Multi GPU programming

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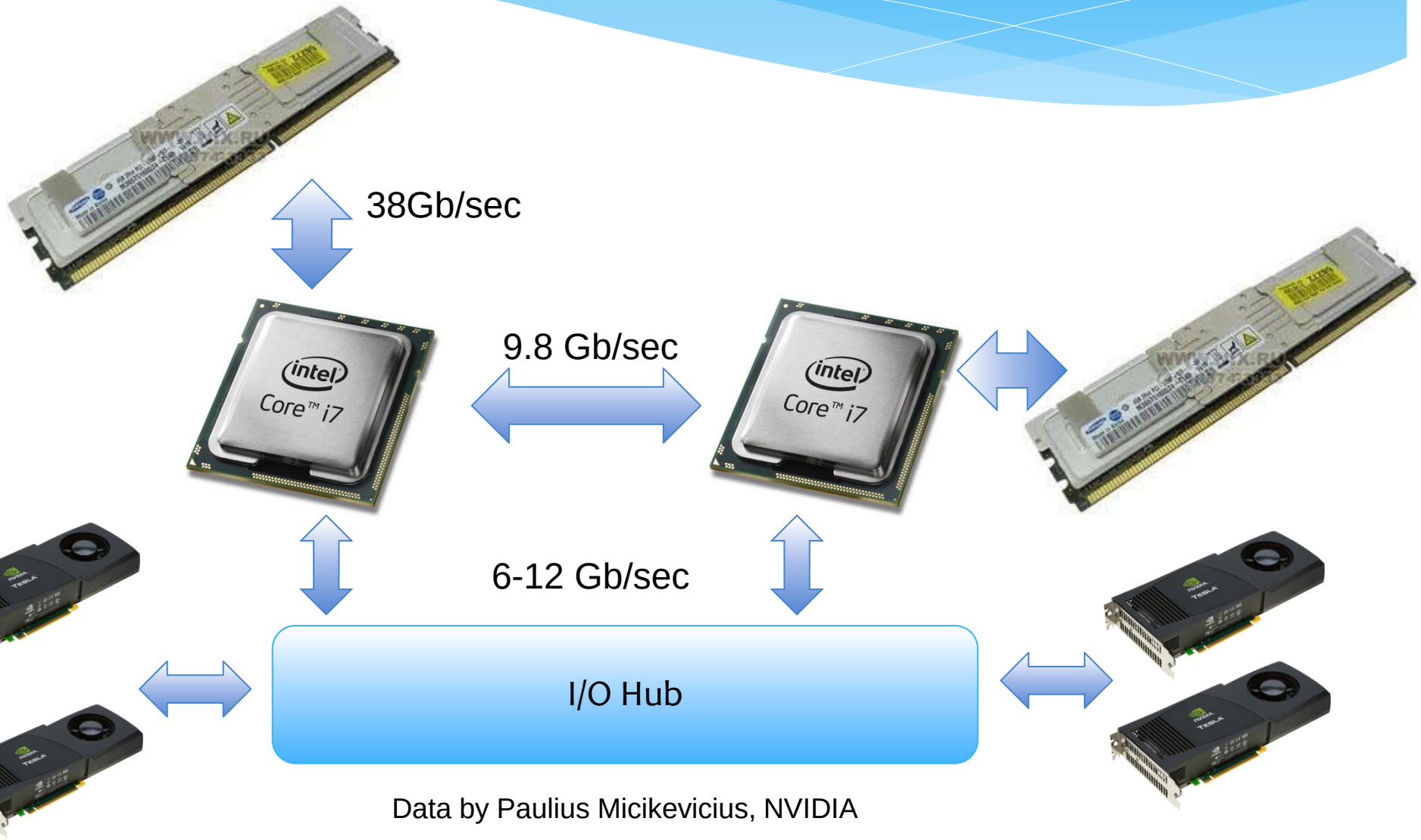
Why multi-GPU?

