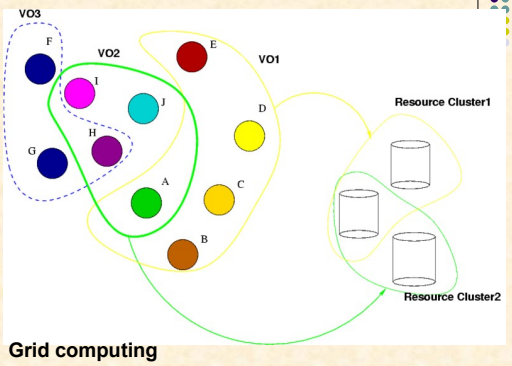
了解各种（非众核）并行程序设计思想

Programmable Memory Hierarchy

- Registers
- Cache
- Physical memory
- Virtual memory
- Local disk storage
- RAID (via LAN) / Distributed shared-memory
- Data Grid

Ideas of parallel computation

- Multi-threading (e.g. Java)
- Concurrent processes (e.g. Unix)
- SIMD (e.g. Connection Machine-2)
- SPMD (e.g. MPI)
- MIMD (e.g. CORBA)
- Message-passing
- Memory-sharing
- Bulk-Synchronous Parallelism
- Work-flow task parallelism, data parallelism



Grid computing

MPI集群编程示例

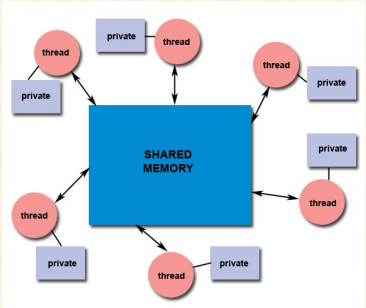
IB/verbs 编程示例

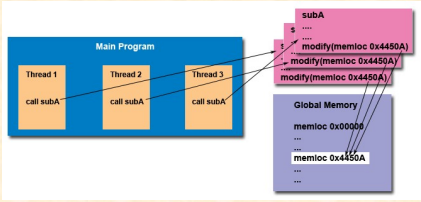
```
while (totscnt < (user_param->iters * user_param->numofqps)  || totccnt < (user_param->iters * user_param->numofqps) ) {
  /* main loop to run over all the qps and post each time n messages */
  for (index =0 ; index < user_param->numofqps ; index++) {
      ctx->wr.wr.rdma.remote_addr = rem_dest[index]->vaddr;
      ctx->wr.wr.rdma.rkey = rem_dest[index]->rkey;
      qp = ctx->qp[index];
      ctx->wr.wr_id      = index ;
      while (ctx->scnt[index] < user_param->iters && (ctx->scnt[index] - ctx->ccnt[index]) < user_param->maxpost[index]) {
      tposted[totscnt] = get_cycles();
      if (ibv_post_send(qp, &ctx->wr, &bad_wr)) {
            fprintf(stderr, "Couldn't post send: qp index = %d qp scnt=%d total scnt %d\n",
                    index,ctx->scnt[index],totscnt);
            return 1;
      }
      ctx->scnt[index]= ctx->scnt[index]+1;
      ++totscnt;
    }
  }
  /* finished posting now polling */
  if (totccnt < (user_param->iters * user_param->numofqps) ) {
    int ne;
    do {
      ne = ibv_poll_cq(ctx->cq, 1, &wc);
    } while (ne == 0);
    tcompleted[totccnt] = get_cycles();  // XXXX ask for the timing
    if (ne < 0) {
      fprintf(stderr, "poll CQ failed %d\n", ne);
      return 1;
    }
```

