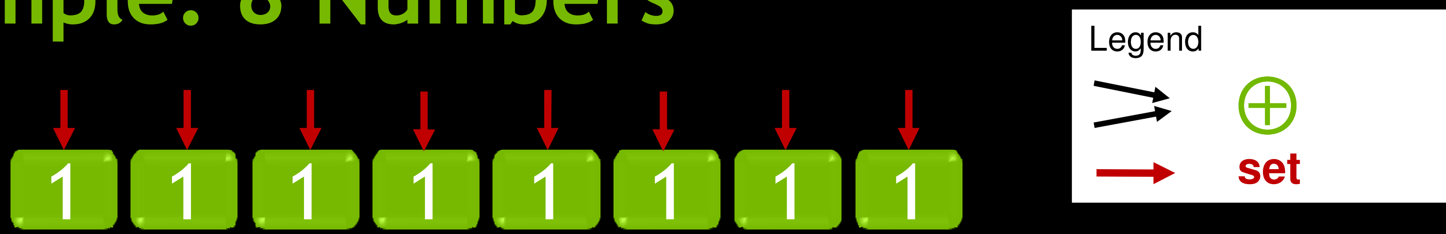
- Integrate image rows
- Integrate image columns

Known as Parallel Scan (one CUDA thread per element):

- Input:
- Output:

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Input: | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Output: | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |

# Scan Sample: 8 Numbers



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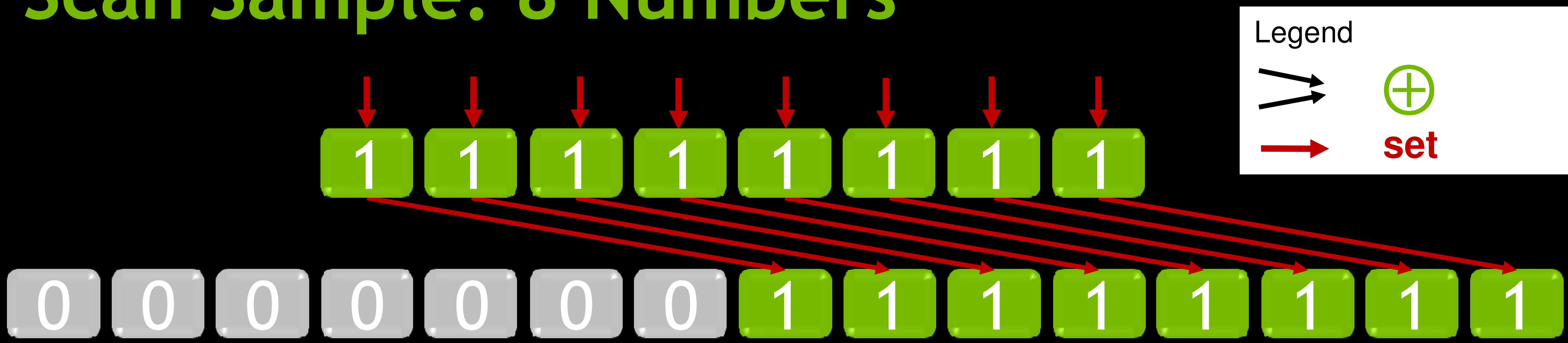

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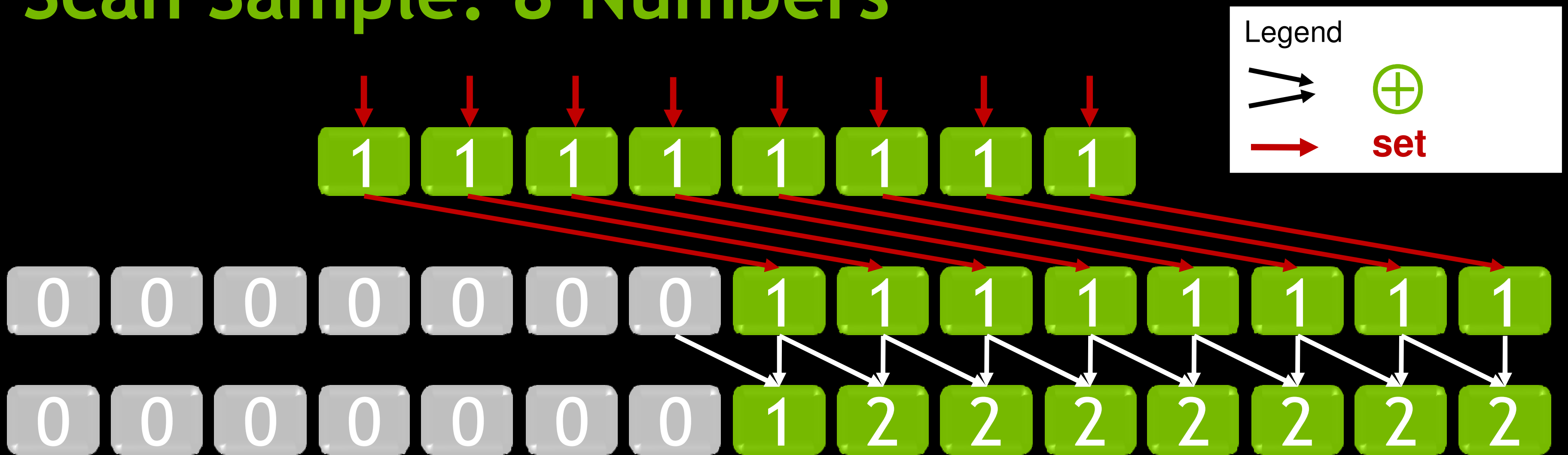

