# Introduction to Parallel Programming

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# Overview

- Types of parallel computers.
- Parallel programming options.
- How to write parallel applications.
- How to compile.
- How to debug/profile.
- Summary, future expansion.
- Please give us feedback

https://www.surveymonkey.com/r/KHVDC5H

# Parallel architectures

Single processor:

- SISD – single instruction single data.

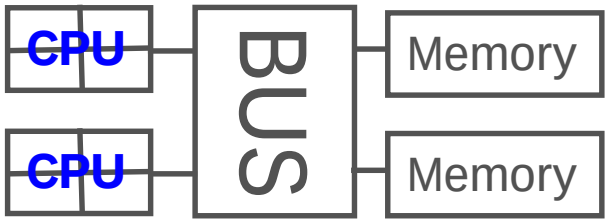
Multiple processors:

- SIMD - single instruction multiple data.
- MIMD – multiple instruction multiple data.
  - Shared Memory
  - Distributed Memory
- Current processors combine SIMD and MIMD
  - Multi-core CPUs w/ SIMD instructions (AVX, SSE)
  - GPUs with many cores and SIMT

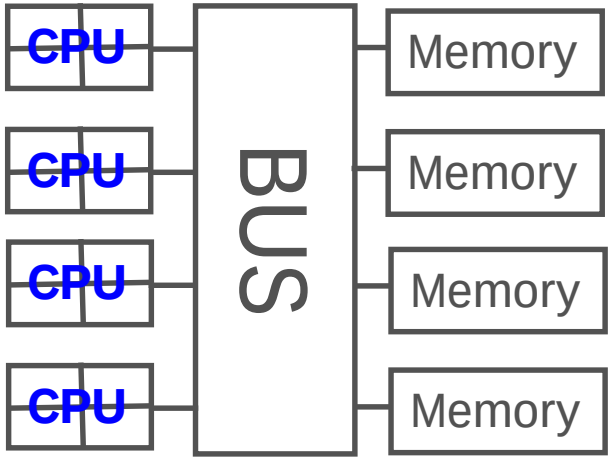
# Shared memory

- All processors have access to local memory
- Simpler programming
- Concurrent memory access
- More specialized hardware
- CHPC :
  Linux clusters 12, 16, 20, 24, 28 core nodes
  GPU nodes

Dual quad-core node

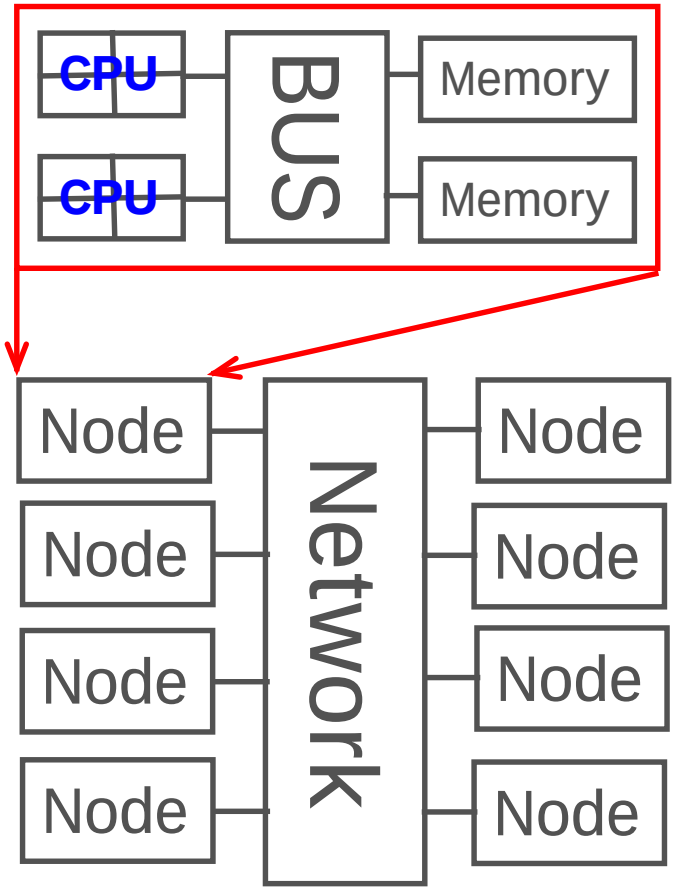



Many-core node (e.g. SGI)



