



Stichting NIOC

---

## Stichting NIOC en de NIOC kennisbank

Stichting NIOC ([www.nioc.nl](http://www.nioc.nl)) stelt zich conform zijn statuten tot doel: het realiseren van congressen over informatica onderwijs en voorts al hetgeen met een en ander rechtstreeks of zijdelings verband houdt of daartoe bevorderlijk kan zijn, alles in de ruimste zin des woords.

De stichting NIOC neemt de archivering van de resultaten van de congressen voor zijn rekening. De website [www.nioc.nl](http://www.nioc.nl) ontsluit onder "Eerdere congressen" de gearchiveerde websites van eerdere congressen. De vele afzonderlijke congresbijdragen zijn opgenomen in een kennisbank die via dezelfde website onder "NIOC kennisbank" ontsloten wordt.

Op dit moment bevat de NIOC kennisbank alle bijdragen, incl. die van het laatste congres (NIOC2023, gehouden op donderdag 30 maart 2023 jl. en georganiseerd door NHL Stenden Hogeschool). Bij elkaar bijna 1500 bijdragen!

We roepen je op, na het lezen van het document dat door jou is gedownload, de auteur(s) feedback te geven. Dit kan door je te registreren als gebruiker van de NIOC kennisbank. Na registratie krijg je bericht hoe in te loggen op de NIOC kennisbank.

Het eerstvolgende NIOC vindt plaats op donderdag 27 maart 2025 in Zwolle en wordt dan georganiseerd door Hogeschool Windesheim. Kijk op [www.nioc2025.nl](http://www.nioc2025.nl) voor meer informatie.

Wil je op de hoogte blijven van de ontwikkeling rond Stichting NIOC en de NIOC kennisbank, schrijf je dan in op de nieuwsbrief via

[www.nioc.nl/nioc-kennisbank/aanmelden-nieuwsbrief](http://www.nioc.nl/nioc-kennisbank/aanmelden-nieuwsbrief)

Reacties over de NIOC kennisbank en de inhoud daarvan kun je richten aan de beheerder:

R. Smedinga [kennisbank@nioc.nl](mailto:kennisbank@nioc.nl).

Vermeld bij reacties jouw naam en telefoonnummer voor nader contact.



**Research master project at LIT**  
1 September 2011 – 1 September 2013

**LIT**  
INSTITUUT  
TECHNOLOGISCHE  
LIMBURG

**Accelerating sequential computer vision  
algorithms using commodity parallel hardware**

**NIOC 4 April 2013**

**Jaap van de Loosdrecht**

NHL Centre of Expertise in Computer Vision  
Van de Loosdrecht Machine Vision BV

**NHL**  
COMPUTER VISION

**visionlab**

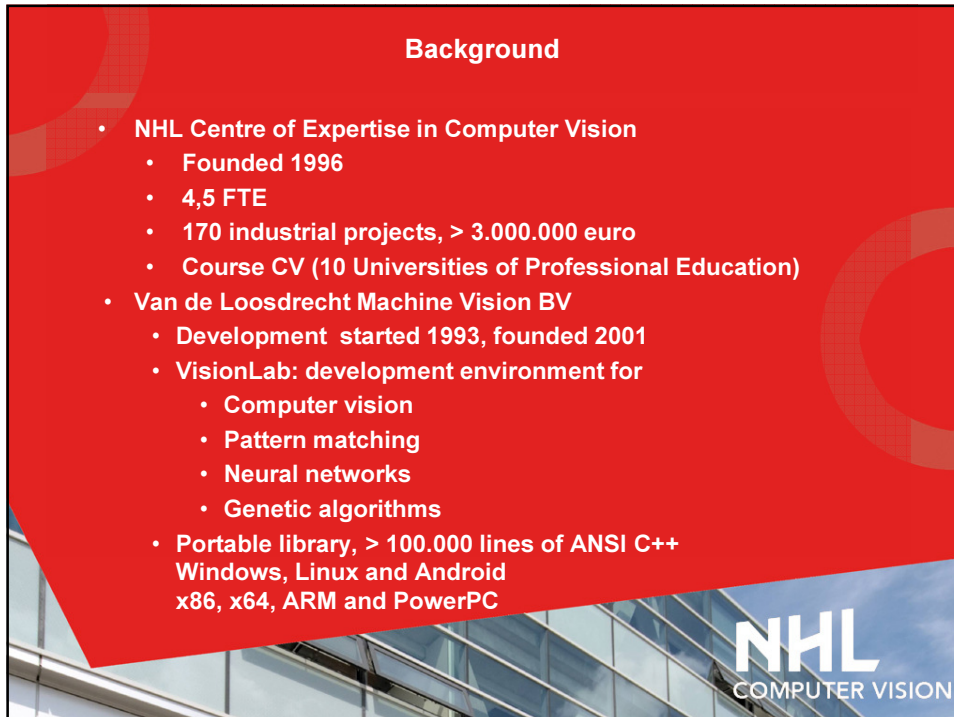
**vclm**  
VAN DE LOOSDRECHT  
CENTRUM  
COMPUTER VISION



**Overview**

- Background and motivation
- CPU versus GPU architecture
- Choice of the standards for multi-core programming
  - OpenMP
  - OpenCL
  - Benchmark examples
  - Evaluation and recommendations
- Future work
- Conclusions

**NHL**  
COMPUTER VISION



### Background

- NHL Centre of Expertise in Computer Vision
  - Founded 1996
  - 4,5 FTE
  - 170 industrial projects, > 3.000.000 euro
  - Course CV (10 Universities of Professional Education)
- Van de Loosdrecht Machine Vision BV
  - Development started 1993, founded 2001
  - VisionLab: development environment for
    - Computer vision
    - Pattern matching
    - Neural networks
    - Genetic algorithms
  - Portable library, > 100.000 lines of ANSI C++  
Windows, Linux and Android  
x86, x64, ARM and PowerPC

**NHL**  
COMPUTER VISION



### Research master project at Limerick Institute of Technology

Motivation:


- From 2004 onwards the clock frequency of CPUs has not increased significantly
- Computer Vision applications have an increasing demand for more processing power
- The only way to get more performance is to go for parallel programming

Apply parallel programming techniques to meet the challenges posed in computer vision by the limits of sequential architectures

**NHL**  
COMPUTER VISION

### Aims and objectives

- Examine, compare and evaluate existing programming languages and environments for parallel computing on multi-core CPUs and GPUs
- Choose one standard for
  - Multi-core CPU programming
  - GPU programming
- Re-implement a number of standard and well-known algorithms in computer vision using a parallel programming approach
- Test performance of implemented parallel algorithms and compare performance to existing sequential implementation of VisionLab
- Evaluate test results, benefits and costs of parallel approaches to implementation of computer vision algorithms



### Related research

Other research projects:

- Quest for one domain specific algorithm to compare the best sequential with best parallel implementation on a specific hardware
- Framework for auto parallelisation or vectorization  
In research, not yet generic applicable

This project is distinctive:

- Investigate how to speedup a whole library by parallelizing the algorithms in an economical way and execute them on multiple platforms
  - 100.000 lines of ANSI C++ code
  - Generic library
  - Portability and vendor independency
  - Variance in execution times
  - Run time prediction if parallelization is beneficial



### Introduction CPU and GPU architecture

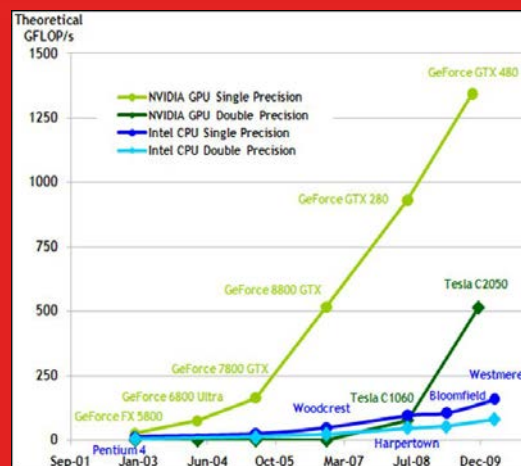
#### Observations:

- The last years CPU's do not much become faster than about 4 GHz
- Multi-core CPU PC's are now widely available at low costs
- Graphics cards have much more computing power than CPUs and are available at low costs

*"The Free Lunch Is Over: A Fundamental Turn Toward Concurrency in Software"* Sutter (2005) predicted that the only way to get more processing power in the future, is to go for parallel programming, and that it is not going to be an easily way

