Hewlett Packard
Enterprise

DEBUGGING AT SCALE

HPE/Cray tools

June 10, 2024

AGENDA

- Stack Trace Analysis Tool (STAT)
  - For when nothing appears to be happening…
- Abnormal Termination Processing (ATP)
  - For when things break unexpectedly… (Collecting back-trace information)
- GDB4HPC
  - Scaling the GDB debugger
- CCDB
  - Using the Cray Comparative Debugger
- VALGRIND4HPC
  - Valgrind-based debugging tool for parallel applications
- SANTIZERS4HPC
  - Use several tools to check program correctness at run-time for parallel applications

DEBUGGING IN PRODUCTION AND AT SCALE

- The failing application may have been using tens of or hundreds of thousands of processes
  - If a crash occurs one, many, or all of the processes might issue a signal.
  - We don’t want the core files from every crashed process, they’re slow and too big!
  - We don’t want a backtrace from every process, they’re difficult to comprehend and analyze.

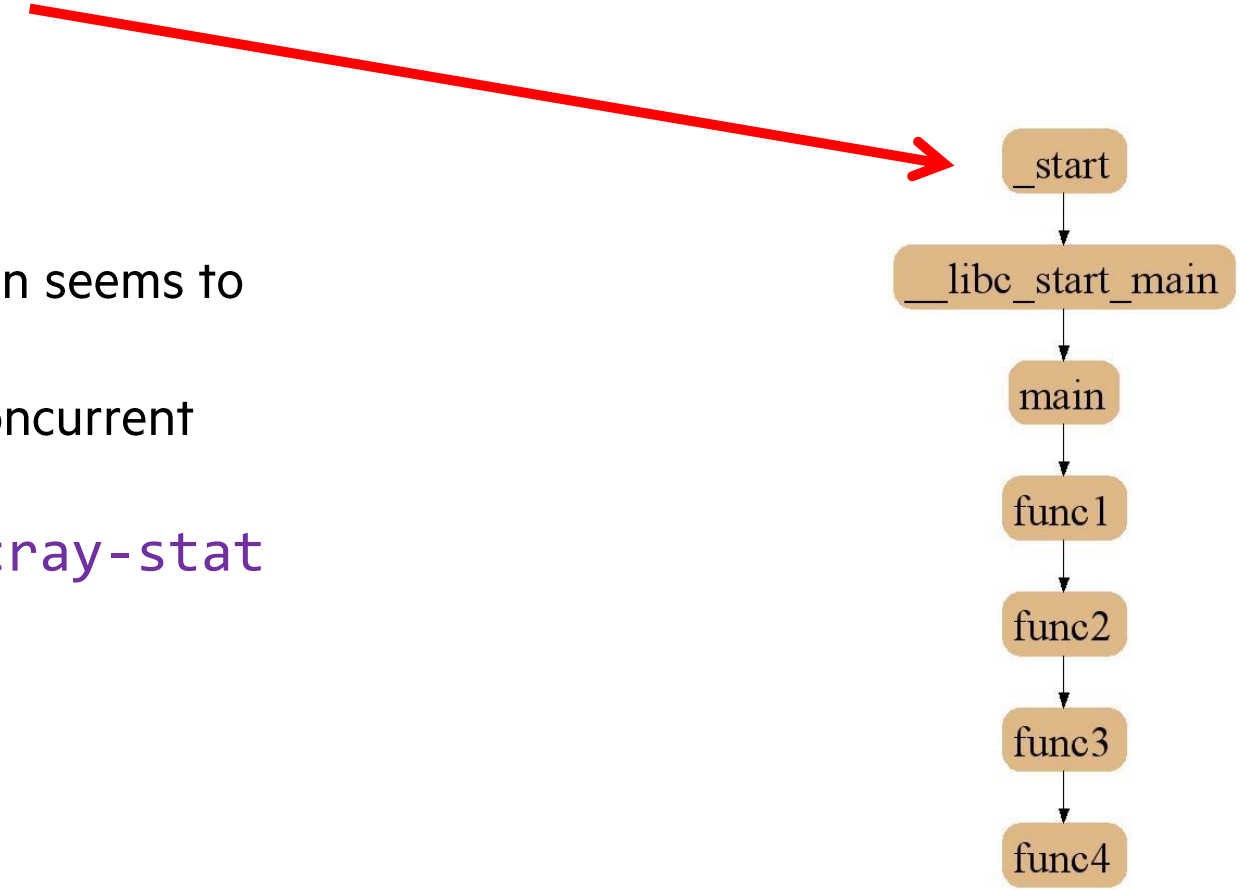
STAT - STACK TRACE ANALYSIS TOOL