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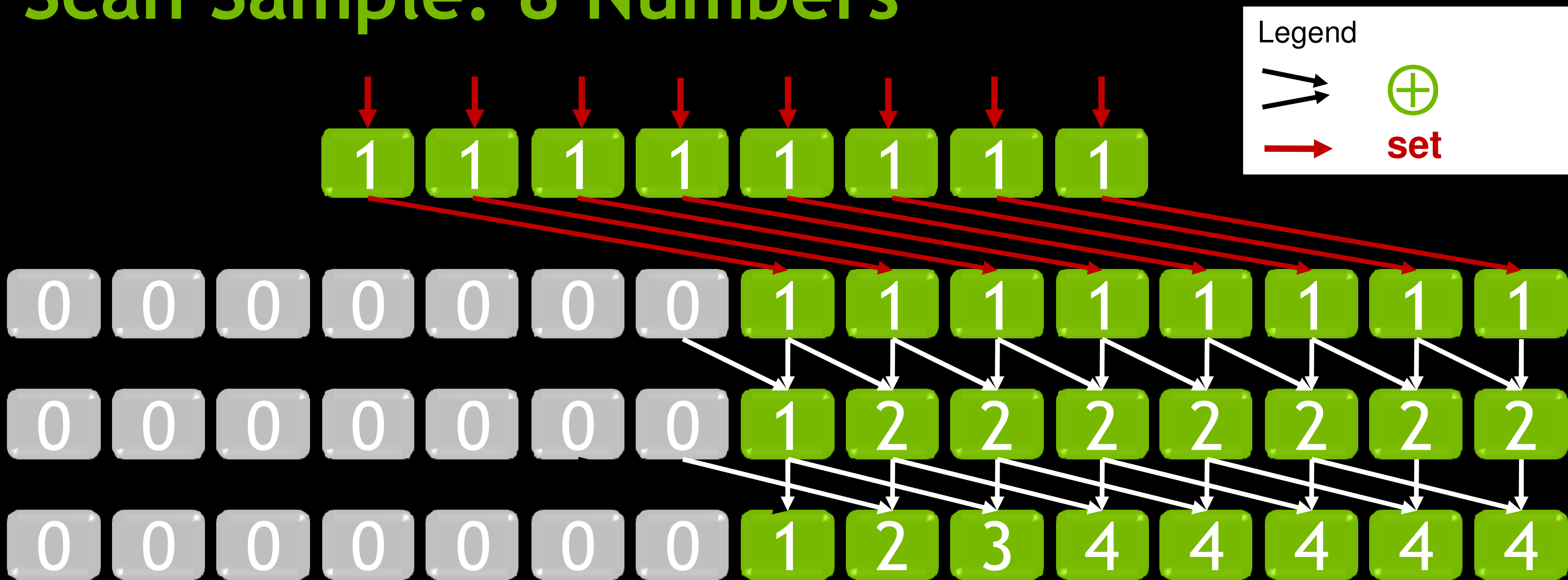