# Distributed memory

- Process has access only to its local memory
- Data between processes must be communicated
- More complex programming
- Cheap commodity hardware
- CHPC: Linux clusters




8 node cluster (64 cores)

# Parallel programming options

## Shared Memory

- Threads – POSIX Pthreads, OpenMP (CPU, MIC), OpenACC, CUDA (GPU)
  - Thread – own execution sequence but shares memory space with the original process
- Message passing – processes
  - Process – entity that executes a program – has its own memory space, execution sequence

## Distributed Memory

- Message passing libraries
- Vendor specific – non portable
- General – MPI, PVM, language extensions (Co-array Fortran, UPC. …)

# OpenMP basics

- Compiler directives to parallelize
- Fortran – source code comments

  `!$omp parallel/!$omp end parallel`
- C/C++ - #pragmas

  `#pragma omp parallel`
- Small set of subroutines
- Degree of parallelism specification
- `OMP_NUM_THREADS` or `omp_set_num_threads(INTEGER n)`

# MPI Basics

- Communication library
- Language bindings:
  - C/C++ - `int MPI_Init(int argv, char* argc[])`
  - Fortran - `MPI_Init(INTEGER ierr)`
- Quite complex (100+ subroutines)

  but only small number used frequently
- User defined parallel distribution

# MPI vs. OpenMP

- Complex to code
- Slow data communication

- Ported to many architectures
- Many tune-up options for parallel execution

- Easy to code
- Fast data exchange

- Memory access (thread safety)
- Limited usability
- Limited user's influence on parallel execution

# Program example

- saxpy – vector addition: $\bar{z} = a\bar{x} + \bar{y}$
- simple loop, no cross-dependence, easy to parallelize

```
subroutine saxpy_serial(z, a, x, y, n)
integer i, n
real z(n), a, x(n), y(n)

do i=1, n
  z(i) = a*x(i) + y(i)
enddo
return
```

# OpenMP program example

```
subroutine saxpy_parallel_omp(z, a, x, y, n)
integer i, n
real z(n), a, x(n), y(n)

!$omp parallel do
do i=1, n
  z(i) = a*x(i) + y(i)
enddo
return
```

setenv OMP_NUM_THREADS 16

# MPI program example

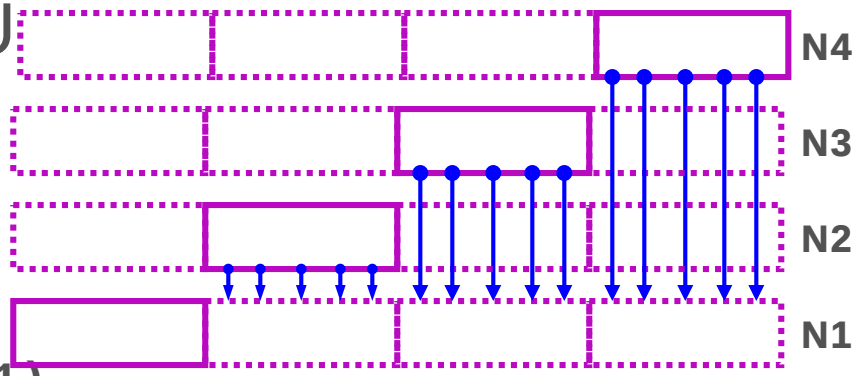
```
subroutine saxpy_parallel_mpi(z, a, x, y, n)
integer i, n, ierr, my_rank, nodes, i_st, i_end
real z(n), a, x(n), y(n)

call MPI_Init(ierr)
call MPI_Comm_rank(MPI_COMM_WORLD,my_rank,ierr)
call MPI_Comm_size(MPI_COMM_WORLD,nodes,ierr)
i_st = n/nodes*my_rank+1
i_end = n/nodes*(my_rank+1)

do i=i_st, i_end
   z(i) = a*x(i) + y(i)
enddo
call MPI_Finalize(ierr)
return
```

**z(i) operation on 4 processes**

| | | | |
|---|---|---|---|
| z(1 ... n/4) | z(n/4+1 ... 2*n/4) | z(2*n/4+1 ... 3*n/4) | z(3*n/4+1 ... n) |