* To further speedup computation
* Working set exceeds a single GPU's memory
* Having multiple GPUs per node improves perf/W
  * Amortize the CPU server cost among more GPUs
  * Same goes for the price

Hybrid systems

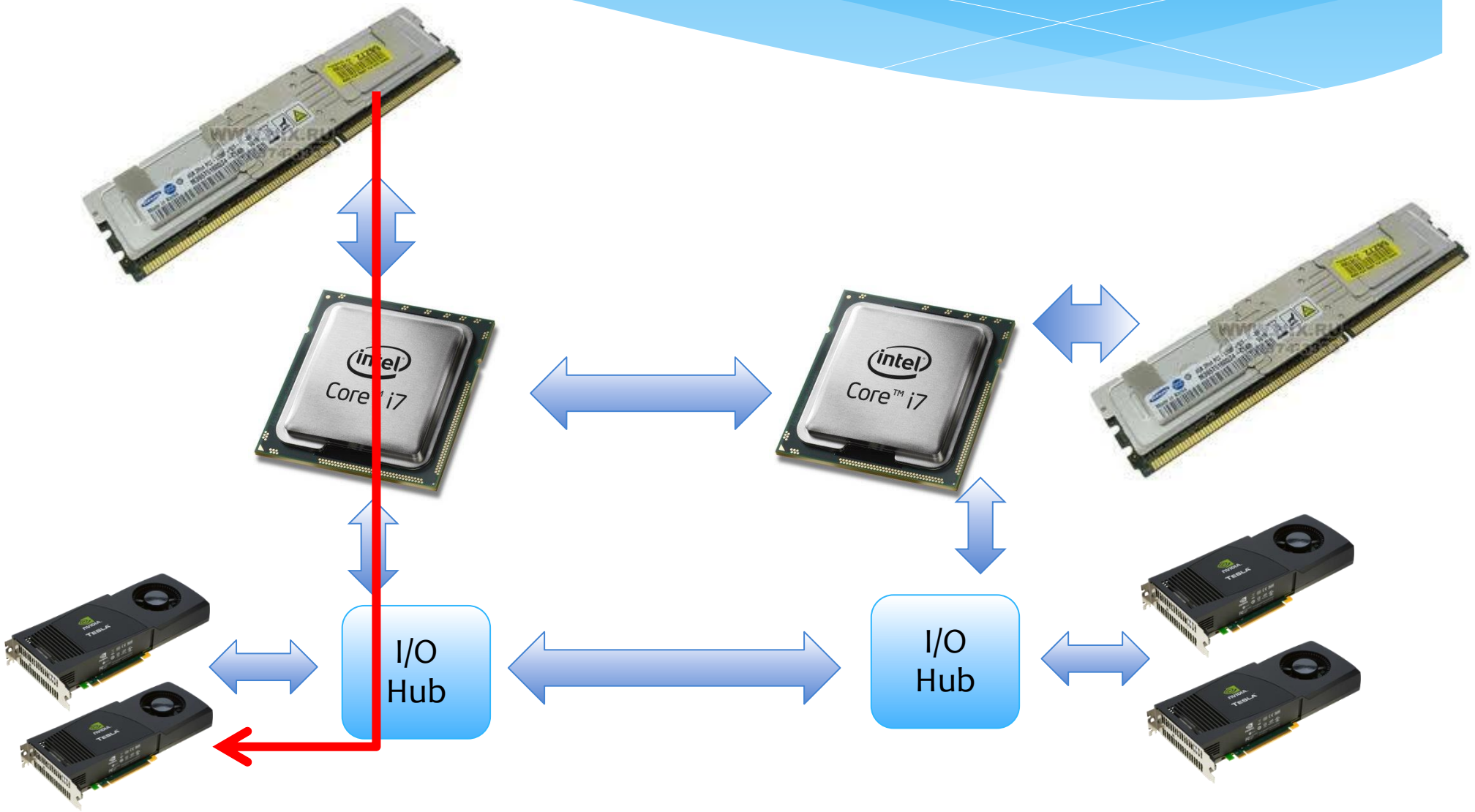


Data by Paulius Micikevicius, NVIDIA

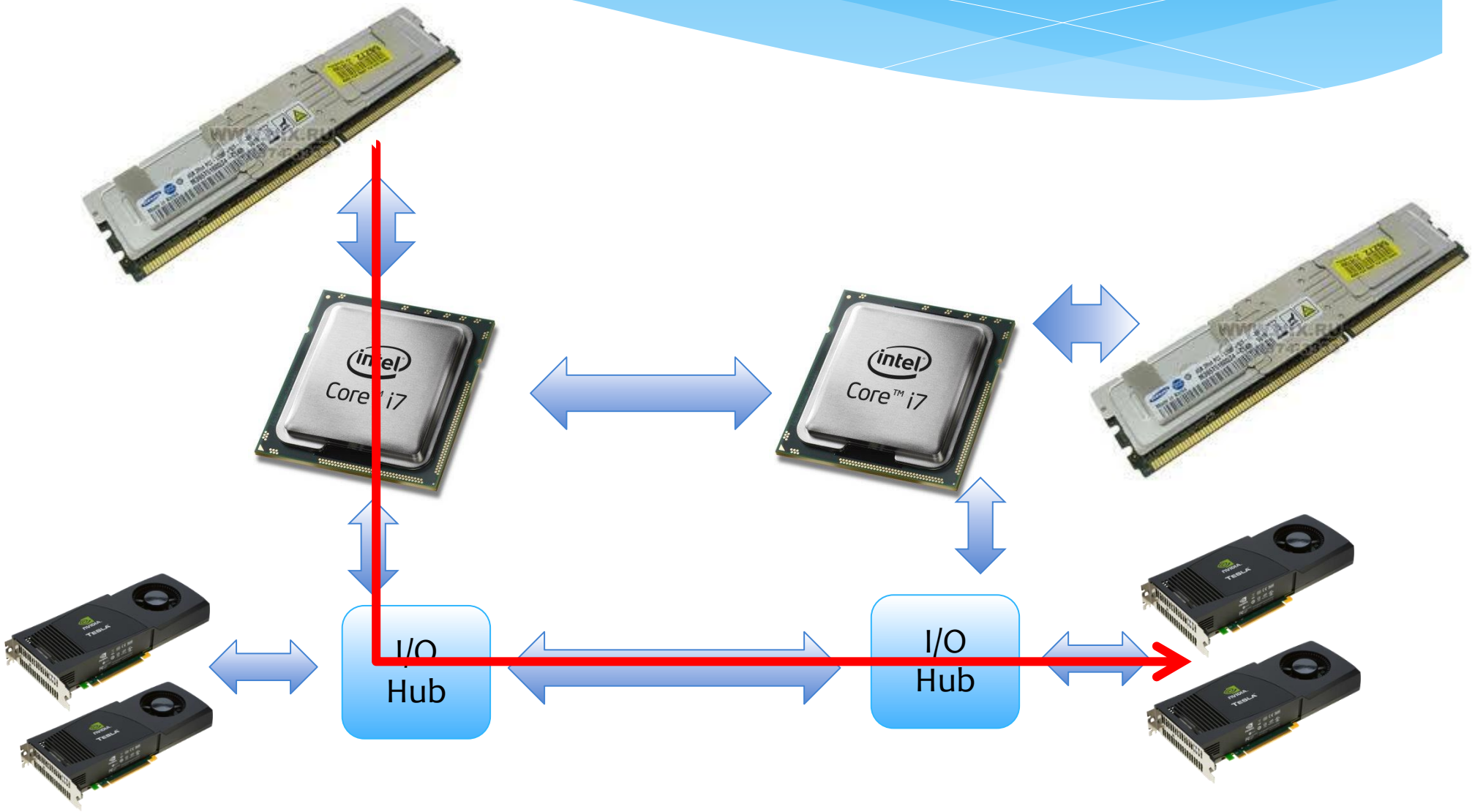
Notes on NUMA architecture

* CPU NUMA affects PCIe transfer throughput in dual-IOH systems
  * Transfers to "remote" GPUs achieve lower throughput
    * One additional QPI hop
  * This affects any PCIe device, not just GPUs
    * Network cards, for example
  * When possible, lock CPU threads to a socket that's "closest" to the GPU
    * For example, by using numactl, GOMP_CPU_AFFINITY, KMP_AFFINITY, etc.
* Number of hops slightly effect on data transfer throughput