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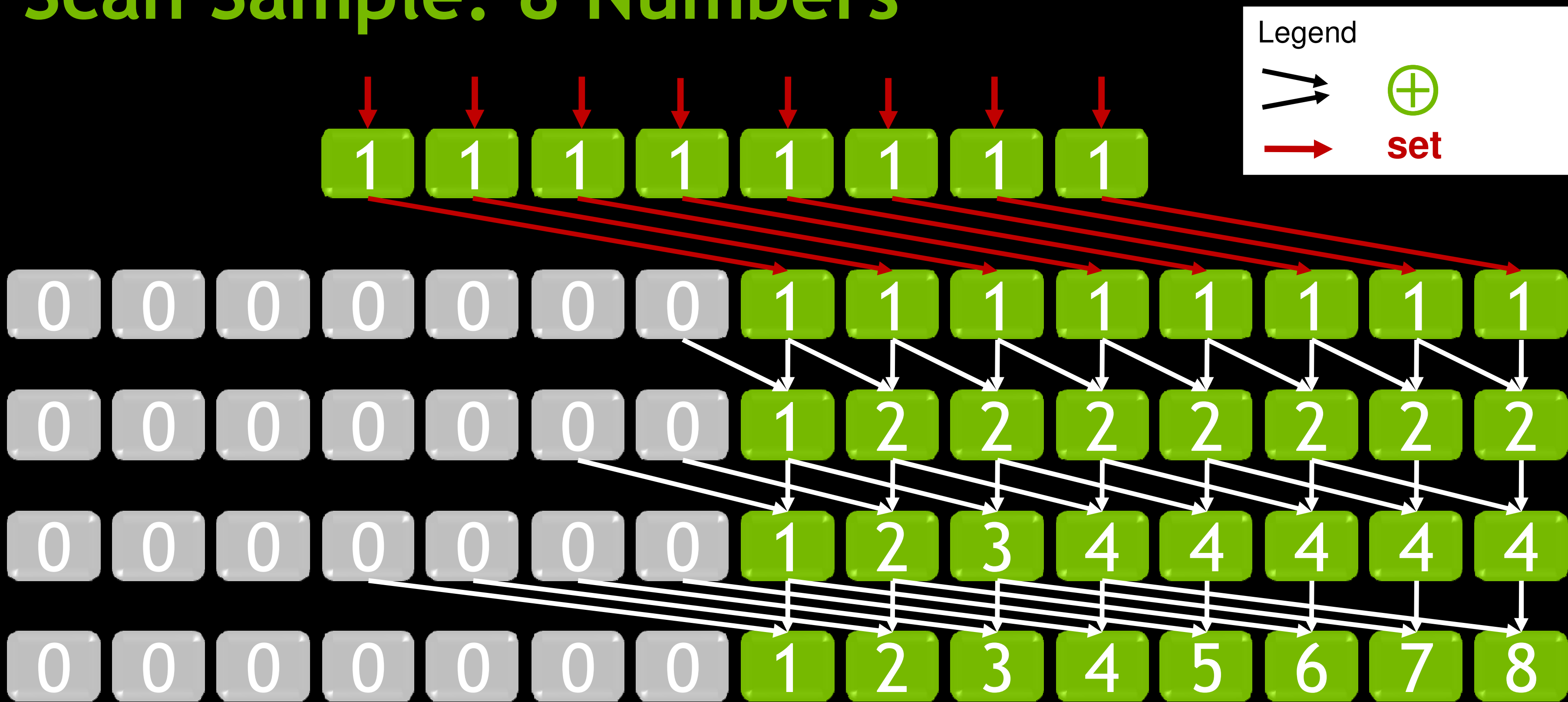