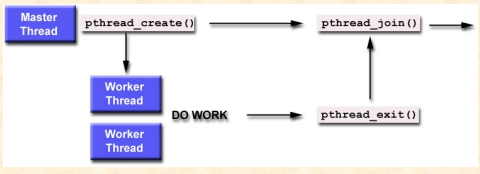
Pthread多核编程示例

```
#include <stdio.h>
#include <stdlib.h>
#include <pthread.h>

void *print_message_function( void *ptr );

main()
{
pthread_t thread1, thread2;
char *message1 = "Thread 1";
char *message2 = "Thread 2";
int iret1, iret2;

/* Create independent threads each of which will execute function */

iret1 = pthread_create( &thread1, NULL, print_message_function, (void*) message1);
iret2 = pthread_create( &thread2, NULL, print_message_function, (void*) message2);

/* Wait till threads are complete before main continues. Unless we */
/* wait we run the risk of executing an exit which will terminate */
/* the process and all threads before the threads have completed. */

pthread_join( thread1, NULL);
pthread_join( thread2, NULL);

printf("Thread 1 returns: %d\n",iret1);
printf("Thread 2 returns: %d\n",iret2);
exit(0);
}

void *print_message_function( void *ptr )
{
char *message;
message = (char *) ptr;
printf("%s \n", message);
}
```

PTHREAD







Thread 1	Thread 2	Balance
Read balance: $1000		$1000
	Read balance: $1000	$1000
	Deposit $200	$1000
Deposit $200		$1000
Update balance $1000+$200		$1200
	Update balance $1000+$200	$1200

```
#include <unistd.h>    /* Symbolic Constants */
#include <sys/types.h>  /* Primitive System Data Types */
#include <pthread.h>   /* POSIX Threads */
#include <semaphore.h>  /* Semaphore */
void handler ( void *ptr );
sem_t mutex;int counter; /* shared variable */
int main(){    int i[2];
pthread_t thread_a; pthread_t thread_b;
i[0] = 0; /* argument to threads */   i[1] = 1;
sem_init(&mutex, 0, 1);     /* initialize mutex to 1 - semaphore */
pthread_create (&thread_a, NULL, (void *) &handler, (void *) &i[0]);
pthread_create (&thread_b, NULL, (void *) &handler, (void *) &i[1]);
pthread_join(thread_a, NULL);    pthread_join(thread_b, NULL);
sem_destroy(&mutex); /* destroy semaphore */
exit(0);} /* main() */
```

```
void handler ( void *ptr ) {
    int x;    x = *((int *) ptr);
    printf("Thread %d: Waiting to enter critical region...\n", x);
    sem_wait(&mutex);      /* down semaphore */
/* START CRITICAL REGION */
    printf("Thread %d: Now in critical region...\n", x);
    printf("Thread %d: Counter Value: %d\n", x, counter);
    printf("Thread %d: Incrementing Counter...\n", x);    counter++;
    printf("Thread %d: New Counter Value: %d\n", x, counter);
    printf("Thread %d: Exiting critical region...\n", x);
 /* END CRITICAL REGION */
    sem_post(&mutex);      /* up semaphore */
    pthread_exit(0); /* exit thread */
}
```

MPI

A Typical MPI Program

```
#include "mpi.h"
          :
main(int argc, char** argv) {
          :
    /* No MPI functions called before this */
    MPI_Init(&argc, &argv);
          :
    MPI_Finalize();
    /* No MPI functions called after this */
          :
} /* main */
```

```
#include <stdio.h>
#include "mpi.h"
main(int argc, char** argv) {
    int my_rank;        /* Rank of process */
    int p;              /* Number of processes */
    int source;         /* Rank of sender */
    int dest;           /* Rank of receiver */
    int tag = 50;       /* Tag for messages */
    char message[100];  /* Storage for the message */
    MPI_Status status;  /* Return status for receive */
    MPI_Init(&argc, &argv);
    MPI_Comm_rank(MPI_COMM_WORLD, &my_rank);
    MPI_Comm_size(MPI_COMM_WORLD, &p);
    if (my_rank != 0) {
        sprintf(message, "Greetings from process %d!",
            my_rank);
        dest = 0;
        /* Use strlen(message)+1 to include '\0' */
        MPI_Send(message, strlen(message)+1, MPI_CHAR, dest,
            tag, MPI_COMM_WORLD);
    } else { /* my_rank == 0 */
        for (source = 1; source < p; source++) {
```

```
            MPI_Recv(message, 100, MPI_CHAR, source, tag,
                MPI_COMM_WORLD, &status);
            printf("%s\n", message);
        }
    }

    MPI_Finalize();
} /* main */
```