For when nothing appears to be happening…

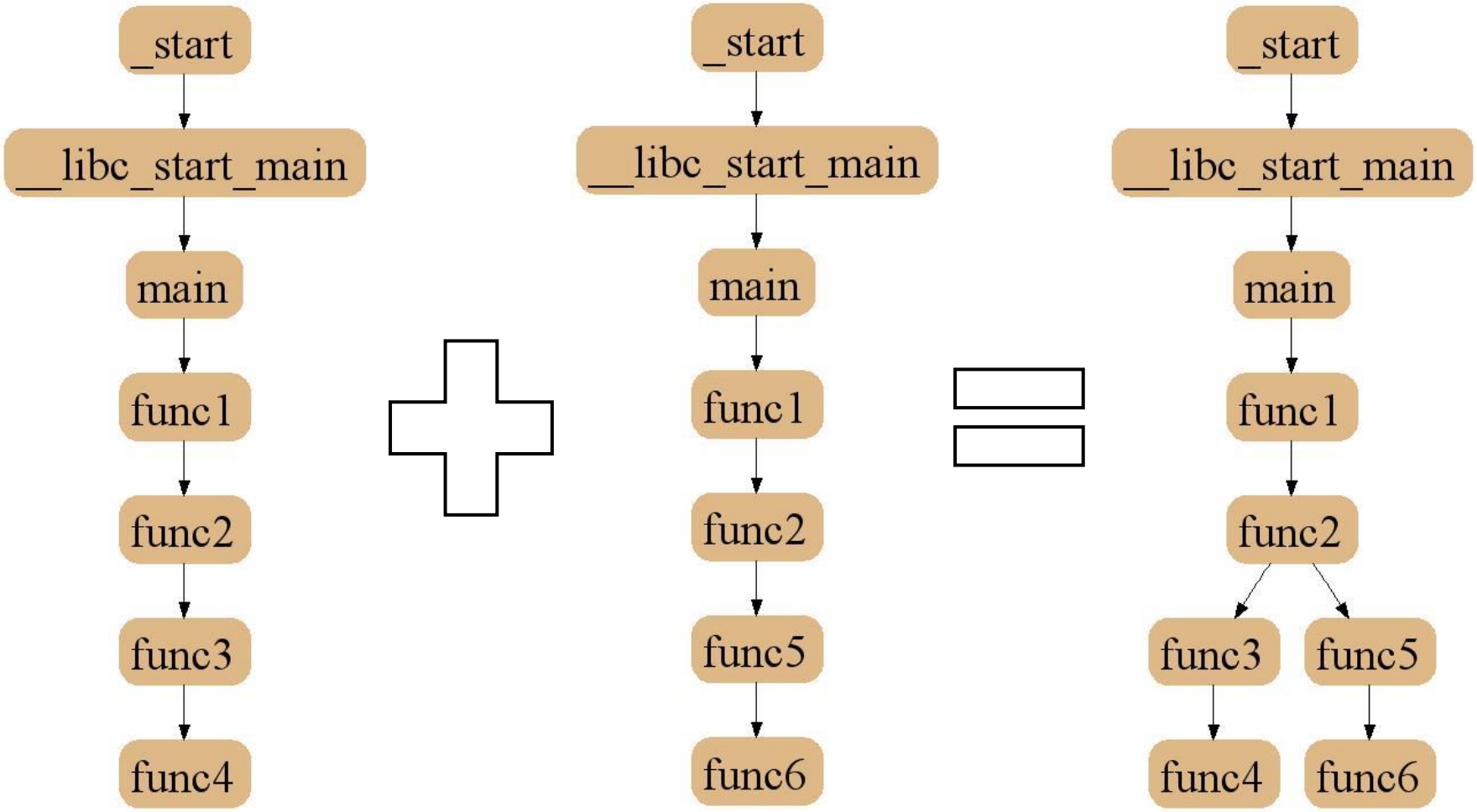
DEMO 3A_STAT

DESCRIPTION

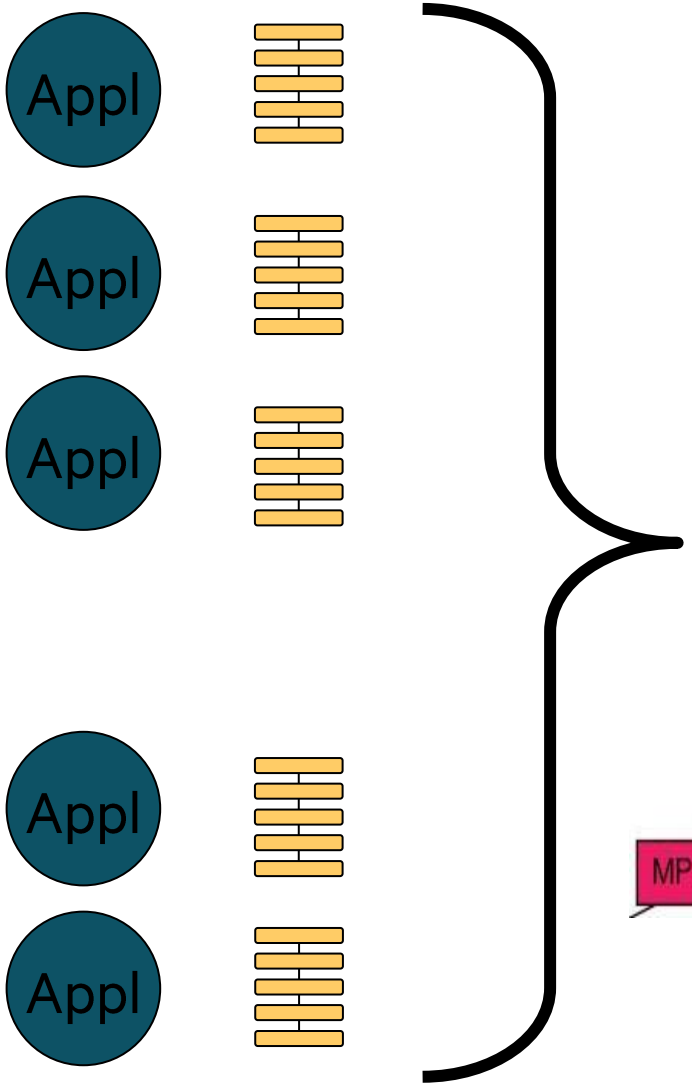
- Gathers and merges stack traces from a running application's parallel processes.
- Creates call graph prefix tree
  - Compressed representation
  - Scalable visualization
  - Scalable analysis
- It is very useful when application seems to be stuck/hung
- Scales to many thousands of concurrent process.
- Available through the module `cray-stat`