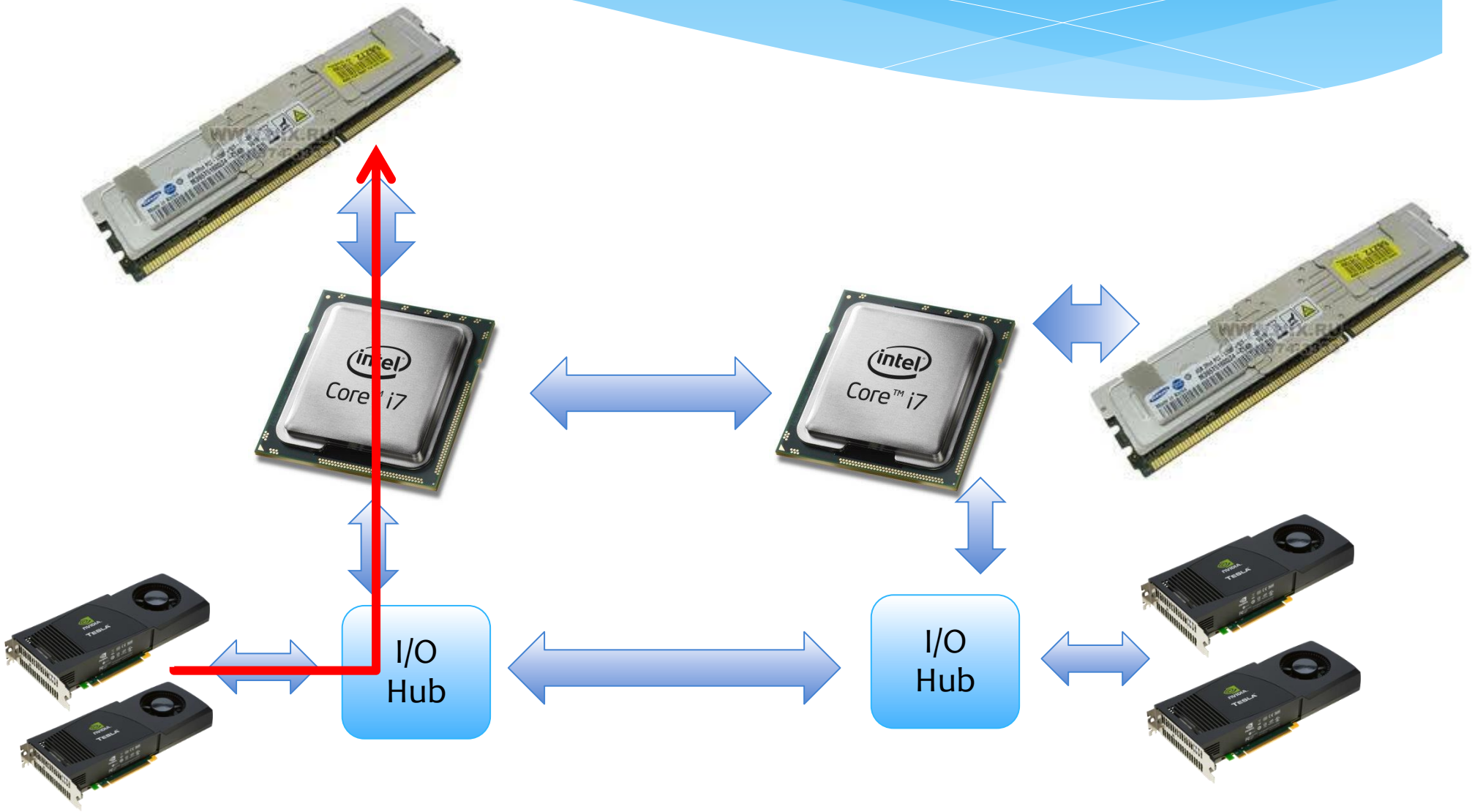
Local H2D Copy: 5.7 GB/s



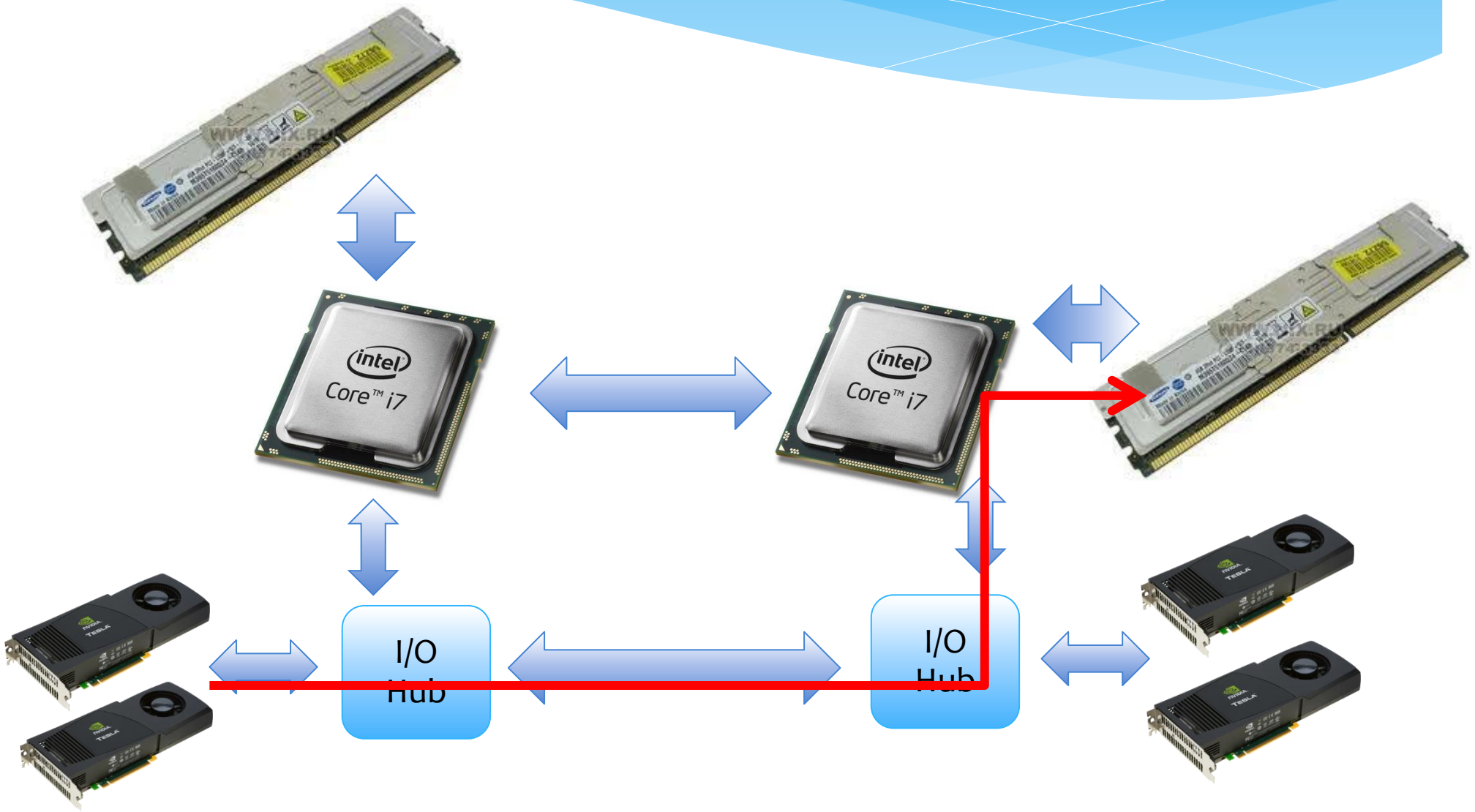
Remote H2D Copy: 4.9 GB/s



Local D2H Copy: 6.3 GB/s



Remote D2H Copy: 4.9 GB/s



Number of CUDA-enabled GPUs

```
int deviceCount;
cudaGetDeviceCount(&deviceCount);
int device;
for (device = 0; device < deviceCount; ++device) {
        cudaDeviceProp deviceProp;
        cudaGetDeviceProperties(&deviceProp, device);
        printf("Device %d has compute capability %d.%d.\n",
                device, deviceProp.major, deviceProp.minor);
}
```

CUDA context

* **CUDA context –** device-specific runtime configuration info (allocated device-memory, error codes, etc.)
* Many CUDA calls require existing context
* Initially thread/process does not have current CUDA context
* If thread/process does not have CUDA context, but it is required, then it will be created implicitly
* One device can have multiple contexts (driver API)

Context management

* CUDA runtime API:
  * Context is created implicitly
  * Switching context: cudaSetDevice(<device number>)
* Driver API:
  * cuCtxCreate/cuCtxDestroy
  * uCtxPushCurrent/cuCtxPopCurrent

GPU devices and CPU thread CUDA 3.2

* CPU thread assigned with one GPU *
* GPU could be selected explicitly (cudaSetDevice()) or implicitly – by default.
* By default GPU with index «0» is selected
* cudaSetDevice should be the first CUDA related call.