When the program is compiled and run with two processes, the output should be

```
Greetings from process 1!
```

If it's run with four processes, the output should be

```
Greetings from process 1!
Greetings from process 2!
Greetings from process 3!
```

MPI_Send and MPI_Receive

```
int MPI_Send(void* message, int count,
    MPI_Datatype datatype, int dest, int tag,
    MPI_Comm comm)

int MPI_Recv(void* message, int count,
    MPI_Datatype datatype, int source, int tag,
    MPI_Comm comm, MPI_Status* status)
```

MPI datatype	C datatype
MPI_CHAR	signed char
MPI_SHORT	signed short int
MPI_INT	signed int
MPI_LONG	signed long int
MPI_UNSIGNED_CHAR	unsigned char
MPI_UNSIGNED_SHORT	unsigned short int
MPI_UNSIGNED	unsigned int
MPI_UNSIGNED_LONG	unsigned long int
MPI_FLOAT	float
MPI_DOUBLE	double
MPI_LONG_DOUBLE	long double
MPI_BYTE	
MPI_PACKED	

(Explicit) Synchronisation

```
int MPI_Barrier(MPI_Comm comm)
```

MPI_Barrier provides a mechanism for synchronizing all the processes in the communicator comm. Each process blocks (i.e., pauses) until every process in comm has called MPI_Barrier.

Broadcasting

A communication pattern that involves all the processes in a communicator is a *collective communication*. As a consequence, a collective communication usually involves more than two processes. A *broadcast* is a collective communication in which a single process sends the same data to every process. In MPI the function for broadcasting data is MPI_Bcast:

```
int MPI_Bcast(void* message, int count,
    MPI_Datatype datatype, int root, MPI_Comm comm)
```

```
void Get_data2(int my_rank, float* a_ptr, float* b_ptr,
    int* n_ptr) {
    int root = 0;  /* Arguments to MPI_Bcast */
    int count = 1;

    if (my_rank == 0)
      {
          printf("Enter a, b, and n\n");
          scanf("%f %f %d", a_ptr, b_ptr, n_ptr);
      }
      MPI_Bcast(a_ptr, 1, MPI_FLOAT, root,
          MPI_COMM_WORLD);
      MPI_Bcast(b_ptr, 1, MPI_FLOAT, root,
          MPI_COMM_WORLD);
      MPI_Bcast(n_ptr, 1, MPI_INT, root,
          MPI_COMM_WORLD);
} /* Get_data2 */
```

Reduction

```
int MPI_Reduce(void* operand, void* result,
    int count, MPI_Datatype datatype, MPI_Op op,
    int root, MPI_Comm comm)
```

Operation Name	Meaning
MPI_MAX	Maximum
MPI_MIN	Minimum
MPI_SUM	Sum
MPI_PROD	Product
MPI_LAND	Logical And
MPI_BAND	Bitwise And
MPI_LOR	Logical Or
MPI_BOR	Bitwise Or
MPI_LXOR	Logical Exclusive Or
MPI_BXOR	Bitwise Exclusive Or
MPI_MAXLOC	Maximum and Location of Maximum
MPI_MINLOC	Minimum and Location of Minimum

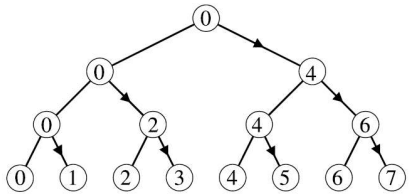
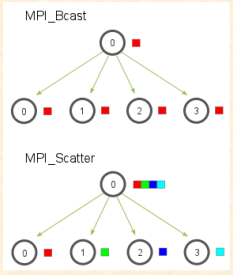


Figure 1: Processors configured as a tree

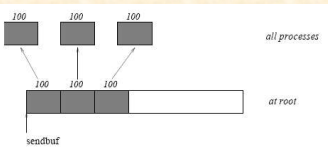
Yet Another Piece of Advice

Advice to implementors. It is strongly recommended that MPI_REDUCE be implemented so that the same result be obtained whenever the function is applied on the same arguments, appearing in the same order. Note that this may prevent optimizations that take advantage of the physical location of processors. (*End of advice to implementors.*)