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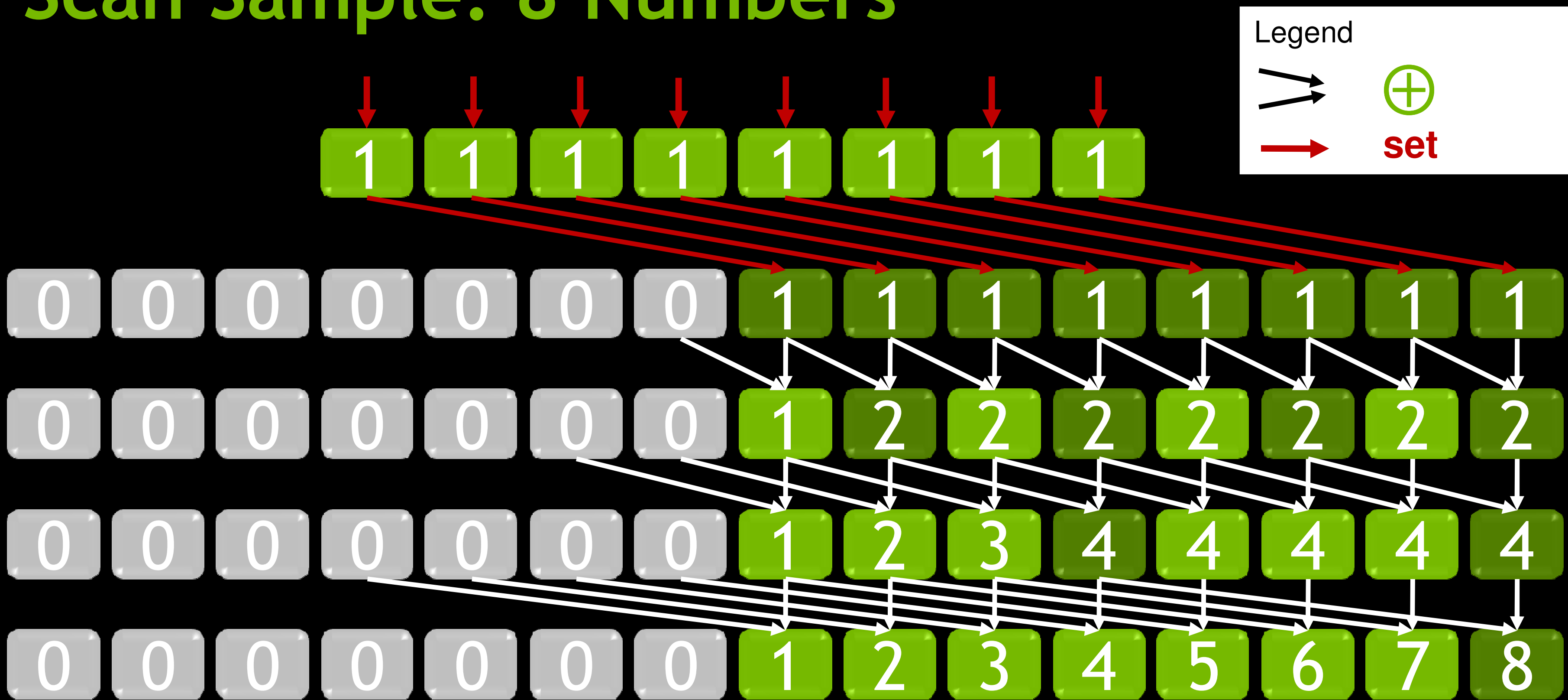
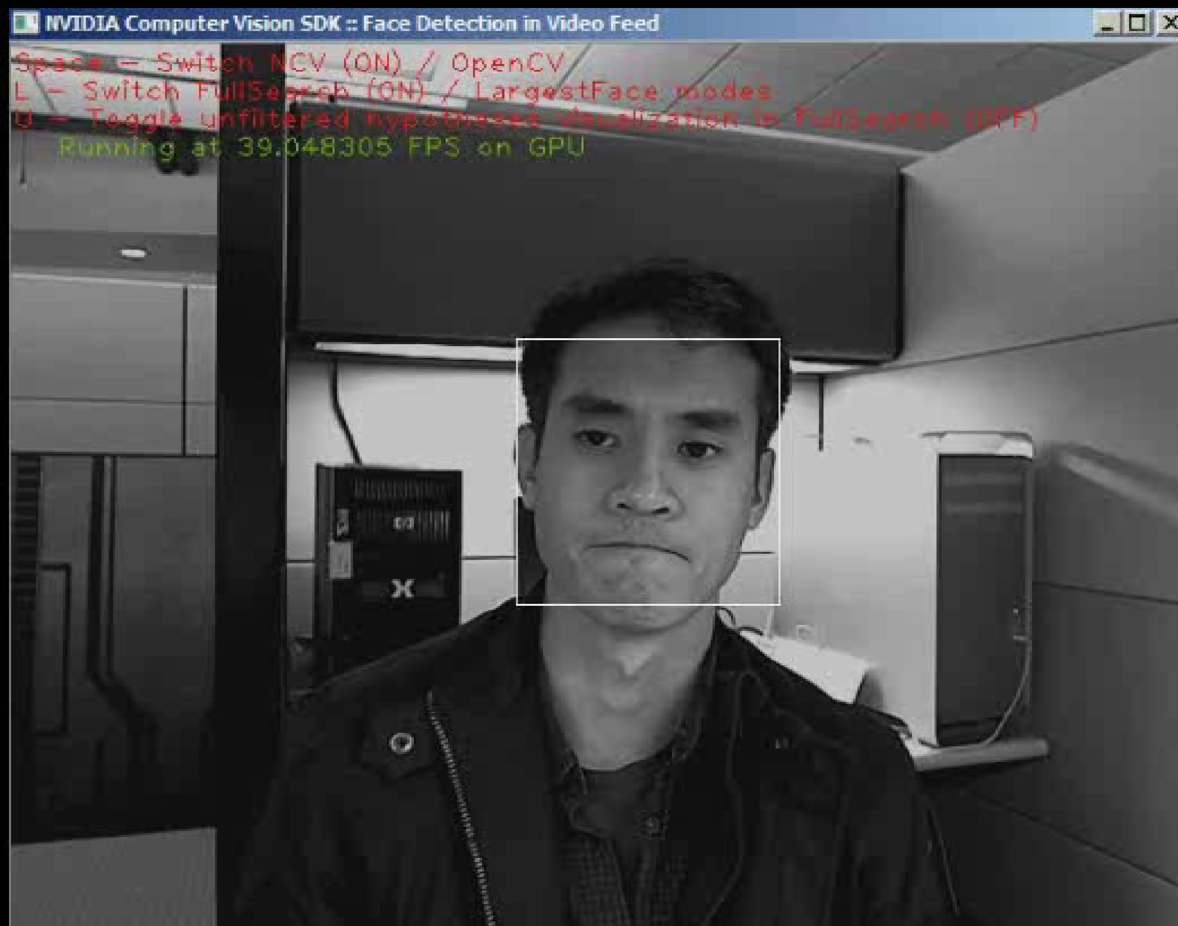
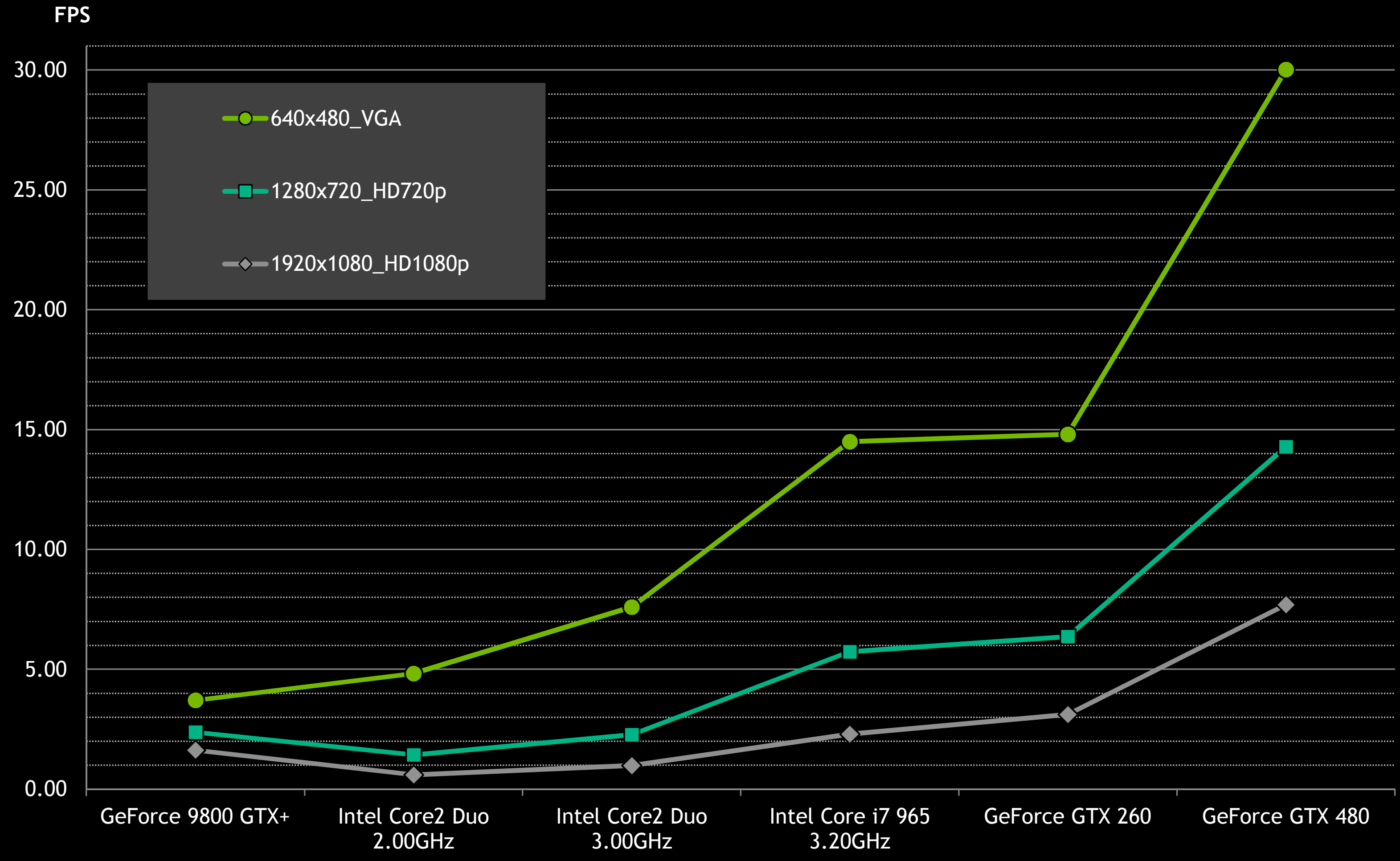