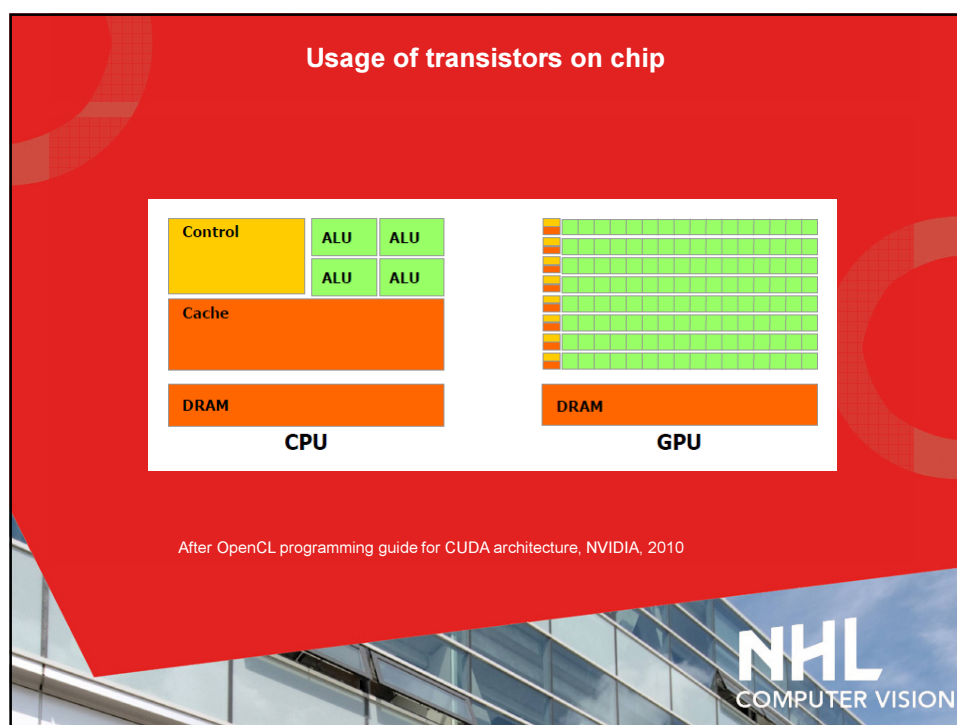
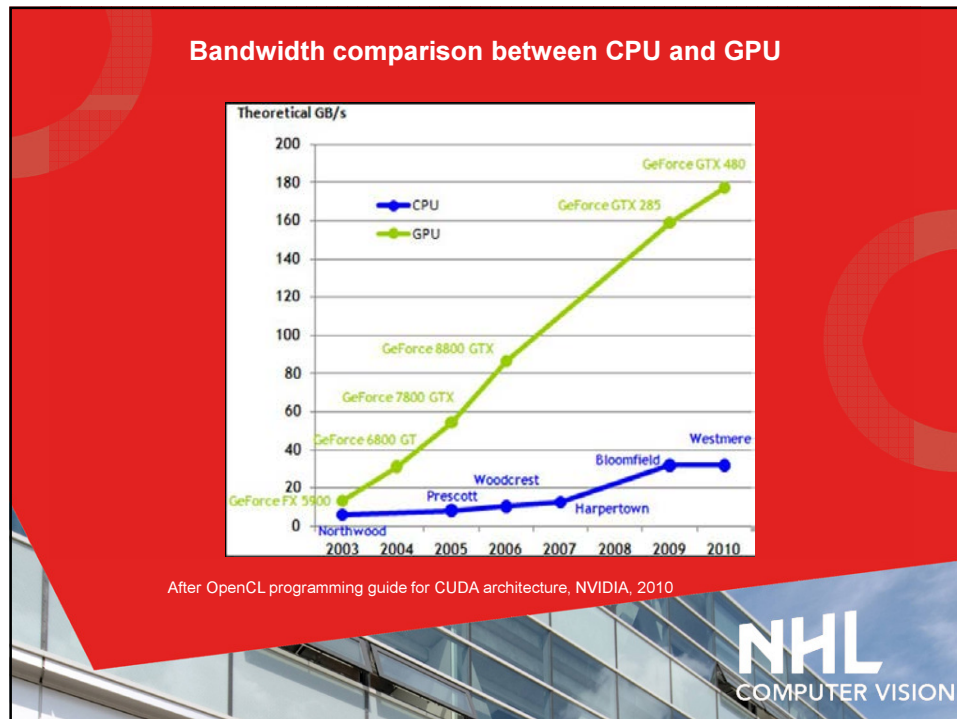
**NHL**  
COMPUTER VISION

### Floating point operations per second comparison between CPU and GPU



After OpenCL programming guide for CUDA architecture, NVIDIA, 2010

**NHL**  
COMPUTER VISION






### CPU architecture

Designed for a wide variety of applications and to provide fast response times to a single task:


- Multi-core MIMD architecture with
  - Branch prediction
  - Out-of-order execution
  - Super-scalar
  - Each core SIMD vector processor
  - Complex hierarchy of cache memory with cache coherence
- Restricted by thermal envelope

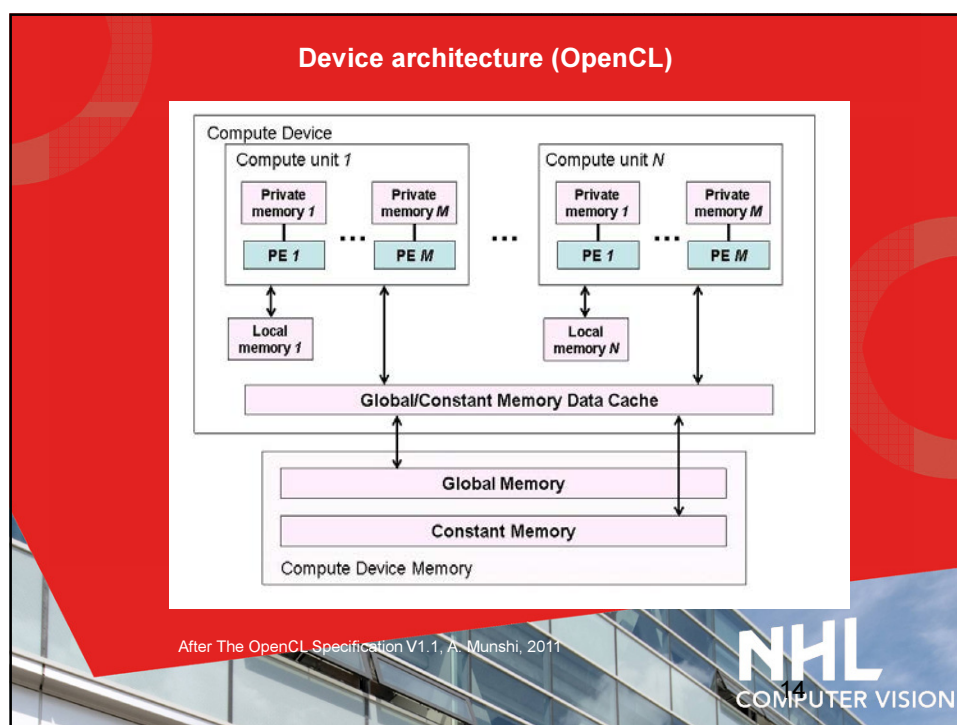
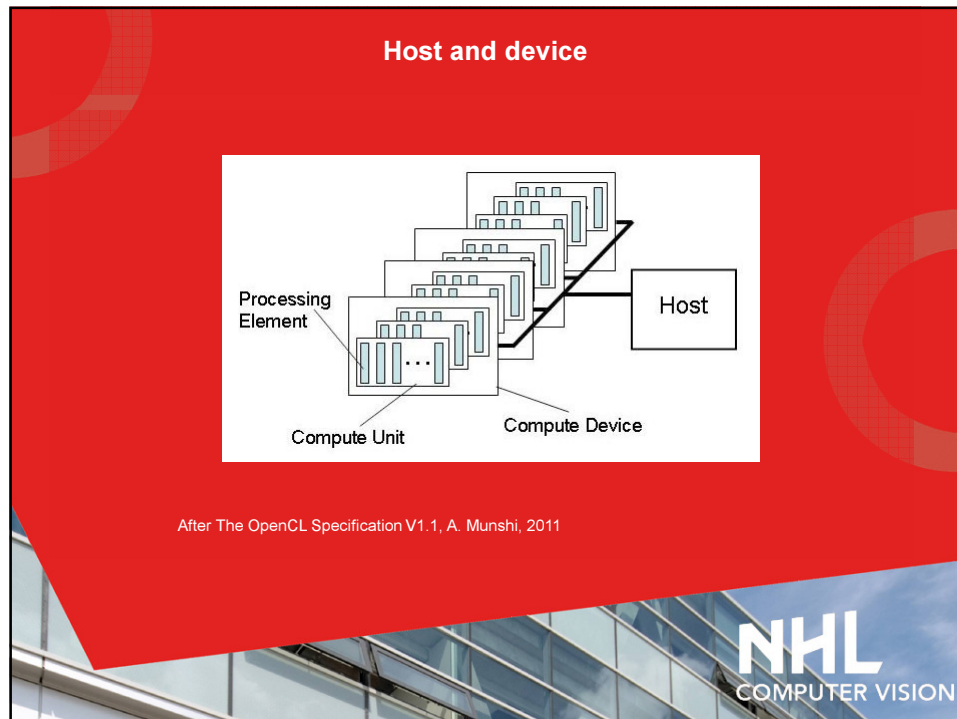