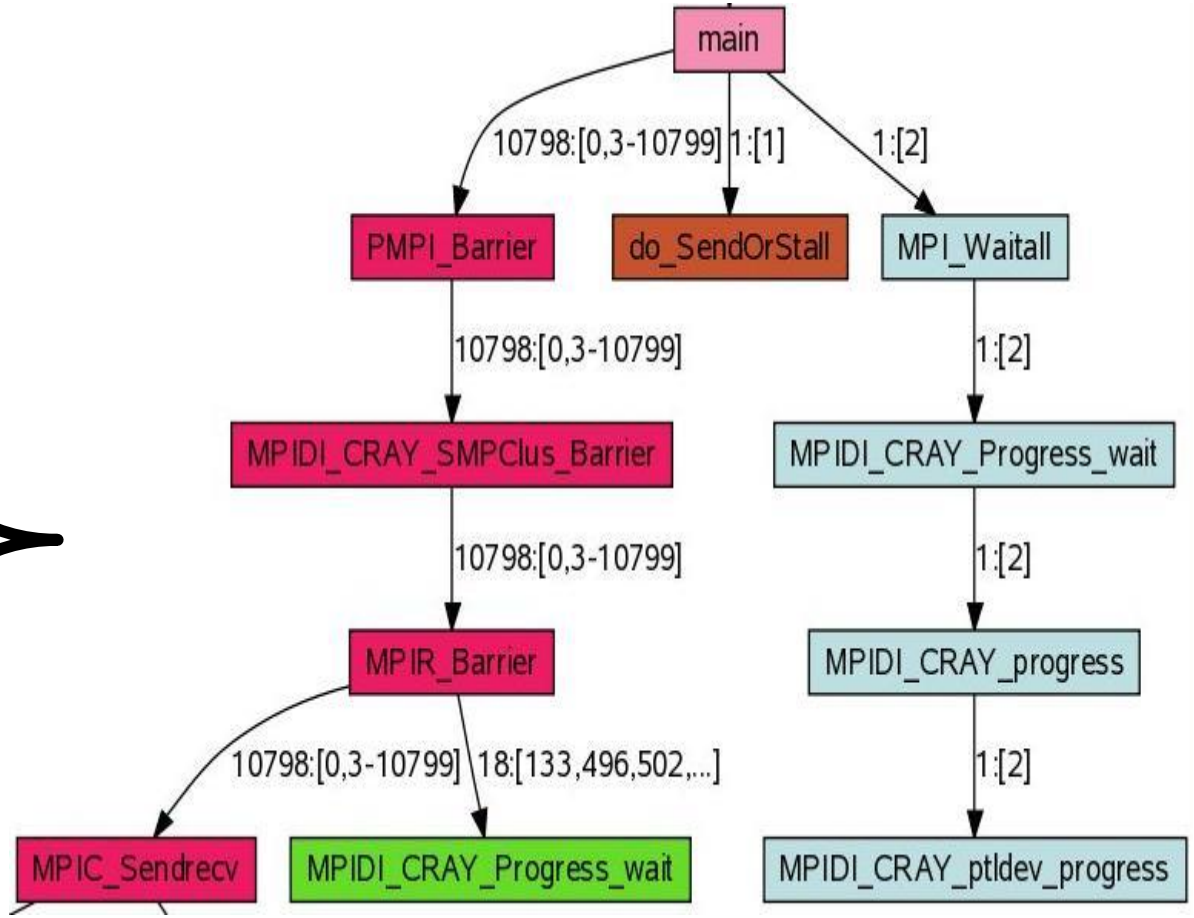


STACK TRACE MERGE EXAMPLE



2D-TRACE/SPACE ANALYSIS





USING STAT FROM AN INTERACTIVE SESSION

```
> module load cray-stat
> srun -n … ./<exe> &
```

- First get an interactive session (via salloc)
- Load the `cray-stat` module and run your application in the background