# MPI program example

- Result on the first CPU




```
include "mpif.h"
integer status(MPI_STATUS_SIZE)
if (my_rank .eq. 0 ) then
  do j = 1, nodes-1
    do i= n/nodes*j+1, n/nodes*(j+1)
      call MPI_Recv(z(i),1,MPI_REAL,j,0,MPI_COMM_WORLD,
&     status,ierr)
    enddo
  enddo
else
  do i=i_st, i_end
     call MPI_Send(z(i),1,MPI_REAL,0,0,MPI_COMM_WORLD,ierr)
  enddo
endif
```

Data | Count

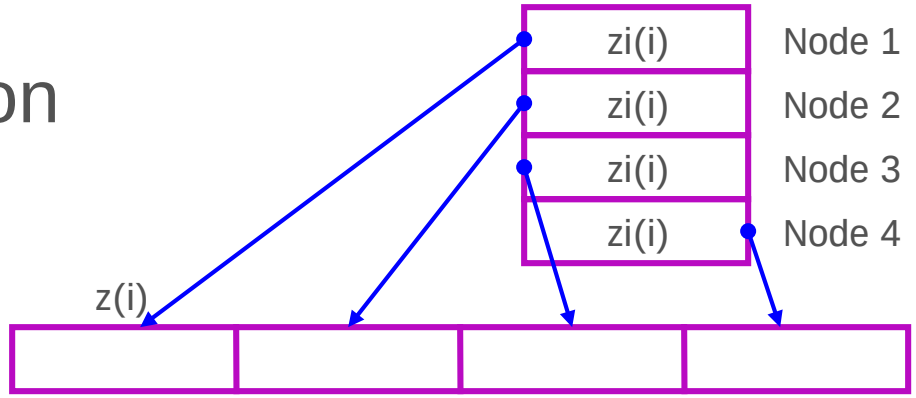
Sender

Recipient

# MPI program example

- Collective communication

```
real zi(n)
j = 1
do i=i_st, i_end
   zi(j) = a*x(i) + y(i)
   j = j +1
enddo
```




**Send data**

**Receive data**

```
call MPI_Gather(zi,n/nodes,MPI_REAL,z,n/nodes,MPI_REAL,
&                0,MPI_COMM_WORLD,ierr)
```

**Root process**

- Result on all nodes

```
call MPI_AllGather(zi,n/nodes,MPI_REAL,z,n/nodes,
&                  MPI_REAL,MPI_COMM_WORLD,ierr)
```

**No root process**

# Clusters - login

- First log into one of the clusters
  `ssh lonepeak.chpc.utah.edu` – Ethernet
  `ssh ember.chpc.utah.edu` – Ethernet, InfiniBand
  `ssh kingspeak.chpc.utah.edu` – Ethernet, InfiniBand

- Then submit a job to get compute nodes

```
srun –N 2 –n 24 –p ember –A chpc –t 1:00:00
--pty=/bin/tcsh -l
sbatch script.slr
```

- Useful scheduler commands
  `sbatch` – submit a job
  `scancel` – delete a job
  `squeue` – show job queue

# Security Policies

- No clear text passwords use ssh and scp
- You may not share your account under any circumstances
- Don’t leave your terminal unattended while logged into your account
- Do not introduce classified or sensitive work onto CHPC systems
- Use a good password and protect it

# Security Policies

- Do not try to break passwords, tamper with files etc.
- Do not distribute or copy privileged data or software
- Report suspicions to CHPC (security@chpc.utah.edu)
- Please see http://www.chpc.utah.edu/docs/policies/security.html for more details

# Compilation - OpenMP

- Different switches for different compilers, –openmp, –fopenmp or –mp

```
module load intel
module load pgi
module load gcc
```

e.g. `pgf77 –mp source.f –o program.exe`

- Nodes with up to 28 cores each
- Further references:

  Compilers man page – `man ifort`

  Compilers websites

  http://www.intel.com/software/products/compilers

  http://gcc.cnu.org

  http://www.pgroup.com/doc/

# Compilation - MPI

- Two common network interfaces
  - Ethernet, InfiniBand
- Different MPI implementations
  - MPICH - Ethernet, InfiniBand
  - OpenMPI – Ethernet, InfiniBand
  - MVAPICH2 - InfiniBand
  - Intel MPI – commercial, Ethernet, InfiniBand

# Compilation - MPI

- **Clusters** – MPICH, OpenMPI, MVAPICH2, Intel MPI
  `/MPI-path/bin/mpixx source.x –o program.exe`
  `xx` = cc, cxx, f77, f90; icc, ifort for Intel MPI
- `MPI-path` = location of the distribution – set by `module load`
  `module load mpich2` MPICH Ethernet, InfiniBand
  `module load openmpi` OpenMPI Ethernet, InfiniBand
  `module load mvapich2` MVAPICH2 InfiniBand
  `module load impi` Intel MPI Ethernet, InfiniBand

  = after this simply use `mpixx`
- Ensure that when running (using `mpirun`), the same module is loaded.