### GPU architecture

Designed for throughput:

- Device architecture
- GPU memory hierarchy
- Warps or wavefronts
- (Coalesced memory access of global memory)
- (Bank conflicts in accessing local memory)







### GPU memory hierarchy

**Compute device memory**


- Accessible by all processor elements
- Largest memory
- Slowest access time
- Divided into a global memory part with read/write access and a constant memory part with only read access

**Local memory**

- Only accessible by the processor elements in a compute unit
- Available in lesser quantities than compute global memory but in larger quantity than private memory
- Faster access time than global memory but slower than private memory

**Private memory**


- Only accessible by one processor element
- Available only in very limited quantity
- Fastest access time



### GPU architecture example

**ATI Radeon 5750 GPU (100 euro, September 2011)**

- 9 compute units with each 16 processor elements
- Each processor element is a five-way very long instruction word (VLIW) SIMD like vector processor
- One of the five sub-processors can execute transcendental instructions
- $9 \times 16 \times 5 = 720$  sub-processors
- Running at 700 Mhz, a peak performance of 1008 GFlops.
- 1 GByte global memory, peak bandwidth of 74 GBytes/s
- 32 KByte local memory for each compute unit, peak bandwidth of 806 GBytes/s
- 1024 registers of private memory for each processor element, peak bandwidth of 4838 GBytes/s



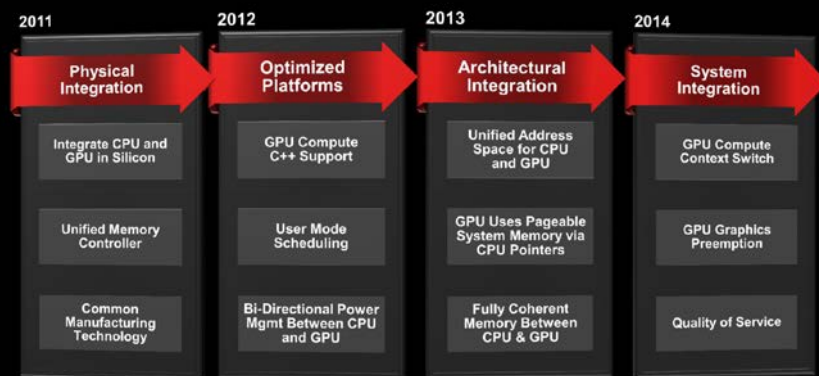
### Warps or wavefronts

- All work-items in a warp execute the same instruction in parallel on all cores of a compute unit (SIMT)
- Typical size for a warp is 16, 32 or 64 work-items
- Branch diversion
- Zero-overhead warp scheduling
- Occupancy rate  
Hide long global memory latency

**NHL**  
COMPUTER VISION

### HSA Roadmap

#### HETEROGENEOUS SYSTEM ARCHITECTURE ROADMAP



5 | The Programmer's Guide to a Universe of Possibility | June 12, 2012

After P. Rogers, AMD 2012

**Fusion**<sup>12</sup>  
AMD DEVELOPER SUMMIT

**NHL**  
COMPUTER VISION


### Survey of 22 standards for parallel programming

**Multi-core CPU:**

- Array Building Blocks
- C++11 Threads
- Cilk Plus
- MCAPI
- MPI
- OpenMP
- Parallel Building Blocks
- Parallel Patterns Library
- Posix Threads
- PVM
- Thread Building Blocks


**GPU and heterogeneous programming:**

- Accelerator
- CUDA
- C++ AMP
- Direct Compute
- HMPP Workbench
- Liquid Metal
- OpenACC
- OpenCL
- PGI Accelerator
- SaC
- Shader languages



### Choice of the standard for multi-core CPU programming (1 Oct 2011)

Requirement ----- Standard	Industry standard	Maturity	Acceptance by market	Future developments	Vendor independence	Portability	Scalable to ccNUMA (optional)	Vector capabilities (optional)	Effort for conversion
Array Building Blocks	No	Beta	New, not ranked	Good	Poor	Poor	No	Yes	Huge
C++11 Threads	Yes	Partly new	New, not ranked	Good	Good	Good	No	No	Huge
Cilk Plus	No	Good	Rank 6	Good	Reasonable No MSVC	Reasonable	No	Yes	Low
MCAPI	No	Poor	Not ranked	Poor	Poor	Poor	Yes	No	Huge
MPI	Yes	Excellent	Rank 7	Good	Good	Good	Yes	No	Huge
OpenMP	Yes	Excellent	Rank 1	Good	Good	Good	Yes, only GNU	No	Low
Parallel Patterns Library	No	Reasonable	New, not ranked	Good	Poor Only MSVC	Poor	No	No	Huge
Posix Threads	Yes	Excellent	Not ranked	Poor	Good	Good	No	No	Huge
Thread Building Blocks	No	Good	Rank 3	Good	Reasonable	Reasonable	No	No	Huge



**Choice of the standard for GPU programming (1 Oct 2011)**

Requirement ----- Standard	Industry standard	Maturity	Acceptance by market	Future developments	Expected familiarization time	Hardware vendor independence	Software vendor independence	Portability	Heterogeneous
Accelerator	No	Good	Not ranked	Bad	Medium	Bad	Bad	Poor	No
CUDA	No	Excellent	Rank 5	Good	High	Bad	Bad	Bad	No
Direct Compute	No	Poor	Not ranked	Unknown	High	Bad	Bad	Bad	No
HMPP	No	Poor	Not ranked	Plan for open standard	Medium	Reasonable	Bad	Good	Yes
OpenCL	Yes	Good	Rank 2	Good	High	Excellent	Good	Good	Yes
PGI Accelerator	No	Reasonable	Not ranked	Unknown	Medium	Bad	Bad	Bad	No

**NHL**  
COMPUTER VISION

**OpenMP**

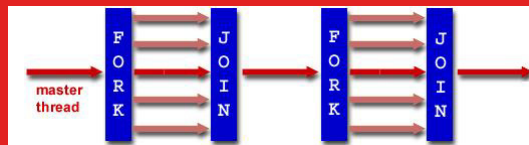
- Introduction
- Examples

See for standard: [www.openmp.org](http://www.openmp.org)

**NHL**  
COMPUTER VISION

## OpenMP introduction

- An API that supports multi-platform shared memory multiprocessing programming in C, C++ and Fortran
- Supports both data parallel and task parallel multiprocessing
- Fork-join programming model



After Introduction to Parallel Computing, Barney, 2011

**NHL**  
COMPUTER VISION

## OpenMP example adding two vectors

```
const int SIZE = 1000;
double a[SIZE], b[SIZE], c[SIZE];
// code for initialising array b and c
#pragma omp for
for (int j = 0; j < SIZE; j++) {
    a[j] = b[j] + c[j];
} // for j
```

Assuming CPU has four cores, at executing time the next events will happen:

- The master thread forks a team of three threads
- All four threads will execute in parallel one quarter of the for loop. The first thread will execute the for loop for  $0 \leq j < 250$ , the second thread will execute the for loop for  $250 \leq j < 500$ , etc
- When all threads have completed their work the threads will join

**NHL**  
COMPUTER VISION

### OpenMP compiler directives

All compiler directives start with “#pragma omp”. There are compiler directives for expressing the type of parallelism:

- For loop directive for data parallelism
- Parallel regions directive for task parallelism
- Single and master directives for sequential executing of code in parallel constructs

There are also compiler directives for synchronisation primitives, like:

- Atomic variables
- Barriers
- Critical sections
- Flushing (synchronizing) memory and caches between threads

**NHL**  
COMPUTER VISION

### Sequential Threshold

```
template <class OrdImageT, class PixelT>
void Threshold (OrdImageT &image, const PixelT low, const PixelT high) {
    PixelT *pixelTab = image.GetFirstPixelPtr();
    int nrPixels = image.GetNrPixels();
    for (int i = 0; i < nrPixels; i++) {
        pixelTab[i] = ((pixelTab[i] >= low) && (pixelTab[i] <= high))
            ? OrdImageT::Object() : OrdImageT::BackGround();
    } // for all pixels
} // Threshold
```