Scattering

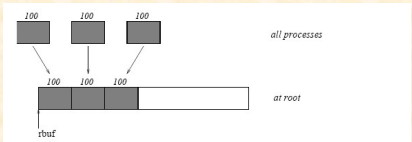
```
int MPI_Scatterv(void* sendbuf, int *sendcounts, int *displs,
                 MPI_Datatype sendtype, void* recvbuf, int recvcount,
                 MPI_Datatype recvtype, int root, MPI_Comm comm)
```



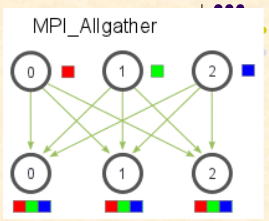
The root process scatters sets of 100 ints to each process in the group.

Gathering

```
int MPI_Gatherv(void* sendbuf, int sendcount, MPI_Datatype sendtype,
                void* recvbuf, int *recvcounts, int *displs,
                MPI_Datatype recvtype, int root, MPI_Comm comm)
```

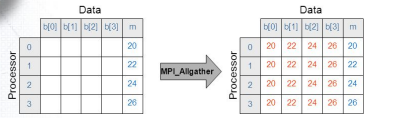


The root process gathers 100 ints from each process in the group.

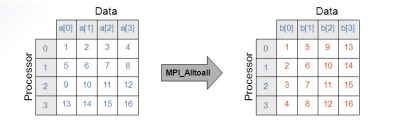


MPI_Allgather(void* send_data,
int send_count,
MPI_Datatype send_datatype,
void* recv_data,
int recv_count,
MPI_Datatype recv_datatype,
MPI_Comm communicator
)

MPI_Allgather / MPI_Alltoall




```
MPI_Allgather(&m,1,MPI_INT,b,1,MPI_INT,MPI_COMM_WORLD);
```



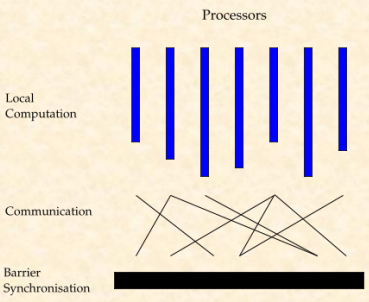

```
MPI_Alltoall(a,1,MPI_INT,b,1,MPI_INT,MPI_COMM_WORLD);
```

MPI 实现 alltoall.c

```
520         /* Do the pairwise exchanges */
521         for (i=1; i<comm_size; i++) {
522             if (pof2 == 1) {
523                 /* use exclusive-or algorithm */
524                 src = dst = rank ^ i;
525             }
526             else {
527                 src = (rank - i + comm_size) % comm_size;
528                 dst = (rank + i) % comm_size;
529             }
530
531             mpi_errno = MPIC_Sendrecv_ft(((char *)sendbuf +
532                                           dst*sendcount*sendtype_extent),
533                                          sendcount, sendtype, dst,
534                                          MPIR_ALLTOALL_TAG,
535                                          ((char *)recvbuf +
536                                           src*recvcount*recvtype_extent),
537                                          recvcount, recvtype, src,
538                                          MPIR_ALLTOALL_TAG, comm, &status, errflag);
539             if (mpi_errno) {
540                 /* for communication errors, just record the error but continue */
541                 *errflag = TRUE;
542                 MPIU_ERR_SET(mpi_errno, MPI_ERR_OTHER, "**fail");
543                 MPIU_ERR_ADD(mpi_errno_ret, mpi_errno);
544             }
545         }
546     }
```

Communication Groups

```
MPI_Group MPI_GROUP_WORLD;
MPI_Group first_row_group;
MPI_Comm first_row_comm;
int row_size;
int* process_ranks;

/* Make a list of the processes in the new
 * communicator */
process_ranks = (int*) malloc(q*sizeof(int));
for (proc = 0; proc < q; proc++)
    process_ranks[proc] = proc;

/* Get the group underlying MPI_COMM_WORLD */
MPI_Comm_group(MPI_COMM_WORLD, &MPI_GROUP_WORLD);

/* Create the new group */
MPI_Group_incl(MPI_GROUP_WORLD, q, process_ranks, &first_row_group);
MPI_Comm_create(MPI_COMM_WORLD, first_row_group,
    &first_row_comm);
```