# GPU Face Detection



# GPU Face Detection Performance



# OpenCV NCV Framework

Features:

- Native and Stack GPU memory allocators
- Protected allocations (fail-safety)
- Containers: NCVMatrix, NCVVector
- Runtime C++ template dispatcher
- NPP_staging – a place for missing NPP functions
  - Integral images
  - Mean and StdDev calculation
  - Vector compaction

# OpenCV NCV Haar Cascade Classifiers

Haar Object Detection from OpenCV GPU module:

- Implemented on top of NCV
- Uses NPP with extensions (NPP_staging)
- Not only faces!
- Suitable for production applications
  - Reliable (fail-safe)
  - Largest Object mode (up to 200 fps)
  - All Objects mode

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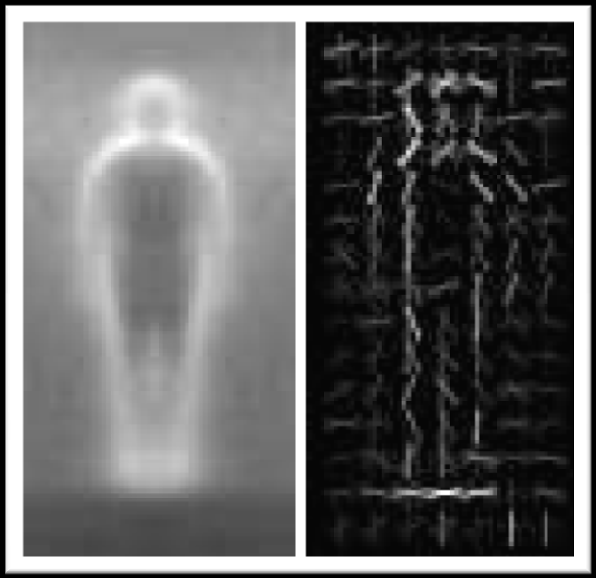
- Pedestrian detection on GPU

# Pedestrian Detection

- HOG descriptor
  - Introduced by Navneet Dalal and Bill Triggs
  - Feature vectors are compatible with the INRIA Object Detection and Localization Toolkit http://pascal.inrialpes.fr/soft/olt/

# Pedestrian Detection: HOG Descriptor

- Object shape is characterized by distributions of:
  - Gradient magnitude
  - Gradient orientation
- Grid of orientation histograms