**NHL**  
COMPUTER VISION

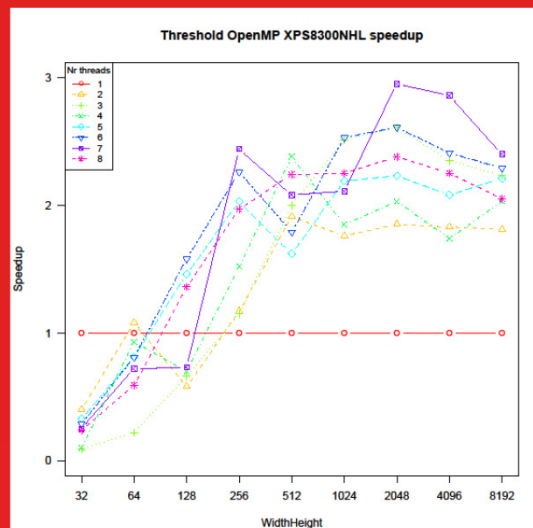


### OpenMP Threshold

```
template <class OrdImageT, class PixelT>
void Threshold (OrdImageT &image, const PixelT low, const PixelT high) {
    PixelT *pixelTab = image.GetFirstPixelPtr();
    int nrPixels = image.GetNrPixels();
    #pragma omp parallel for
        for (int i = 0; i < nrPixels; i++) {
            pixelTab[i] = ((pixelTab[i] >= low) && (pixelTab[i] <= high))
                ? OrdImageT::Object() : OrdImageT::BackGround();
        } // for all pixels
    } // Threshold
```

NHL  
COMPUTER VISION

### OpenMP Threshold speedup graph on i7 2600 (4 cores)



NHL  
COMPUTER VISION

### Sequential Histogram

```
template <class IntImageT>
void Histogram0 (const IntImageT &image, const int hisSize, int *his) {
    typedef typename IntImageT::PixelType PixelT;
    memset(his, 0, hisSize * sizeof(int));
    PixelT *pixelTab = image.GetFirstPixelPtr();
    const int nrPixels = image.GetNrPixels();
    for (int i = 0; i < nrPixels; i++) {
        his[pixelTab[i]]++;
    } // for i
} // Histogram0
```

**NHL**  
COMPUTER VISION

### OpenMP Histogram

Pseudo code:

- Clear global histogram
- Split image in N parts and do in parallel for each part
  - Create and clear local histogram
  - Calculate local histogram
- Add all local histograms to global histogram

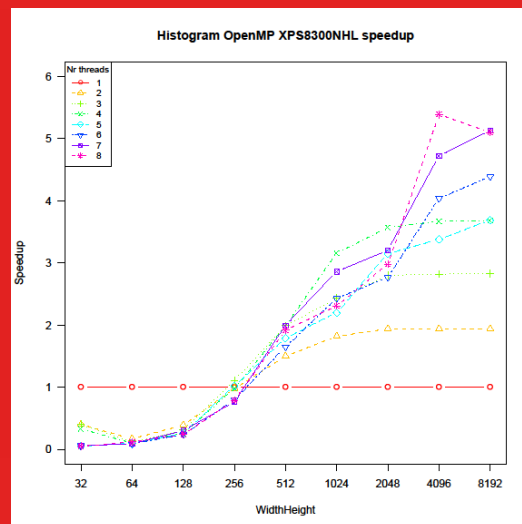
**NHL**  
COMPUTER VISION

## OpenMP Histogram

```
template <class IntImageT>
void Histogram0 (const IntImageT &image, const int hisSize, int *his) {
    typedef typename IntImageT::PixelType PixelT;
    memset(his, 0, hisSize * sizeof(int));
    PixelT *pixelTab = image.GetFirstPixelPtr();
    const int nrPixels = image.GetNrPixels();
    #pragma omp parallel
    {
        int *localHis = new int[hisSize];
        memset(localHis, 0, hisSize * sizeof(int));
        #pragma omp for nowait
        for (int i = 0; i < nrPixels; i++) {
            localHis[pixelTab[i]]++;
        } // for i
        #pragma omp critical (CalcHistogram0)
        {
            for (int h = 0; h < hisSize; h++) {
                his[h] += localHis[h];
            } // for h
        } // omp critical
        delete [] localHis;
    } // omp parallel
} // Histogram0
```

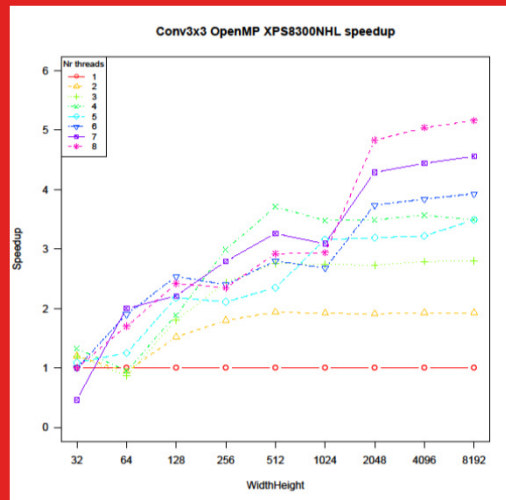
NHL  
COMPUTER VISION

## OpenMP Histogram speedup graph on i7 2600 (4 cores)



NHL  
COMPUTER VISION

### OpenMP Convolution speedup graph on i7 2600 (4 cores)



**NHL**  
COMPUTER VISION

### OpenCL

- Kernel language
- Host API
- Examples

See for standard: [www.khronos.org/opencl](http://www.khronos.org/opencl)

**NHL**  
COMPUTER VISION

## OpenCL kernel language

Subset of ISO C99 with extensions

- No function pointers, recursion, bit fields, variable-length arrays and standard C99 header files
- Extensions: vector types, synchronization, functions to work with work-items/groups, etc

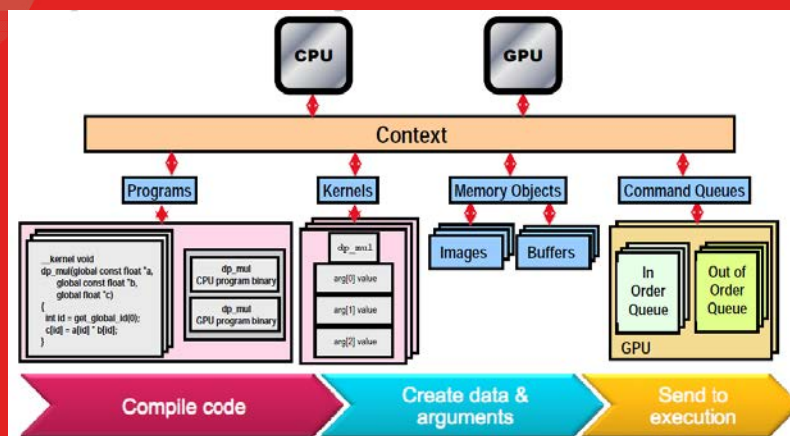
Proposal for OpenCL Static C++ Kernel Language Extension  
Introduces C++ like features such as classes and templates

Kernel for adding of two vectors

```
kernel void VecAdd (global int* c, global int* a, global int* b) {
    unsigned int n = get_global_id(0);
    c[n] = a[n] + b[n];
}
```

**NHL**  
COMPUTER VISION

## OpenCL execution model



After OpenCL. A Standard platform for programming Heterogeneous parallel computers, Mattson et al, 2009

**NHL**  
COMPUTER VISION

## OpenCL Host API

For adding of two vectors (67 C statements, without error checking code)

- Allocate space for vectors and initialize
- Discover and initialize OpenCL platform
- Discover and initialise compute device
- Create a context
- Create a command queue
- Create device buffers
- Create and compile the program
- Create the kernel
- Set the kernel arguments
- Configure the NDRange
- Write host data to device buffers
- Enqueue the kernel for execution
- Read the output buffer back to the host
- Verify result
- Release OpenCL and host resources

**NHL**  
COMPUTER VISION

## OpenCL Threshold kernel One pixel or vector of pixels per kernel

```
kernel void Threshold (global ImageT* image, const PixelT low,
                      const PixelT high) {
    const PixelT object = 1;
    const PixelT background = 0;
    const unsigned int i = get_global_id(0);
    image[i] = ((image[i] >= low) && (image[i] <= high)) ?
                object : background;
} // Threshold
```

“Poor man’s” template for Int16Image:

- ImageT = short, short4, short8 or short16
- PixelT = short

**NHL**  
COMPUTER VISION



## OpenCL Threshold host side VisionLab script

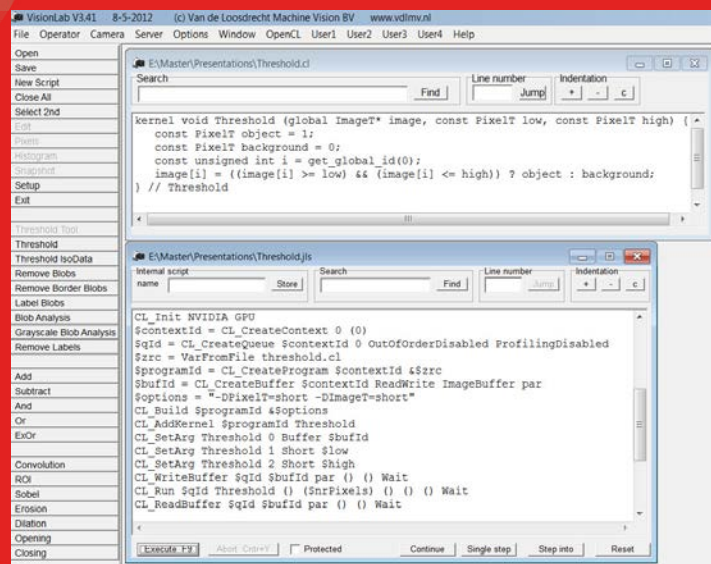
```

CL_Init NVIDIA GPU
$contextId = CL_CreateContext 0 (0)
$qId = CL_CreateQueue $contextId 0 OutOfOrderDisabled ProfilingDisabled
$zrc = VarFromFile threshold.cl
$programId = CL_CreateProgram $contextId &$zrc
$bufId = CL_CreateBuffer $contextId ReadWrite ImageBuffer par
$options = "-DPixelT=short -DImageT=short"
CL_Build $programId &$options
CL_AddKernel $programId Threshold
CL_SetArg Threshold 0 Buffer $bufId
CL_SetArg Threshold 1 Short $low
CL_SetArg Threshold 2 Short $high
CL_WriteBuffer $qId $bufId par () () Wait
CL_Run $qId Threshold () ($nrPixels) () () () Wait
CL_ReadBuffer $qId $bufId par () () Wait

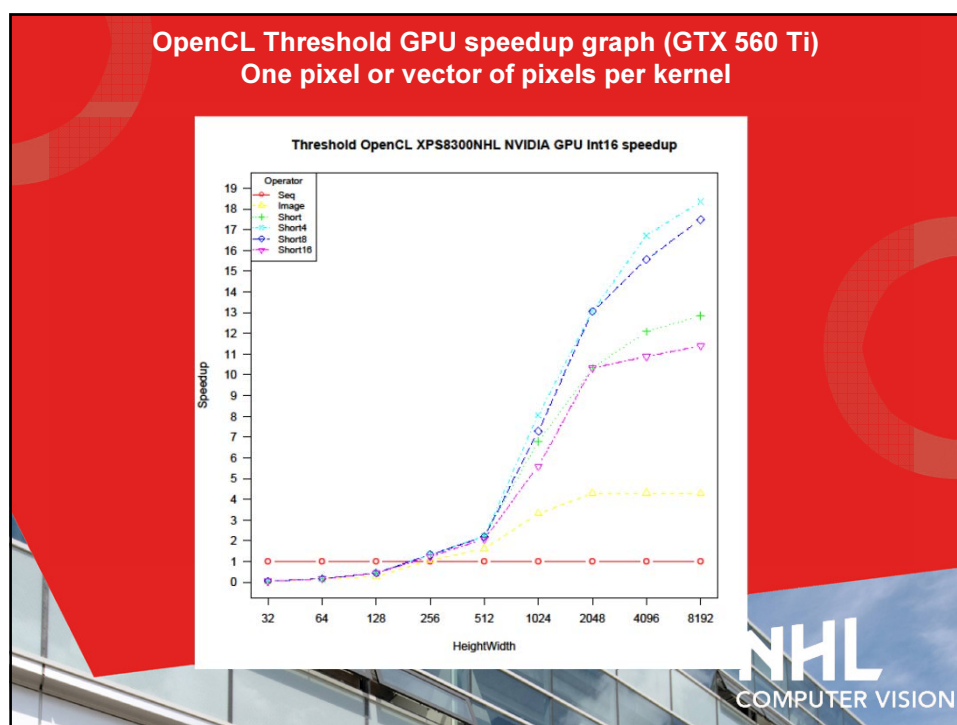
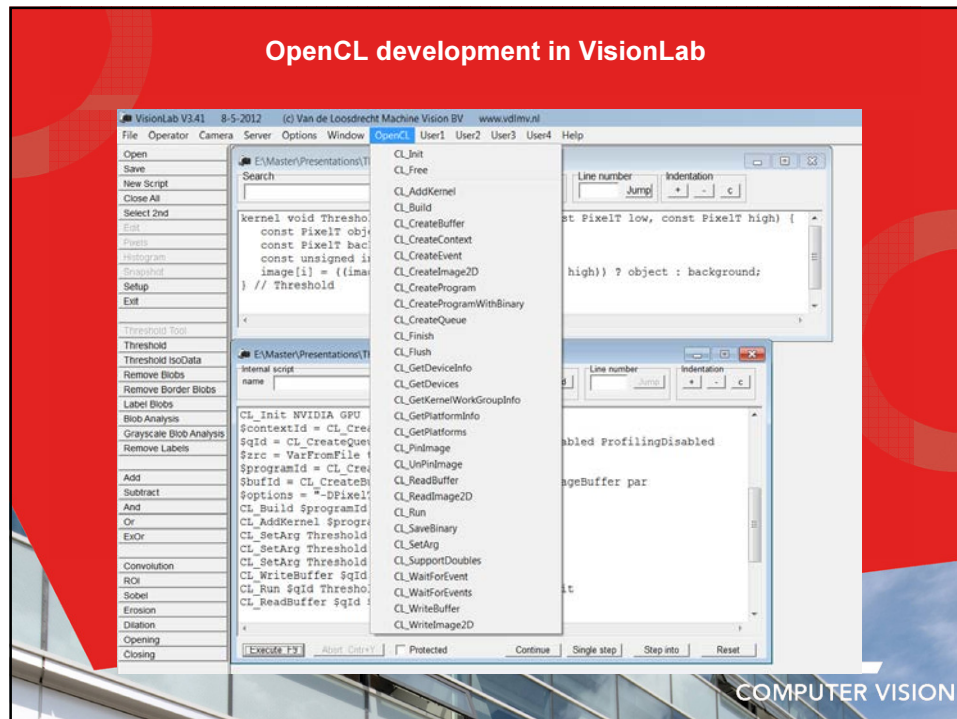
```

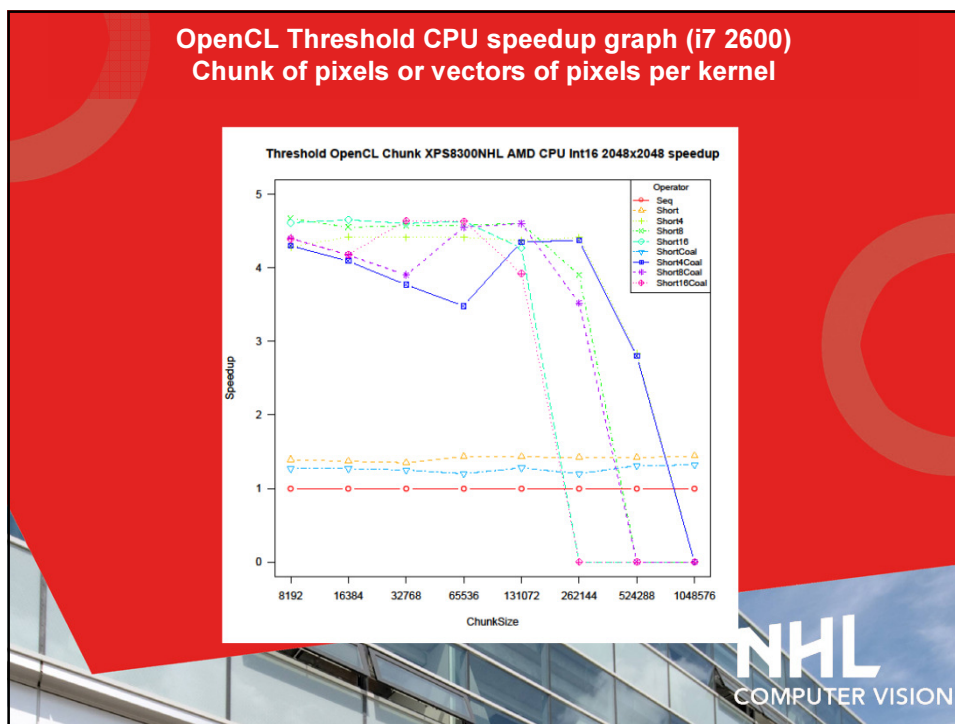
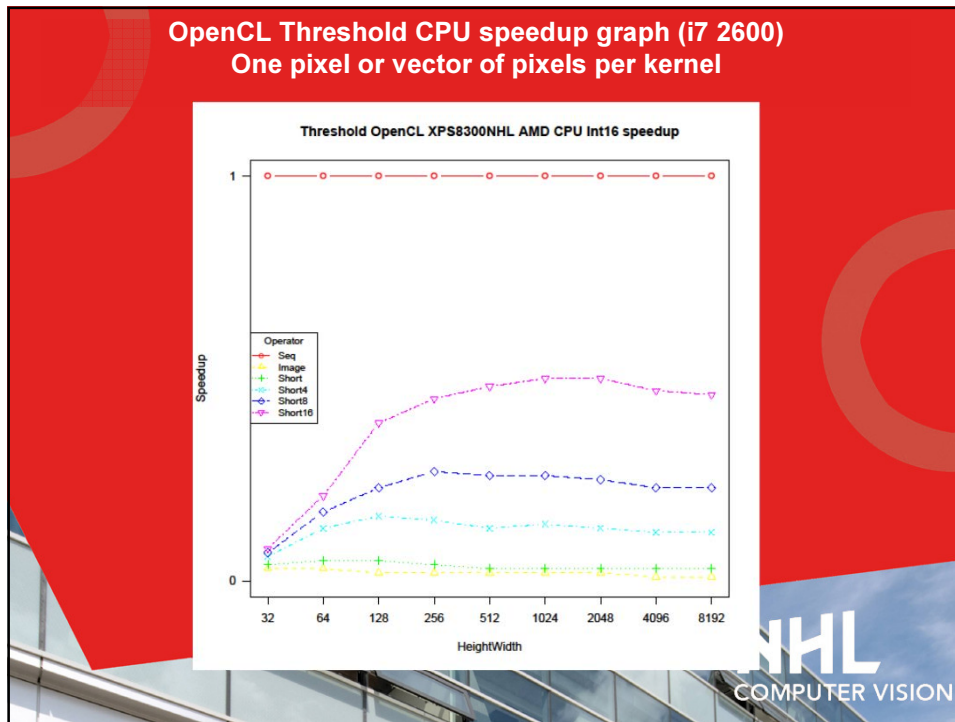
**NHL**  
COMPUTER VISION