GPU集群LINPACK

LINPACK (wiki)

- The **LINPACK Benchmarks** are a measure of a system's floating point computing power. Introduced by Jack Dongarra, they measure how fast a computer solves a dense *N* by *N* system of linear equations *Ax* = *b*, which is a common task in engineering. The solution is obtained by Gaussian elimination with partial pivoting, with 2/3·*N*^3 + 2·*N*^2 floating point operations. The result is reported in millions of floating point operations per second.
- Massimiliano Fatica, *Accelerating linpack with CUDA on heterogenous clusters*, GPGPU'09.

Slides extracted from the above paper

Hardware Configuration

1. SUN Ultra 24 workstation with an Intel Core2 Extreme Q6850 (3.0GHz) CPU and 8GB of memory plus a Tesla C1060 card.
2. Cluster with 8 nodes, each node connected to half of a Tesla S1070 system, containing 4 GPUs, so that each node is connected to 2 GPUs. Each node has 2 Intel Xeon E5462 (2.8GHz with 1600Mhz FSB) and 16GB of memory. The nodes are connected with SDR (Single Data Rate) Infiniband.

Pinned Memory

```
// Regular malloc/free
 double *A;
 A = malloc(N*N*sizeof(double));
 free(A);


// Page-locked version
 double *A;
 cudaMallocHost(A,N*N*sizeof(double));
 cudaFreeHost(A);
```

PCI Bandwidth

	Sun Ultra 24	
	Pageable memory	Pinned memory
H2D	2132 MB/s	5212 MB/s
D2H	1882 MB/s	5471 MB/s

	Supermicro 6015TW	
	Pageable memory	Pinned memory
H2D	2524 MB/s	5651 MB/s
D2H	2084 MB/s	5301 MB/s

Solving Linear Equations

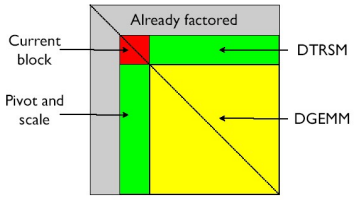


Figure 1: LU factorization: the grey area represents the portion of the matrix already factored. The red area is the current block being factorized. Once this factorization is ready, it is applied to the sub-matrix on the right. The final step is to update the trailing sub-matrix in yellow.

LU Decomposition

$L\,U = A.$

$A\,x = (L\,U)\,x = L\,(U\,x) = b.$

$$\begin{bmatrix} l_{11} & 0 & 0 \\ l_{21} & l_{22} & 0 \\ l_{31} & l_{32} & l_{33} \end{bmatrix} \begin{bmatrix} u_{11} & u_{12} & u_{13} \\ 0 & u_{22} & u_{23} \\ 0 & 0 & u_{33} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}$$

$$\begin{bmatrix} l_{11}\,u_{11} & l_{11}\,u_{12} & l_{11}\,u_{13} \\ l_{21}\,u_{11} & l_{21}\,u_{12} + l_{22}\,u_{22} & l_{21}\,u_{13} + l_{22}\,u_{23} \\ l_{31}\,u_{11} & l_{31}\,u_{12} + l_{32}\,u_{22} & l_{31}\,u_{13} + l_{32}\,u_{23} + l_{33}\,u_{33} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}.$$

first solve $L\,y = b$ for y. This can be done by forward substitution

$$y_1 = \frac{b_1}{l_{11}}$$

$$y_i = \frac{1}{l_{ii}}\left(b_i - \sum_{j=1}^{i-1} l_{ij}\,y_j\right)$$

for $i = 2 \ldots N$. Then solve $U\,x = y$ for x. This can be done by back substitution

$$x_N = \frac{y_N}{u_{N,N}}$$

$$x_i = \frac{1}{u_{ii}}\left(y_i - \sum_{j=i+1}^{N} u_{ij}\,x_j\right)$$

for $i = N-1 \ldots 1$.