* - false for driver level.

GPU devices and CPU thread CUDA 4.0

* Any CPU thread can communicate with any GPU
* cudaSetDevice() function select active GPU
* Parallel kernel execution from different CPU threads is possible.

Multi-thread/parallel programming

* OpenMP
* POSIX Threads
* WinThreads
* MPI
* IPC
* etc.

Copying data between GPUs

CUDA 3.2

cudaMemcpy(Host, GPU1);

cudaMemcpy(GPU2, Host);

CUDA 4.0

cudaMemcpy(GPU1, GPU2);

Tesla 20xx (Fermi) required 64-bit applications

Unified Virtual Addressing CUDA 4.0

* CPU and GPU allocations use unified virtual address space.
* Driver/device can determine from an address where data resides
* A given allocation still resides on a single device (an array doesn't span several GPUs)
* One parameter (cudaMemcpyDefault) instead of 4 (cudaMemcpyHostToHost, cudaMemcpyHostToDevice, cudaMemcpyDeviceToHost, cudaMemcpyDeviceToDevice)
* Requires:
  * 64-bit Linux or 64-bit Windows with TCC driver
  * Fermi or later architecture GPUs (compute capability 2.0 or higher)
  * CUDA 4.0 or later

UVA and Multi-GPU Programming

* Two interesting aspects:
  * Peer-to-peer (P2P) memcopies
  * Accessing another GPU's addresses
* Both require peer-access to be enabled:
  * cudaDeviceEnablePeerAccess (peer_device, 0)
    * Enables current GPU to access addresses on peer_device GPU
  * cudaDeviceCanAccessPeer(&accessible, dev_X, dev_Y)
    * Checks whether dev_X can access memory of dev_Y
    * Returns 0/1 via the first argument
    * Peer-access is not available if:
      * One of the GPUs is pre-Fermi
      * GPUs are connected to different Intel IOH chips on the motherboard

Peer-to-peer memcopy

* cudaMemcpyPeerAsync (void* dst_addr, int dst_dev,
  void* src_addr, int src_dev,
  size_t num_bytes, cudaStream_t stream)
  * Copies the bytes between two devices
  * Currently performance is maximized when stream belongs to the source GPU
  * There is also a blocking (as opposed to Async) version
* If peer-access is enabled:
  * Bytes are transferred along the shortest PCIe path
  * No staging through CPU memory
* If peer-access is not available
  * CUDA driver stages the transfer via CPU memory

How Does P2P Memcopy Help Multi-GPU?

* Ease of programming
  * No need to manually maintain memory buffers on the host for inter-GPU exchanges
* Increased throughput
  * Especially when communication path does not include IOH (GPUs connected to a PCIe switch):
    * Single-directional transfers achieve up to ~6.6 GB/s
    * Duplex transfers achieve ~12.2 GB/s
    * 4-5 GB/s if going through the host
  * GPU-pairs can communicate concurrently if paths don't overlap

Multi-thread/parallel programming

* This section briefly describe approaches to developing of parallel programs.

OpenMP

* Implementation – directives (extension of C, Fortran, ...), library
* Runtime-library is responsible for thread creation/completion, user can specify threads properties explicitly.
* User can manage threads interaction.