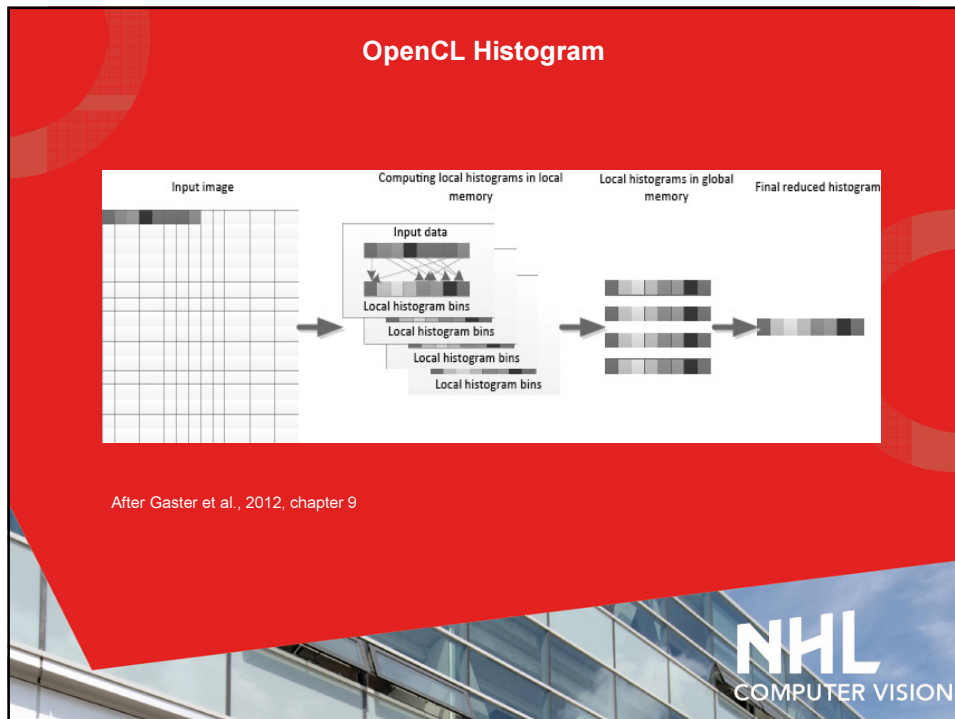
## OpenCL development in VisionLab



COMPUTER VISION







### OpenCL Histogram kernel (part 1)

```
kernel void HistogramKernel (const global short *image,
                             const uint nrPixels, const uint hisSize,
                             local int *localHis, global int *histogram) {
    const uint globalId = get_global_id(0);
    const uint localId = get_local_id(0);
    const uint localSize = get_local_size(0);
    const uint groupId = get_group_id(0);
    const uint numGroups = get_num_groups(0);
    // clear localHis
    const uint maxThreads = MIN(hisSize, localSize);
    const uint binsPerThread = hisSize / maxThreads;
    uint i, idx;
    if (localId < maxThreads) {
        for (i = 0, idx = localId; i < binsPerThread;
             i++, idx += maxThreads) {
            localHis[idx] = 0;
        }
    }
    barrier(CLK_LOCAL_MEM_FENCE);
}
```

**NHL**  
COMPUTER VISION

### OpenCL Histogram kernel (part 2)

```
// calculate local histogram
const uint pixelsPerGroup = nrPixels / numGroups;
const uint pixelsPerThread = pixelsPerGroup / localSize;
const uint stride = localSize;
for (i = 0, idx = (groupId * pixelsPerGroup) + localId;
     i < pixelsPerThread; i++, idx += stride) {
    (void) atom inc (&localHis[image[idx]]);
}
barrier(CLK_LOCAL_MEM_FENCE);
// copy local histogram to global
if (localId < maxThreads) {
    for (i = 0, idx = localId; i < binsPerThread;
         i++, idx += maxThreads) {
        histogram[(groupId * hisSize) + idx] = localHis[idx];
    }
}
} // HistogramKernel
```

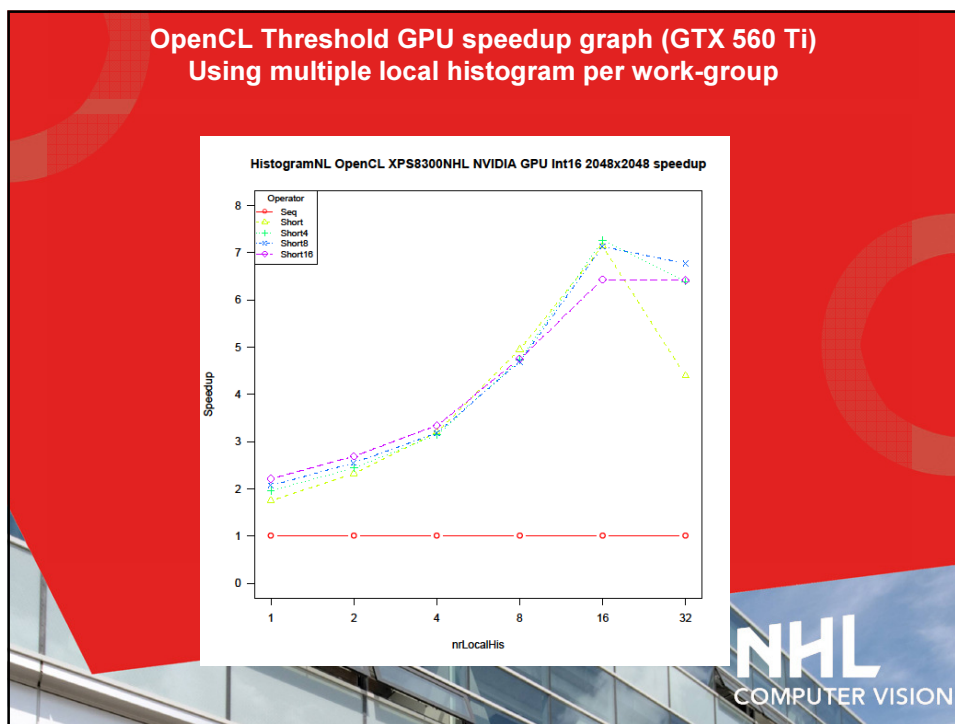
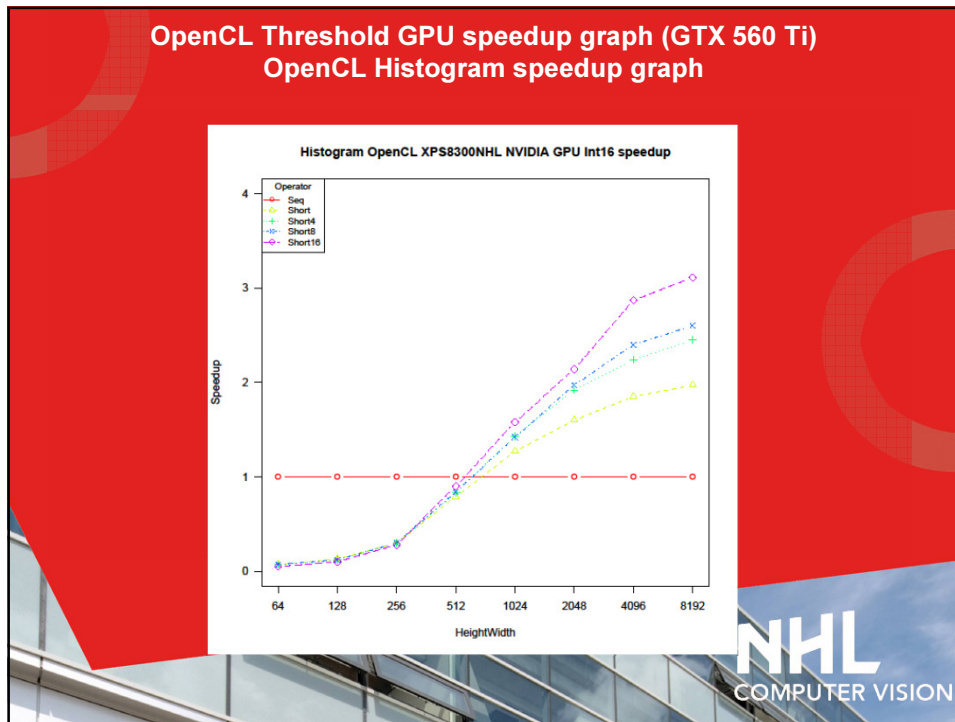
**NHL**  
COMPUTER VISION