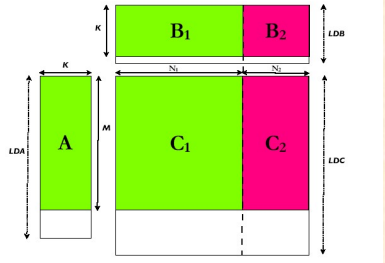


Figure 3: The green portion is performed on the GPU, while the red one is performed on the CPU)

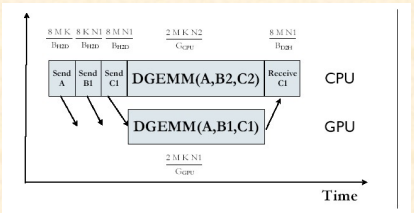


Figure 4: Data flow to split the DGEMM call between CPU cores and GPU.

B_{H2D}: Bandwidth from host to device expressed in GB/s

G_{GPU}: Sustained performance of DGEMM on the GPU expressed in $GFlops$

G_{CPU}: Sustained performance of DGEMM on the CPU expressed in $GFlops$

B_{D2H}: Bandwidth from device to host expressed in GB/s

A DGEMM call on the host CPU performs $2KMN$ operations, so if the CPU cores can perform this operation at G_{CPU} the total time is:

$$T_{CPU}(M,K,N) = 2\frac{MKN}{G_{CPU}}$$

The total time to offload a DGEMM call to the GPU has an I/O component that accounts for both the data transfer from the CPU memory space to the GPU memory space and vice versa plus a computational part once the data is on the GPU. We can express this time as:

$$T_{GPU}(M,K,N) = 8\frac{(MK+KN+MN)}{B_{H2D}} + 2\frac{MKN}{G_{GPU}} + 8\frac{(MN)}{B_{D2H}}$$

the factor 8 is the size of a double in bytes.
The optimal split will be

$T_{CPU}(M,K,N2) = T_{GPU}(M,K,N1)$ with $N = N1+N2$

For an initial approximation of the optimal split fraction $\eta = N1/N$, we can omit the transfer time ($O(N^2)$) compared to the computation ($O(N^3)$). From a simple manipulation, the optimal split is

$$\eta = \frac{G_{GPU}}{G_{GPU} + G_{CPU}}$$

On the cluster, where the quad core Xeon has a DGEMM performance of 40 GFlops and the GPU a DGEMM performance of 82 GFlops, this formula predicts $\eta = 0.67$, very close to the optimal value of 0.68 found by experiments.

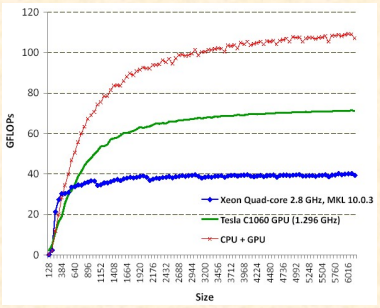
```
// Copy A from CPU memory to GPU memory devA
   status = cublasSetMatrix (m, k     , sizeof(A[0]), A, lda, devA, m_gpu);
// Copy B1  from CPU memory to GPU memory devB
   status = cublasSetMatrix (k ,n_gpu, sizeof(B[0]), B, ldb, devB, k_gpu);
// Copy C1  from CPU memory to GPU memory devC
   status = cublasSetMatrix (m, n_gpu, sizeof(C[0]), C, ldc, devC, m_gpu);

// Perform  DGEMM(devA,devB,devC) on GPU
// Control immediately return to CPU
   cublasDgemm('n', 'n', m, n_gpu, k, alpha, devA, m,devB, k, beta, devC, m);

// Perform  DGEMM(A,B2,C2) on CPU
   dgemm_cpu('n','n',m,n_cpu,k, alpha, A, lda,B+ldb*n_gpu, ldb, beta,C+ldc*n_gpu, ldc);

// Copy devC  from GPU memory to CPU memory C1
   status = cublasGetMatrix (m, n, sizeof(C[0]), devC, m, C, *ldc);
```

It turns out that on Intel systems using Front Side Bus (FSB), it is better not to overlap the transfer to the GPU with computations on the CPU (the memory system cannot supply data to both the PCIe and the CPU at maximum speed).