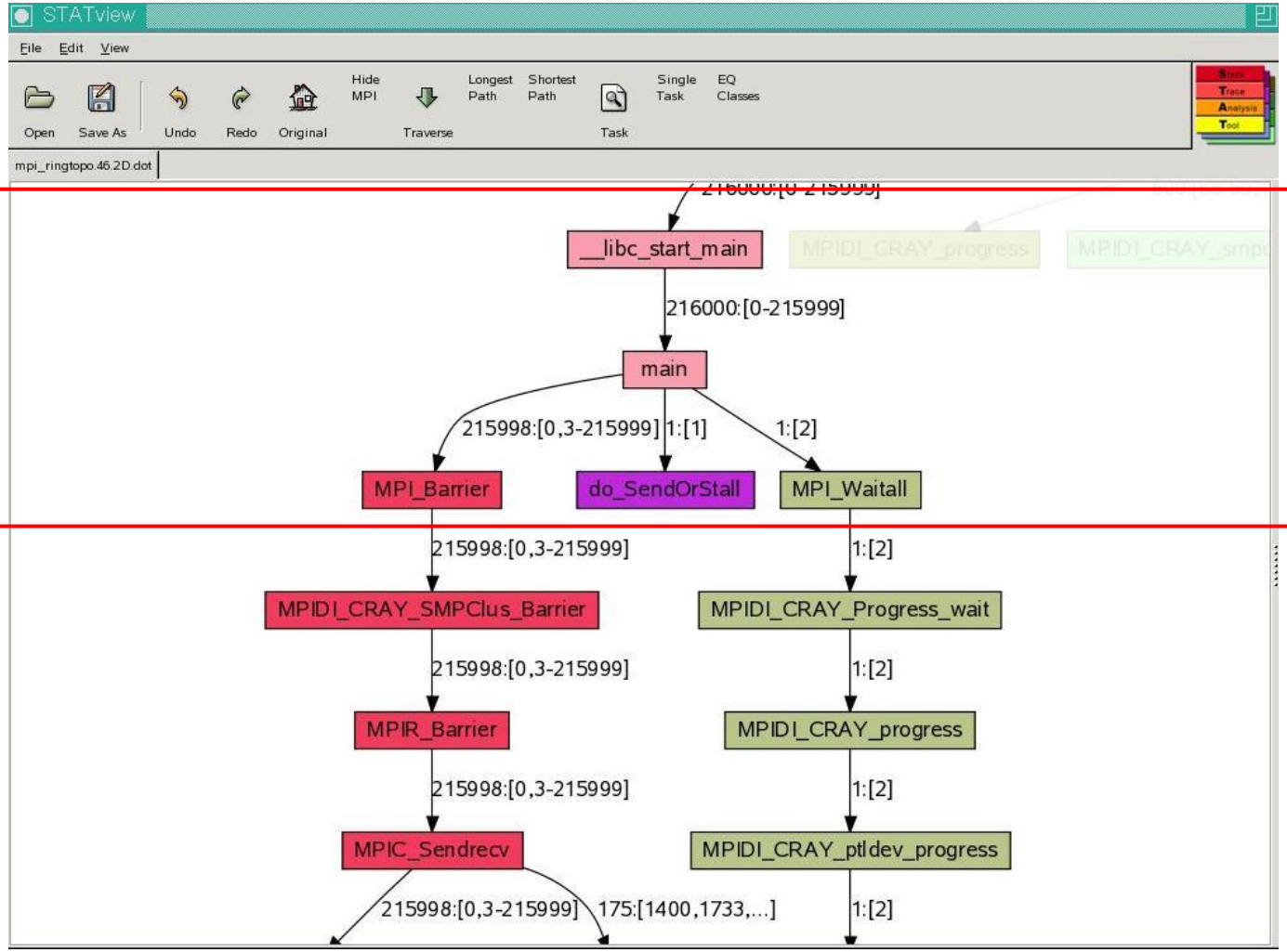
```
> stat-cl <pid_of_srun>
```

- Wait until application reaches the suspicious state
- Then launch the command line tool `stat-cl` with the process id of the `srun` as an argument and wait until it returns
- Terminate the running application with `scancel` or `kill` the `srun`

```
> stat-view stat_results/<exe>.0000/00.<exe>.0000.2D.dot
```

- Now you can start the graphical interface `stat-view`
- In order to use the graphical tool `stat-gui` to get the traces instead of the `stat-cl` please refer to `man stat-gui`
- More info: `man stat-cl`, `man stat-view`, and `man stat-gui`

MERGED STACK



USING STAT IN A BATCH JOB

```
module load cray-stat
stat-cl -s 30 -C srun -n … ./<exe>
```

- Prepend the `stat-cl` command to `srun` in your batch script
- The `-s <n>` option indicates that STAT should wait `<n>` seconds and then attempt to perform the snapshot. Therefore, this value should be sufficiently large that the application can be reliably assumed to be in the hung state

```
> stat-view stat_results/<exe>.0000/00.<exe>.0000.2D.dot
```

- Now you can start the graphical interface `stat-view`
- More info: `man stat-cl`, `man stat-view`, and `man stat-gui`

ATP - ABNORMAL TERMINATION PROCESSING

For when things break unexpectedly…
(Collecting back-trace information)