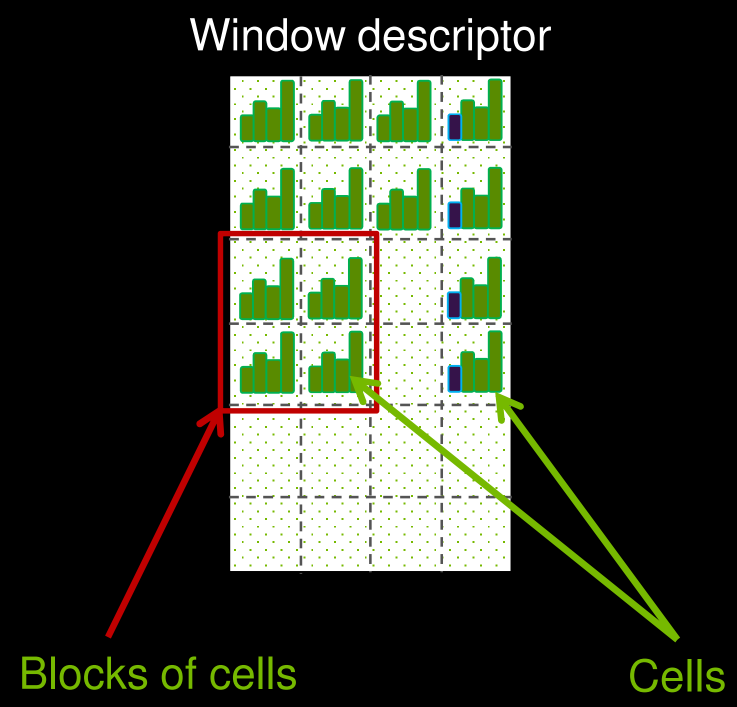
Magnitude Orientation

# Pedestrian Detection: Working on Image

- Gamma correction
- Gradients calculation
- Sliding window algorithm
- Multi-scale

# Pedestrian Detection: Inside Window

- Compute histograms inside cells
- Normalize blocks of cells
- One cell may belong to >1 block
- Apply linear SVM classifier



# Pedestrian Detection: Step 1

**Gradients computation** → Block histograms calculation → Histograms normalization → Linear SVM

- Gamma correction improves quality
- Sobel filter 3x3 by columns and rows
- Output: magnitude and angle

$$\mathbf{G}_x = \begin{bmatrix} -1 & 0 & +1 \\ -2 & 0 & +2 \\ -1 & 0 & +1 \end{bmatrix} * \text{Image}$$

$$\mathbf{G}_y = \begin{bmatrix} -1 & -2 & -1 \\ 0 & 0 & 0 \\ +1 & +2 & +1 \end{bmatrix} * \text{Image}$$

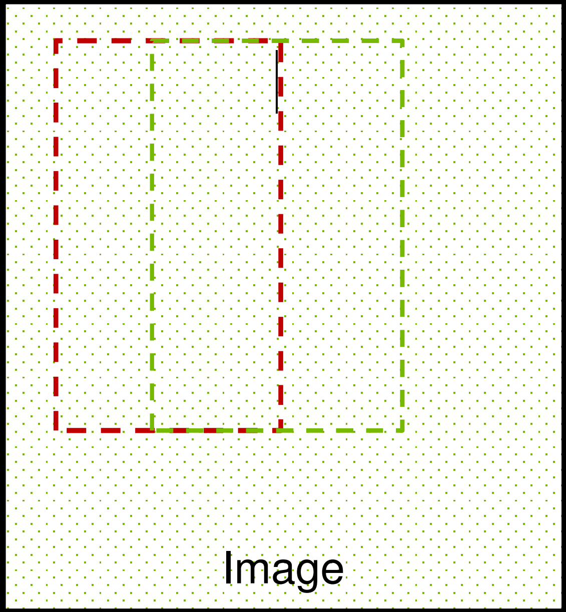
$$\mathbf{G} = \sqrt{\mathbf{G}_x{}^2 + \mathbf{G}_y{}^2}$$

$$\mathbf{\Theta} = \arctan\left(\frac{\mathbf{G}_y}{\mathbf{G}_x}\right)$$

# Pedestrian Detection: Step 2

Gradients computation → **Block histograms calculation** → Histograms normalization → Linear SVM

- Big intersection in close positions
- Require window stride to be multiple of cell size
- Histograms of blocks are computed independently