# Running a parallel job – Clusters

- MPICH Interactive batch

```
srun –N 2 –n 24 –p ember –A chpc –t 1:00:00
--pty=/bin/tcsh -l
… wait for prompt …
module load intel mpich2
mpirun –np $SLURM_NTASKS program.exe
```

- MPICH Batch

```
sbatch –N 2 –n 24 –p ember –A chpc –t 1:00:00
script.slr
```

- OpenMP Batch

```
srun –N 1 –n 1 –p ember –A chpc –t 1:00:00
--pty=/bin/tcsh -l
setenv OMP_NUM_THREADS 12
program.exe
```

# Compiling and running a parallel job – desktops

- Use MPICH or OpenMPI, MPICH is my preferred

```
module load mpich2
mpixx source.x –o program.exe
```

xx = cc, cxx, f77, f90; icc, ifort for Intel MPI

- MPICH2 running

```
mpirun –np 4 ./program.exe
```

- OpenMP running

```
setenv OMP_NUM_THREADS 4
./program.exe
```

- See more details/combinations at `https://www.chpc.utah.edu/documentation/software/mpilibraries.php`

# Single executable across desktops and clusters

- MPICH, MVAPICH2 and Intel MPI are cross-compatible using the same ABI
  - Can e.g. compile with MPICH on a desktop, and then run on the cluster using MVAPICH2 and InfiniBand
- Intel and PGI compilers allow to build "unified binary" with optimizations for different CPU platforms
  - But in reality it only works well under Intel compilers
- On a desktop

```
module load intel mpich2
mpicc –axCORE-AVX2 program.c –o program.exe
mpirun –np 4 ./program.exe
```

- On a cluster

```
srun –N 2 –n 24 ...
module load intel mvapich2
mpirun –np $SLURM_NTASKS ./program.exe
```

- https://www.chpc.utah.edu/documentation/software/single-executable.php

# Debuggers

- Useful for finding bugs in programs
- Several free
  - `gdb` – GNU, text based, limited parallel
  - `ddd` – graphical frontend for gdb
- Commercial that come with compilers
  - `pgdbg` – PGI, graphical, parallel but not intuitive
  - `pathdb, idb` – Pathscale, Intel, text based
- Specialized commercial
  - **`totalview`** – graphical, parallel, CHPC has a license
  - `ddt` - Distributed Debugging Tool
  - **Intel Inspector XE** – memory and threading error checker
- How to use:
- `http://www.chpc.utah.edu/docs/manuals/software/par_devel.html`