DEMO 3B_ATP

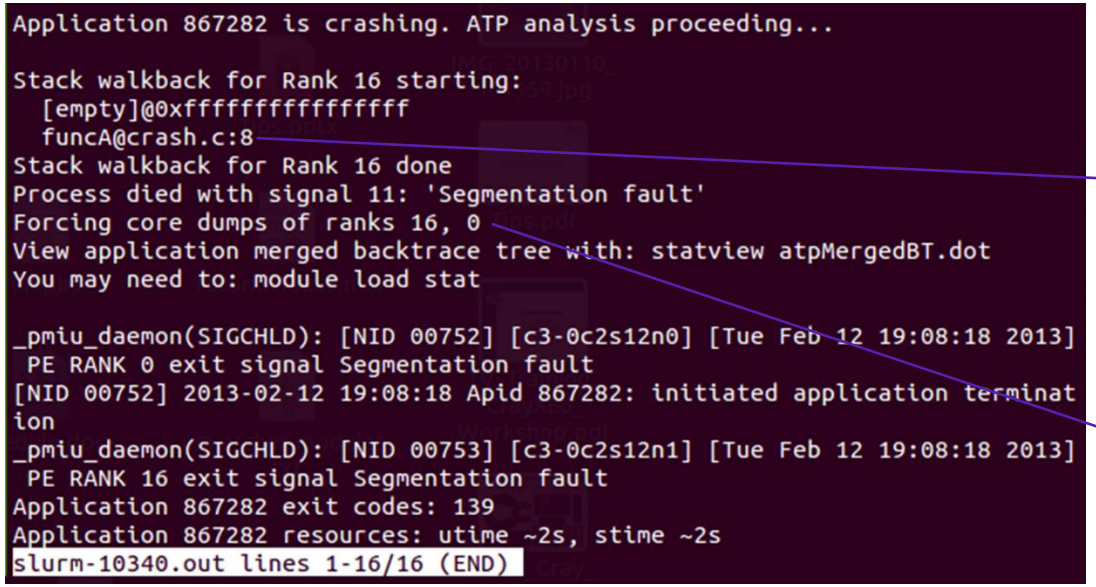
DESCRIPTION

- Abnormal Termination Processing is a lightweight monitoring framework that detects crashes and provides more analysis instead of silently terminating.
  - Designed to be so light weight it can be used all the time with almost no impact on performance.
  - Almost completely transparent to the user
    - Requires `atp module` to be loaded during compilation (usually included by default)
    - Output controlled by the `ATP_ENABLED` environment variable (set by user, `ATP_ENABLED=1` for enabling it)
  - Tested at scale (tens of thousands of processors)
- ATP rationalizes parallel debug information into three easier to use forms:
  1. A single stack trace of the first failing process to stderr
  2. A visualization of every processes stack trace when it crashed
  3. A selection of representative core files for analysis

ATP USAGE

```
export ATP_ENABLED=1
ulimit -c unlimited
module load atp
```

- Job scripts must include the changes above. Note that ATP respects ulimits on corefiles.
- After abnormal termination the application will not simply crash but proceed with the ATP analysis.
- Backtrace of first crashing process to stderr and the merged backtrace stored in dot files:
  - `atpMergedBT.dot` –Backtraces merged by function name only (smaller number of branches)
  - `atpMergedBT_line.dot`–Backtraces merged by function name and line number (more accurate but larger trace)