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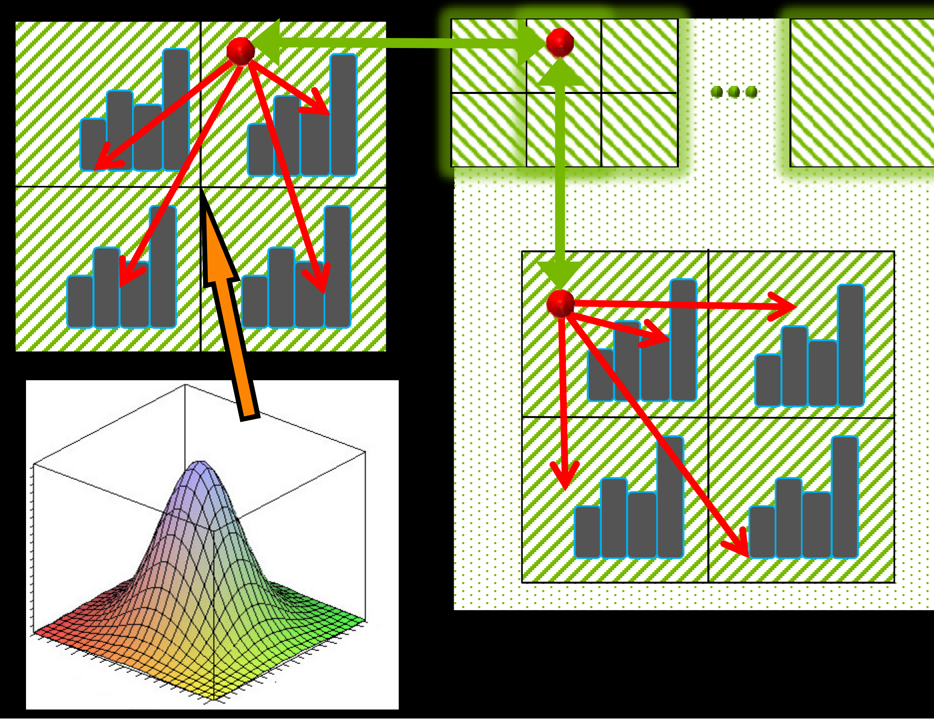
# Pedestrian Detection: Step 2

Gradients computation → **Block histograms calculation** → Histograms normalization → Linear SVM

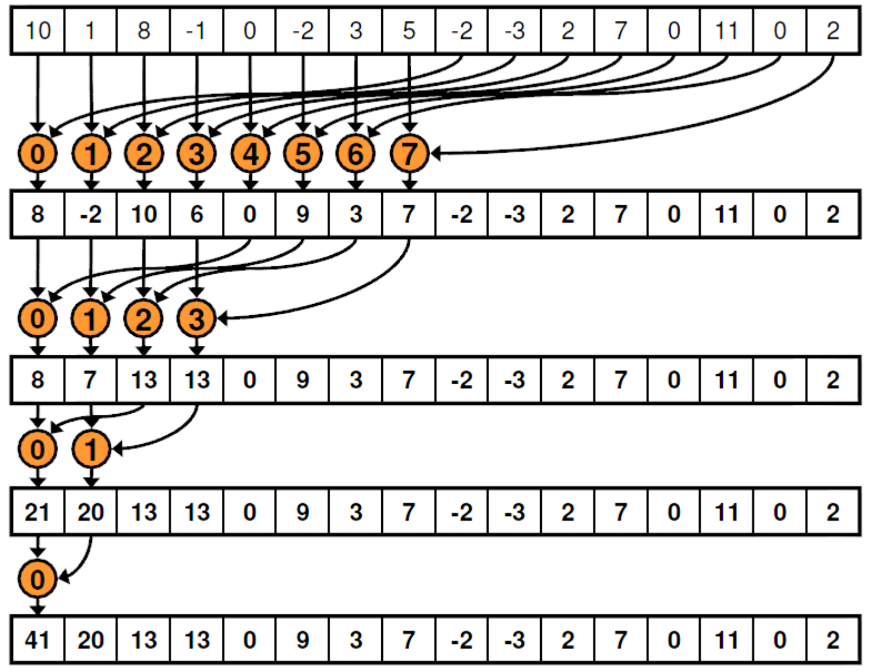
- Pixels vote in proportion to gradient magnitude
- Tri-linear interpolation
  - 2 orientation bins
  - 4 cells
- Gaussian
  - Decreases weight of pixels near block boundary



# Pedestrian Detection: Step 3

Gradients computation → Block histograms calculation → **Histograms normalization** → Linear SVM

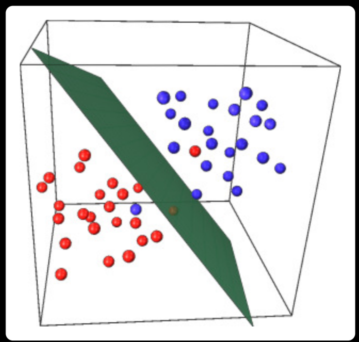
- Normalization
  - L2-Hys norm
    - L2 norm, clipping, normalization
  - 2 parallel reductions in shared memory