# Debuggers - parallel

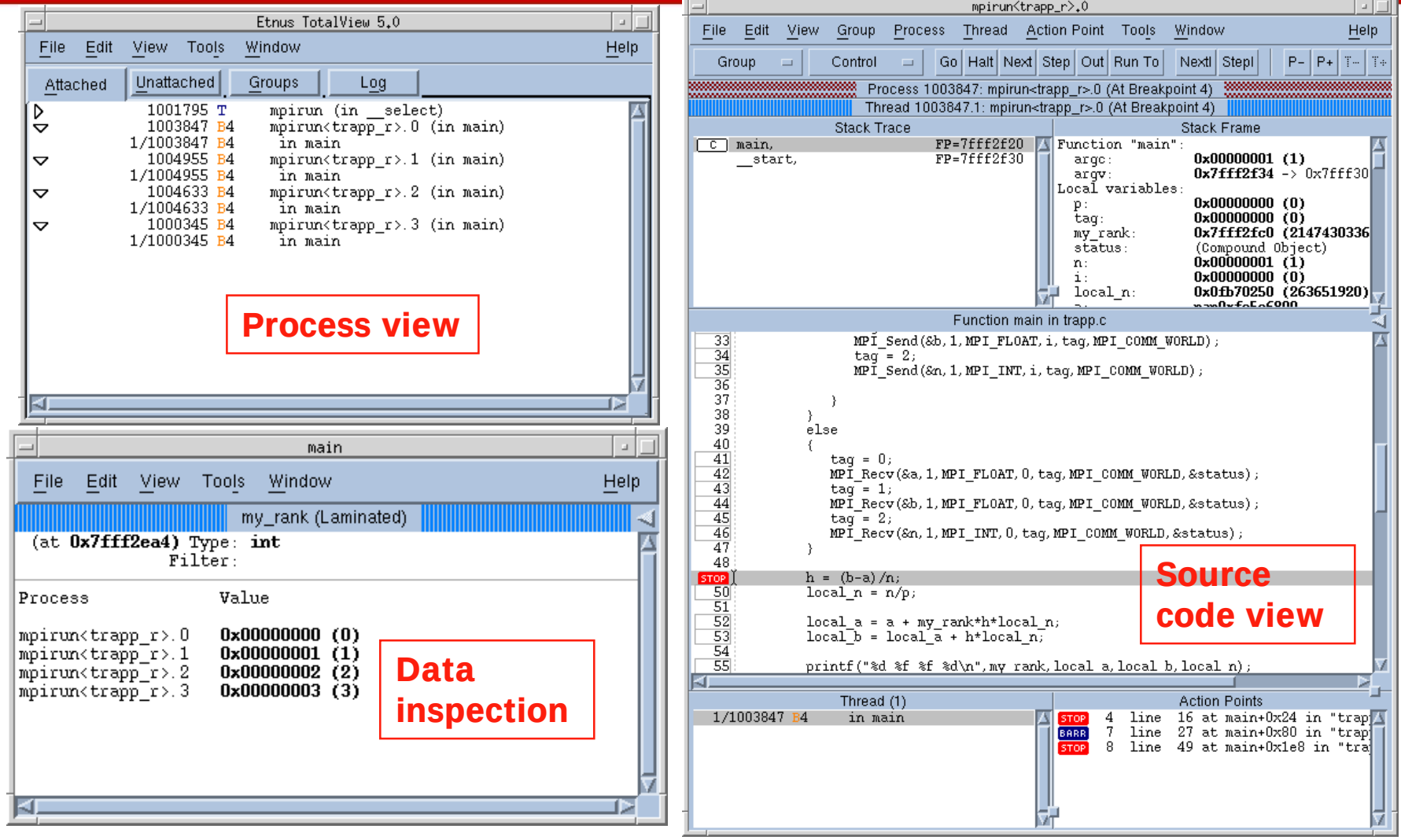
- Parallel debugging more complex due to interaction between processes
- Totalview is the debugger of choice at CHPC
- Expensive but academia get discount
- How to run it:
  - compile with –g flag
  - automatic attachment to OpenMP threads
  - wizard to set up MPI debugging session
- Details:

`http://www.chpc.utah.edu/docs/manuals/software/totalview.html`

- Further information

`http://www.roguewave.com/products-services/totalview`

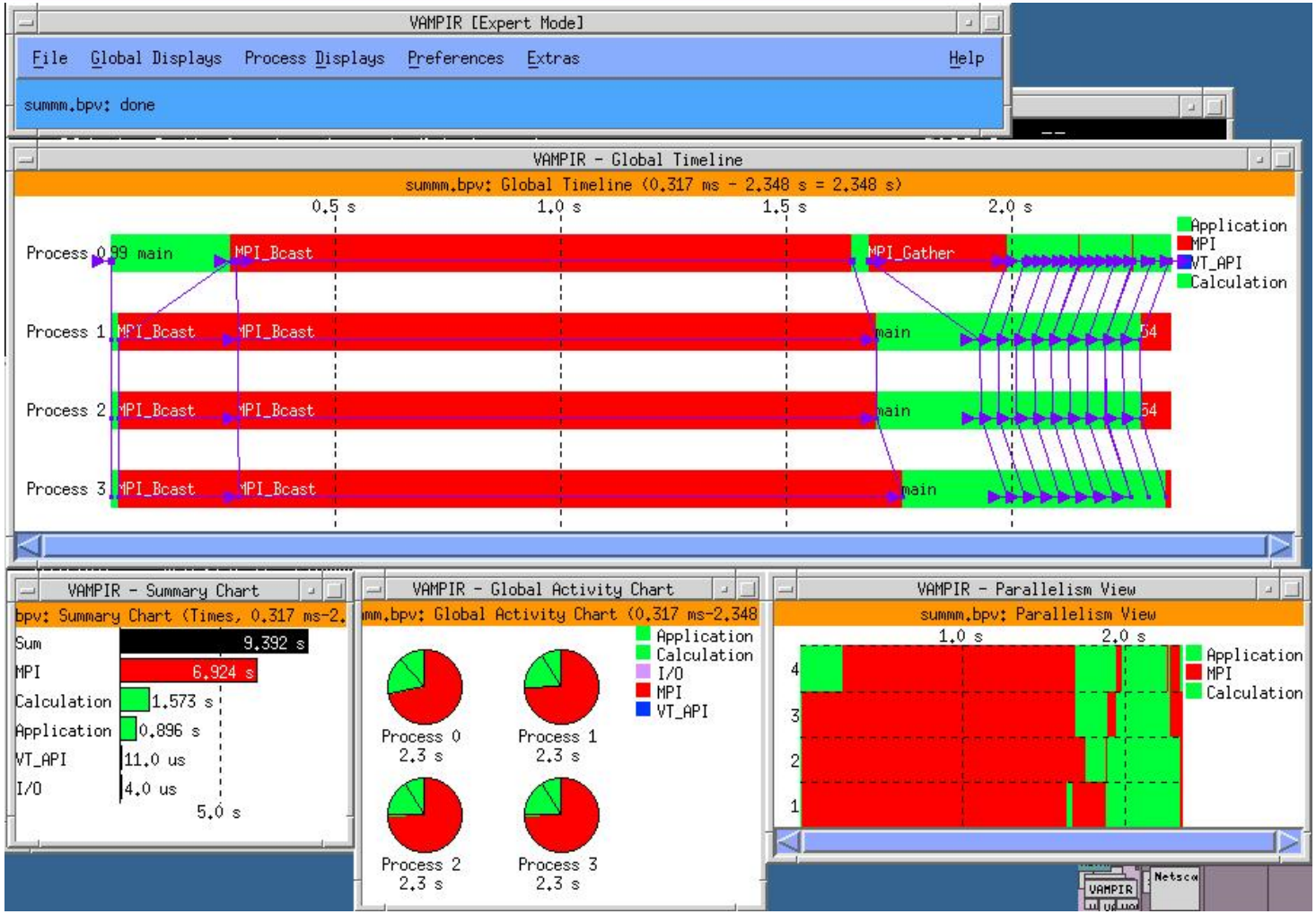
# Debuggers – parallel



# Profilers

- Measure performance of the code
- Serial profiling
  - discover inefficient programming
  - computer architecture slowdowns
  - compiler optimizations evaluation
  - gprof, pgprof, pathopt2, Intel tools
- Parallel profiling
  - target is inefficient communication
  - Intel Trace Collector and Analyzer, AdvisorXE, VTune

# Profilers - parallel



# Libraries

- Serial
  - BLAS, LAPACK – linear algebra routines
  - MKL, ACML – hardware vendor libraries
- Parallel
  - ScaLAPACK, PETSc, NAG, FFTW
  - MKL – dense and sparse matrices

`http://www.chpc.utah.edu/docs/manuals/software/mat_l.html`

# Summary

- Shared vs. Distributed memory
- OpenMP
  - Limited to 1 cluster node
  - Simple parallelization
- MPI
  - Clusters
  - Must use communication

`http://www.chpc.utah.edu/docs/presentations/intro_par`

# References

- OpenMP

  `http://www.openmp.org/`

  Chandra, et. al. - Parallel Programming in OpenMP

  Chapman, Jost, van der Pas – Using OpenMP
- MPI

  `http://www-unix.mcs.anl.gov/mpi/`

  Pacheco - Parallel Programming with MPI

  Gropp, Lusk, Skjellum - Using MPI 1, 2
- MPI and OpenMP

  Pacheco – An Introduction to Parallel Programming

# Future Presentations

- Introduction to MPI
- Introduction to OpenMP
- Debugging with Totalview
- Profiling with TAU/Vampir
- Intermediate MPI and MPI-IO
- Mathematical Libraries at the CHPC

Feedback

https://www.surveymonkey.com/r/KHVDC5H