The DGEMM function call in CUBLAS maps to several different kernels depending on the size of the matrices. The best performance is achieved when M is multiple of 64 and K and N multiple of 16. Performance numbers for different choices of M, K and N are shown in table 5. When all the above conditions are satisfied, the GPU can achieve 82.4 Gflops, 95% of the peak double precision performance.

M	K	N	M%64	K%16	N%16	$Gflops$
448	400	12320	Y	Y	Y	82.4
12320	400	1600	N	Y	Y	72.2
12320	300	448	N	N	Y	55.9
12320	300	300	N	N	N	55.9

Table 3: DGEMM performance on the Tesla S1070 GPU (1.44 GHz) with data resident in GPU memory



The peak performance of the CPU is 48 GFlops, a CPU-only Linpack sustains performance in the $70\% - 80\%$ range for very large problem sizes. The CUDA accelerated version with pinned memory (limited today to 4GB per MPI process) delivers 83.2 Gflops, 66% of the combined 125 GFlops system peak performance (the Tesla C1060 has a peak performance of 77.7 Gflops). The accelerated solution also delivers good performance for small problem sizes and is not very sensitive to the size of NB.

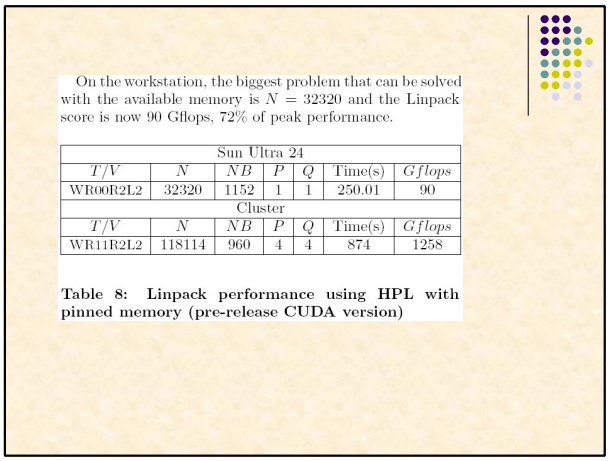
T/V	N	NB	P	Q	Time(s)	$Gflops$
WR00L2L2	23040	960	1	1	97.91	83.28
WR00L2L2	7432	960	1	1	5.47	50.01
WR00L2L2	7432	1152	1	1	5.47	53.56

Table 4: Linpack performance on a Sun Ultra 24 workstation with 1 Intel(R) Core2 Extreme Q6850 (3.0Ghz) and a Tesla C1060 using HPL with pinned memory for different N and NBs.

Table 5 shows the same results using pageable memory. The use of pinned vs. regular pageable memory increases the performance from 70 to 84 Gflops.

T/V	N	NB	P	Q	Time(s)	$Gflops$
WR00L2L2	23040	960	1	1	117.06	69.66
WR00L2L2	23040	1152	1	1	117.06	70.64
WR00L2L2	7432	960	1	1	6.09	44.94
WR00L2L2	7432	1152	1	1	5.97	45.86

Table 5: Linpack performance on a Sun Ultra 24 workstation with 1 Intel(R) Core2 Extreme Q6850 (3.0Ghz) and a Tesla C1060 using HPL with pageable memory



On the workstation, the biggest problem that can be solved with the available memory is $N = 32320$ and the Linpack score is now 90 Gflops, 72% of peak performance.

Sun Ultra 24						
T/V	N	NB	P	Q	Time(s)	$Gflops$
WR00R2L2	32320	1152	1	1	250.01	90
Cluster						
T/V	N	NB	P	Q	Time(s)	$Gflops$
WR11R2L2	118114	960	4	4	874	1258

Table 8: Linpack performance using HPL with pinned memory (pre-release CUDA version)