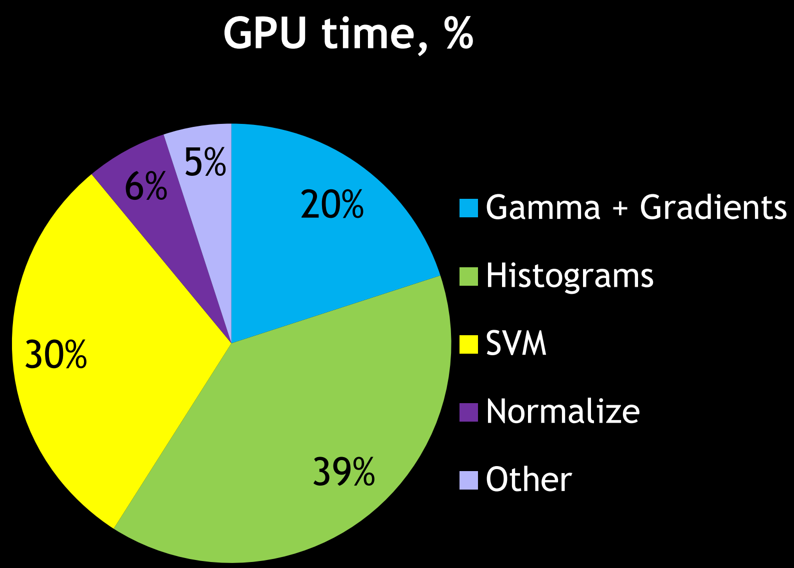


# Pedestrian Detection: Step 4

Gradients computation → Block histograms calculation → Histograms normalization → **Linear SVM**

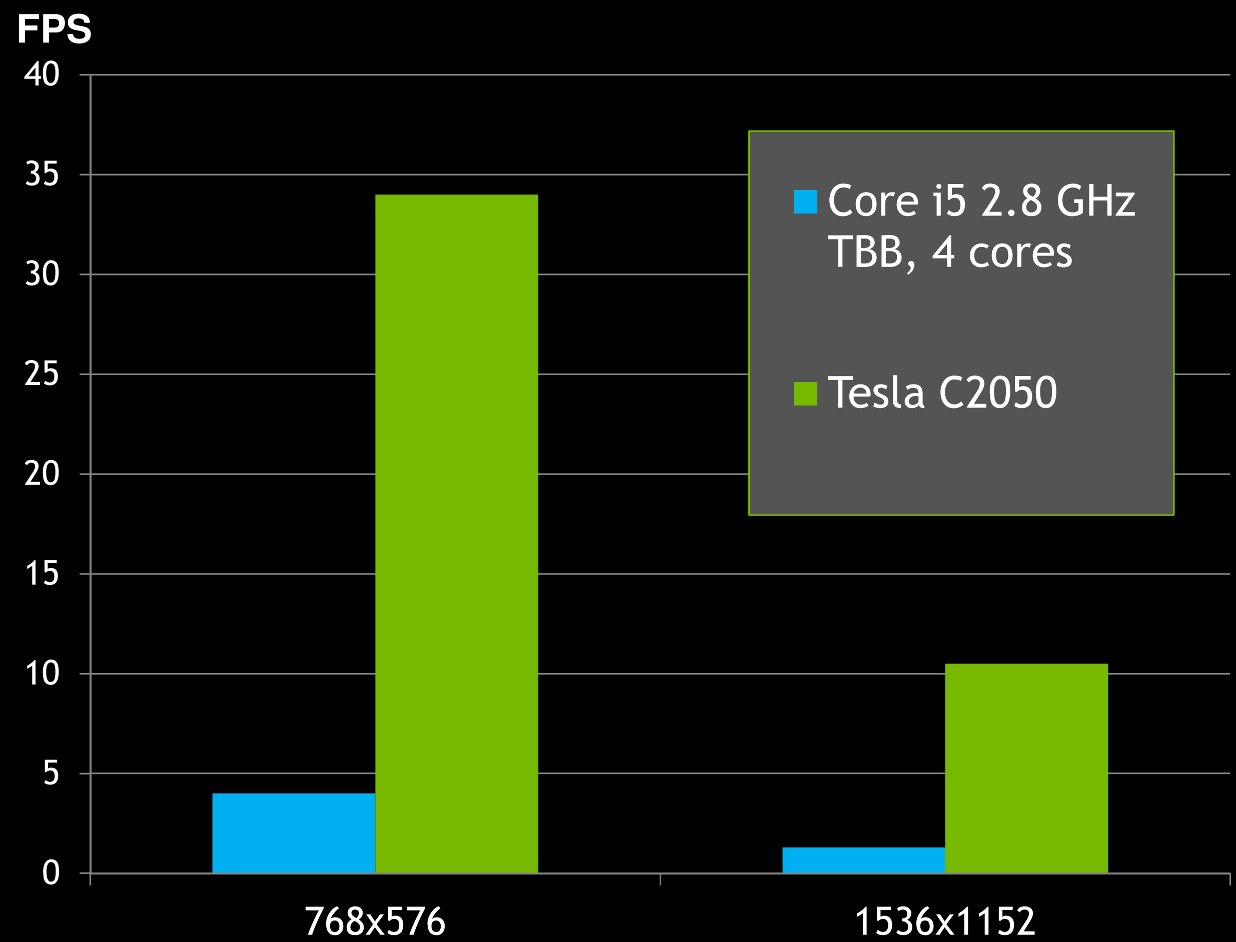
- Linear SVM
  - Classification is just a dot product
  - 1 thread block per window position





# Pedestrian Detection Performance

- 8× times faster!
- Detection rate
  - Same as CPU



# Thank you

CUDA http://developer.nvidia.com/cuda

OpenCV http://opencv.willowgarage.com/wiki

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