OpenMP

* Parallel execution
  #pragma omp parallel
* Number of CPU threads
* **omp_get_num_threads(), OMP_NUM_THREADS**
* Parallel loops
  #pragma omp parallel for
* Parallel sections
  #pragma omp sections

OpenMP

```
#pragma omp parallel sections
{
#pragma omp section
  {
   cudaSetDevice(0);
   ...
  }
#pragma omp section
  {
   cudaSetDevice(1);
   ...
  }
}
```

OpenMP

```
#pragma omp parallel sections
{
#pragma omp section
 { // section for GPUs
   ...
 }
#pragma omp section
 { // section for CPUs
   ...
 }
}
```

OpenMP

```
int nElem = 1024;
cudaGetDeviceCount(&nGPUs);
if(nGPUs >= 1){
     omp_set_num_threads(nGPUs);
#pragma omp parallel
     {
          unsigned int cpu_thread_id = omp_get_thread_num();
          unsigned int num_cpu_threads = omp_get_num_threads();
          cudaSetDevice(cpu_thread_id % nGPUSs); //set device

          dim3 BS(128);
          dim3 GS(nElem / (gpu_threads.x * num_cpu_threads));
               // memory allocation and initialization
          int startIdx = cpu_thread_id * nElem / num_cpu_threads;
          int threadNum = nElem / num_cpu_threads;
          kernelAddConstant<<<GS, BS>>>(pData, startIdx, threadNum);
          // memory copying
     }
```

```
// Section for GPUs.
#pragma omp section
{
#pragma omp parallel for
  for (int i = 0; i < ndevices; i++) {
     config_t* config = configs + i;
     config->idevice = i;
     config->step = 0;
     config->nx = nx; config->ny = ny;
     config->inout_cpu = inout + np * i;
     config->status = thread_func(config);
  }
}
```

OpenMP. Linking

* gcc 4.3
* Command line
  * $ nvcc -Xcompiler \
    -fopenmp -Xlinker\
    -lgomp cudaOpenMP.cu

POSIX threads (pthreads)

* Implementation – library
* User is responsible for creating/completion of threads
* User manage threads communication explicitly
* Documents:
  https://computing.llnl.gov/tutorials/pthreads/
  man pthreads

POSIX threads (pthreads)

* Creating and waiting for threads
  pthread_create, pthread_join
* Critical section
  pthread_mutex_lock, pthread_mutex_unlock, …
* Barriers and conditional waits
  pthread_barrier_wait, pthread_cond_wait

CUDA Utillity Library

```
* static CUT_THREADPROC solverThread(SomeType *plan){
      // Init GPU
      cutilSafeCall( cudaSetDevice(plan->device) );
      // start kernel
      SomeKernel<<<GS, BS>>>(some parameters);
      cudaThreadSynchronize();

      cudaThreadExit();
      CUT_THREADEND;
  }
```

Portability between Windows and Linux.

CUDA Utillity Library

```
SomeType solverOpt[MAX_GPU_COUNT];
CUTThread threadID[MAX_GPU_COUNT];

for(i = 0; i < GPU_N; i++){
   solverOpt[i].device = i; …
}
//Start CPU thread for each GPU
for(gpuIndex = 0; gpuIndex < GPU_N; gpuIndex++){
    threadID[gpuIndex] =

cutStartThread((CUT_THREADROUTINE)solverThread,
                               &SolverOpt[gpuIndex]);
}

//waiting for GPU results
cutWaitForThreads(threadID, GPU_N);
```

MPI – Message Passing Interface

* Implementation – library, daemons
* MPI daemons control launching/state of MPI processes on cluster nodes
* The same program is launched on cluster nodes

* Launching program and creating threads
  mpirun, mpiexec (mpirun –np 4 ./MPI_calc_PI.exe)
* Initialization, deinitialization
  MPI_Init, MPI_Finalize
* Data transfer opertions
  MPI_Send, MPI_Recv, MPI_Bcast, …
* Synchronization
  MPI_Barrier, …

GPU-memory in MPI

* Device address could be passed to MPI routines (CUDA 4.0+)
* Available for OpenMPI trunk (Rolf vandeVaart)

```
[arom@cuda ~/dist]$
svn co http://svn.open-mpi.org/svn/ompi/trunk ompi-trunk
[arom@cuda ~/dist]$ cd ompi-trunk/
[arom@cuda ompi-trunk]$ ./autogen.pl
[arom@cuda ompi-trunk]$ mkdir build
[arom@cuda ompi-trunk]$ cd build
[arom@cuda build]$ ../configure \
--prefix=/home/dmikushin/opt/openmpi_gcc-trunk --with-cuda
[arom@cuda build]$ make install
```