### OpenCL Histogram Reduce kernel

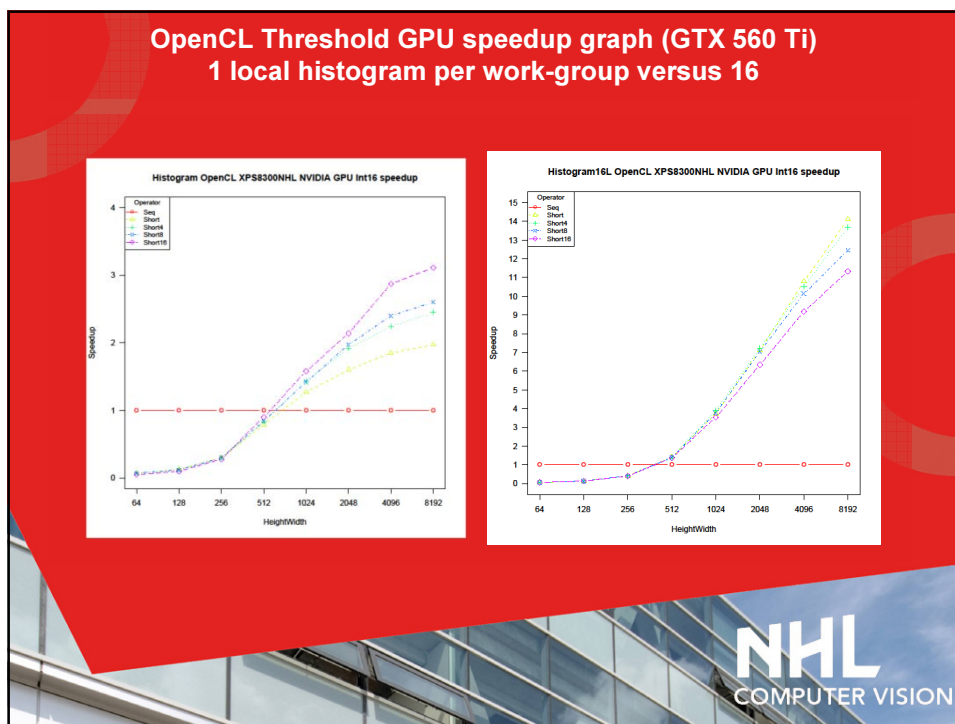
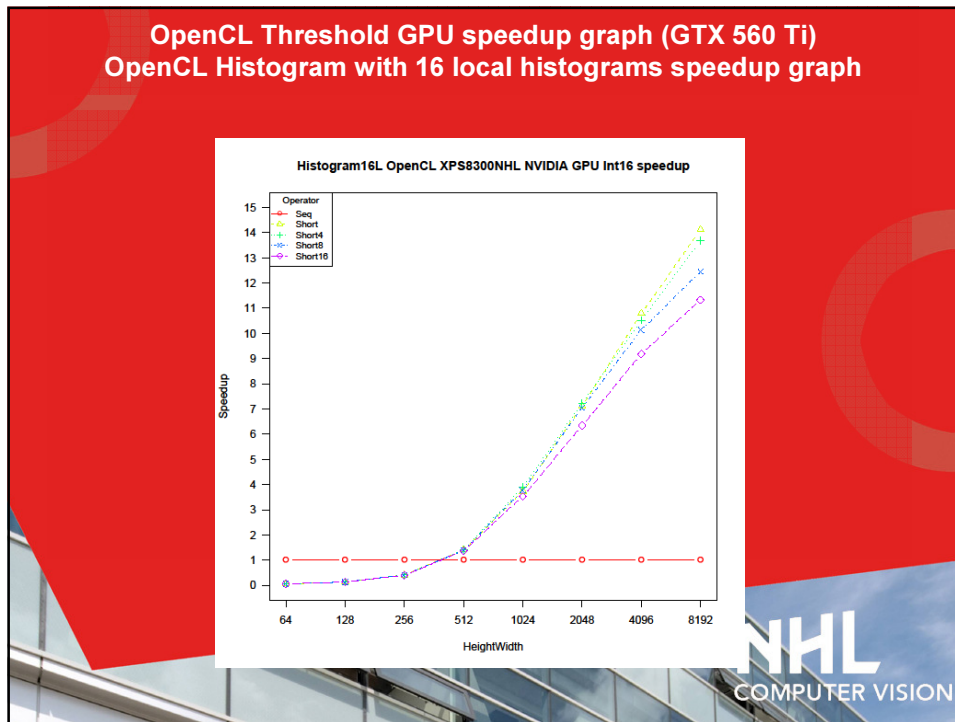
```
kernel void ReduceKernel (const uint nrSubHis, const uint hisSize,
                          global int *histogram) {
    const uint gid = get_global_id(0);
    int bin = 0;
    for (uint i=0; i < nrSubHis; i++)
        bin += histogram[(i * hisSize) + gid];
    histogram[gid] = bin;
} // ReduceKernel
```

**NHL**  
COMPUTER VISION

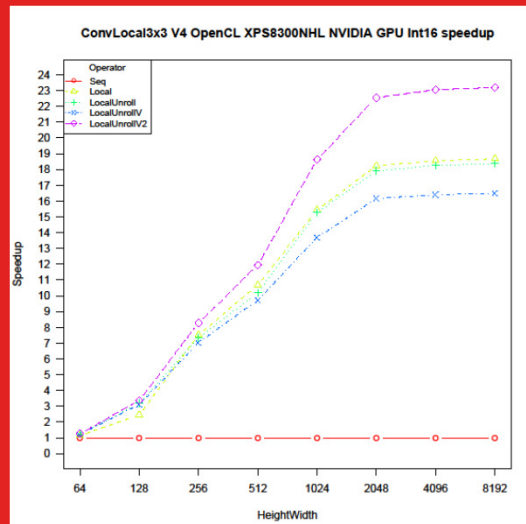




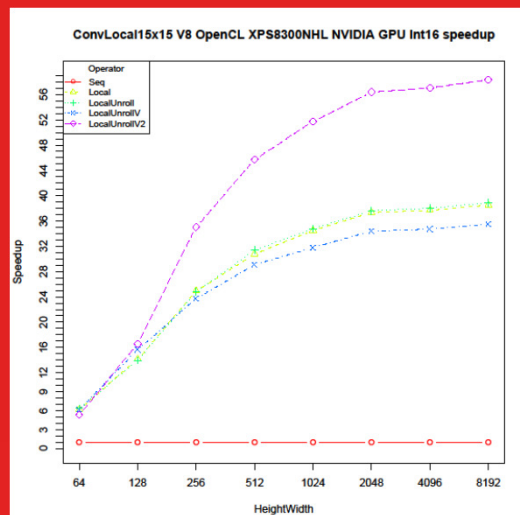




OpenCL Convolution GPU speedup graph (GTX 560 Ti)



OpenCL Convolution GPU speedup graph (GTX 560 Ti)



### Evaluation choice for OpenMP

OpenMP is very well suited for parallelizing many algorithms of a library in an economical way and execute them with an adequate speedup on multiple parallel CPU platforms

- OpenMP easy to learn
- Mature and stable tools
- Very low effort embarrassingly parallel algorithms
- 170 operators parallelized
- Automatic operator parallelization
- Portability tested on quad core ARM running Linux

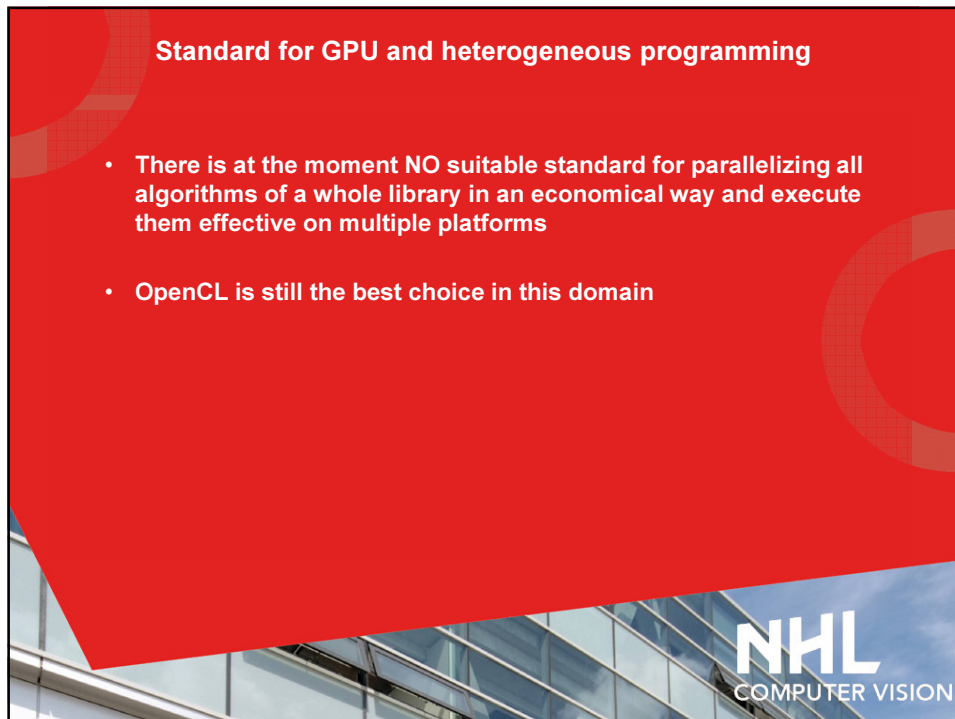
**NHL**  
COMPUTER VISION

### Evaluation choice for OpenCL

OpenCL is not very well suitable for parallelizing all algorithms of a whole library in an economical way and execute them effective on multiple platforms

- Difficult to learn, new mindset needed
- Considerable effort embarrassingly parallel algorithms
- Non embarrassingly parallel algorithms need complete new approaches
- Overhead host – device data transfer
- Considerable speedups possible
- Exploitation vector capabilities CPUs / GPUs
- Heterogeneous computing
- Portable but the performance is not portable

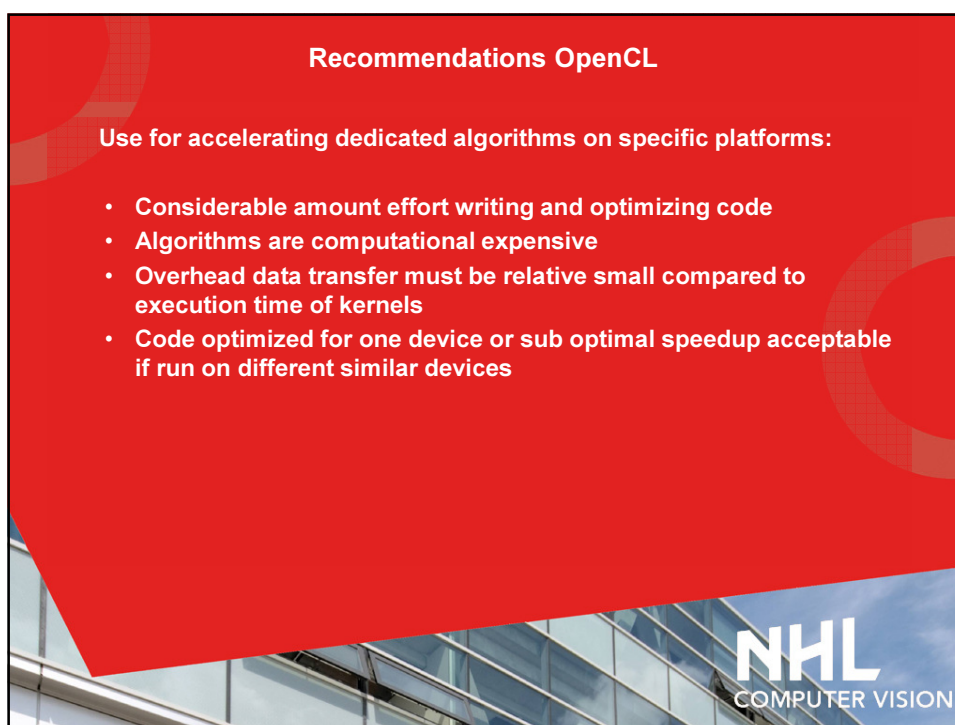
**NHL**  
COMPUTER VISION



### Standard for GPU and heterogeneous programming

- There is at the moment NO suitable standard for parallelizing all algorithms of a whole library in an economical way and execute them effective on multiple platforms
- OpenCL is still the best choice in this domain

NHL  
COMPUTER VISION



### Recommendations OpenCL

Use for accelerating dedicated algorithms on specific platforms:

- Considerable amount effort writing and optimizing code
- Algorithms are computational expensive
- Overhead data transfer must be relative small compared to execution time of kernels
- Code optimized for one device or sub optimal speedup acceptable if run on different similar devices

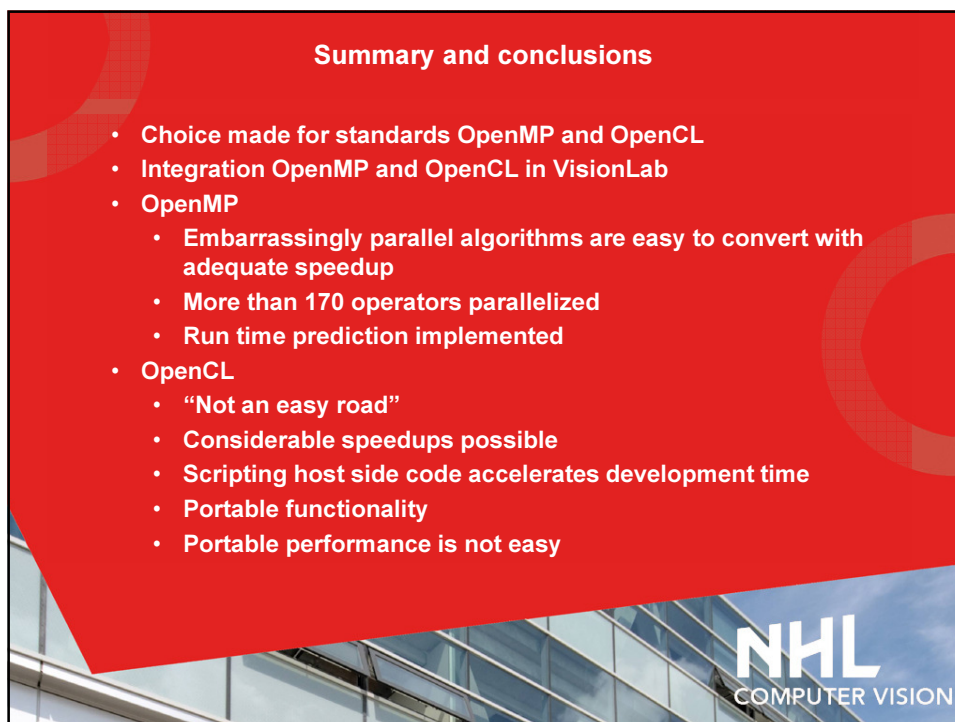
NHL  
COMPUTER VISION



### Future work

- New developments in standards**
  - C++ AMP
  - OpenMP 4.0
- Near future**
  - Parallelize more vision operators
- More distant future**
  - Intelligent buffer management
  - Automatic tuning of parameters
  - Heterogeneous computing

**NHL**  
COMPUTER VISION



### Summary and conclusions

- Choice made for standards OpenMP and OpenCL
- Integration OpenMP and OpenCL in VisionLab
- OpenMP
  - Embarrassingly parallel algorithms are easy to convert with adequate speedup
  - More than 170 operators parallelized
  - Run time prediction implemented
- OpenCL
  - “Not an easy road”
  - Considerable speedups possible
  - Scripting host side code accelerates development time
  - Portable functionality
  - Portable performance is not easy

**NHL**  
COMPUTER VISION

**Questions ?**

Jaap van de Loosdrecht

NHL Centre of Expertise in Computer Vision  
[j.van.de.loosdrecht@tech.nhl.nl](mailto:j.van.de.loosdrecht@tech.nhl.nl)  
[www.nhl.nl/computervision](http://www.nhl.nl/computervision)

Van de Loosdrecht Machine Vision BV  
[jaap@vdlmv.nl](mailto:jaap@vdlmv.nl)  
[www.vdlmv.nl](http://www.vdlmv.nl)