MPI_Init with CUDA

* Create CUDA context prior MPI_Init
* http://www.open-mpi.org/faq/?category=running#mpi-cuda-support
* cudaSetDevice(getenv("OMPI_COMM_WORLD_LOCAL_RANK")%cudaGetDeviceCount());
* Version
  * MVAPICH2
  * OpenMPI
  * Platform MPI

MPI_Send/MPI_Recv

```
// in MPI_Send/_Recv – device- pointers din1/din2
float *din1, *din2;
cuda_status = cudaMalloc((void**)&din1, size);
...
cuda_status = cudaMalloc((void**)&din2, size);
...
MPI_Request request;
int inext = (iprocess + 1) % nprocesses;
int iprev = iprocess - 1; iprev += (iprev < 0) ? nprocesses : 0;
// Pass entire process input device buffer directly to input device buffer of next process.
mpi_status = MPI_Isend(din1, n*n, MPI_FLOAT, inext, 0, MPI_COMM_WORLD, &request);
mpi_status = MPI_Recv(din2, n*n, MPI_FLOAT, iprev, 0, MPI_COMM_WORLD, NULL);
mpi_status = MPI_Wait(&request, MPI_STATUS_IGNORE);
```

IPC – Inter-process communication

* Implementation - library
* User is responsible for processes creating/completion as wel as process' properties
  * **fork(), exit(),** …
* User manage threads communication explicitly
  * Shared memory, condition variables, signals, …
* Documentation:
  man ipc

fork ()

```
// Call fork to create another process.
// Standard: "Memory mappings created in the parent
// shall be retained in the child process."
pid_t fork_status = fork();
// From this point two processes are running the same code,
// if no errors.
if (fork_status == -1){
    fprintf(stderr, "Cannot fork process, errno = %d\n", errno);
    return errno;
}
// By fork return value we can determine the process role:
// master or child (worker)
int master = fork_status ? 1 : 0, worker = !master;
// Get the process ID
int pid = (int)getpid();
```

Working with driver

* Creating context (**cuCtxCreate**). Created context becomes current. Device could have several contexts.
* Context could be detached with **cuCtxPopCurrent** (‘floating’) and attached again (**cuCtxPushCurrent**).
* When necessary context should to be destroyed (**cuCtxDestroy**)

* (!!) creating context prior fork() results in undefined behavior.

Creating context

```
for(int i=0; i<nGPUS; i++){
        CUdevice dev;
        CUresult cu_status = cuDeviceGet(&dev, i);
        if (cu_status != CUDA_SUCCESS) {/* Error handling */ }

        device_t *device = &devices[i];
        cu_status = cuCtxCreate(divice->ctx, 0, dev);
        if (cu_status != CUDA_SUCCESS) {/* Error handling */ }

        CUresult cu_status = cuCtxPopCurrent(divice->ctx);
        if (cu_status != CUDA_SUCCESS) { /* Error handling */ }
}
```

Working with context

```
for(int i=0; i<nGPUS; i++){
        device_t *device = &devices[i];
        // set context active/current
        CUresult cu_status = cuCtxPushCurrent(device->ctx);
        if (cu_status != CUDA_SUCCESS) {/* Error handling */ }

        // allocate memory, launch kernels

        // set context inactive
        cu_status = cuCtxPopCurrent(device->ctx);
        if (cu_status != CUDA_SUCCESS) {/* Error handling */ }
}
```

Destroying context

```
for(int i=0; i<nGPUS; i++){
        device_t *device = &devices[i];
        // set context active/current
        CUresult cu_status = cuCtxPushCurrent(device->ctx);
        if (cu_status != CUDA_SUCCESS) {/* Error handling */ }
        // wait for kernels to complete
        cuda_status = cudaThreadSynchronize();

        // save result, free memory…

        // Destroy context
        cu_status = cuCtxDestroy (device->ctx);
        if (cu_status != CUDA_SUCCESS) {/* Error handling  */ }
}
```

Conclusion

* It is possible to use multiple GPUs
* Multi-thread programming is required (CUDA 3.2)
  * Alternative is usage of driver functions.
* CPU thread can operate with several GPUs (CUDA 4.0)
* UVA allows one not to use Host memory for copying data between GPUs