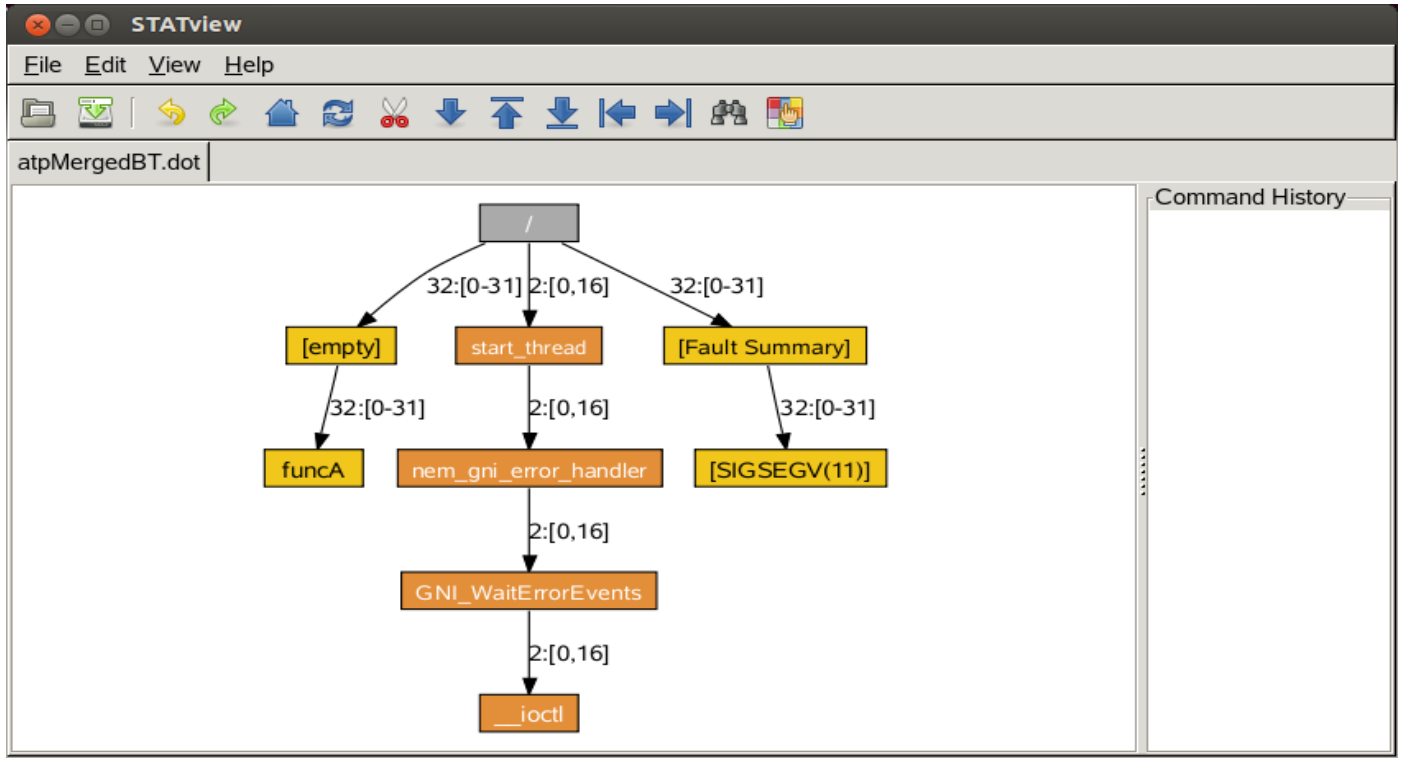
Trace back of crashing process

Core files are being generated.

VIEWING THE RESULTS AFTER THE CRASH

```
> module load cray-stat
> stat-view atpMergedBT.dot
```

- The merged backtrace is inspected via STAT.



- The core files can be inspected with gdb or ARM Forge
- Man page atp for more info

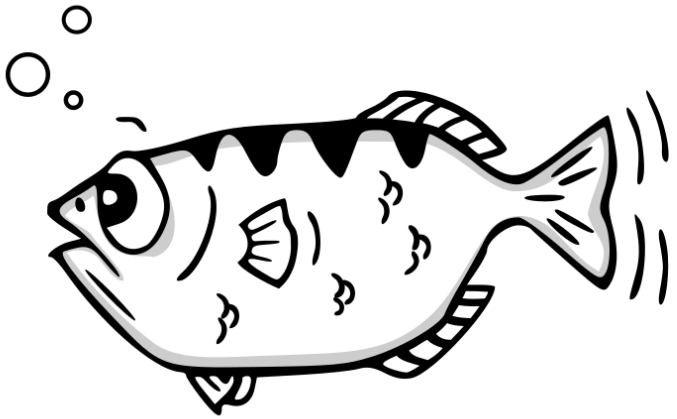
GDB4HPC - GDB FOR HPC

Scaling the GDB Debugger

DEMO 3C_GDB4HPC

GDB

- The gdb debugger is now almost 40 years old
- It can load/start a process, attach to a running process or analyse a core dump
- It provides a command-line interface
- Requires compilation with debugging flags



Common commands (with shorter aliases):

- run (**r**): start or restart a program
- break (**b**): set a breakpoint location
- print (**p**): print the value of a variable or expression
- continue (**c**): continue running after a stop
- next (**n**): execute the next line of source code
- step (**s**): execute the next line, stepping into a function call
- backtrace (**bt**): show the current call stack

GDB CAPABILITIES

- Watch points
- Signal and exception handling
- Conditional stops
- Executing commands at every stop
- Complex expressions (full interpreter)
- Making calls to program functions
- Interacting with threads
- Interpreting core files
- Custom pretty printing (via Python extensions)
- Examining raw data
- Built in shell with user variables and control structures
- And probably a lot more

```
dshanks@ln04:/VH1-debug/run> gdb ../bin/vh1-mpi-cray core
GNU gdb (GDB; SUSE Linux Enterprise 15) 10.1
Copyright (C) 2020 Free Software Foundation, Inc.
License GPLv3+: GNU GPL version 3 or later
<http://gnu.org/licenses/gpl.html>
This is free software: you are free to change and
redistribute it.
There is NO WARRANTY, to the extent permitted by law.
Type "show copying" and "show warranty" for details.
This GDB was configured as "x86_64-suse-linux".
Type "show configuration" for configuration details.
For bug reporting instructions, please see:
<http://bugs.opensuse.org/>.
Find the GDB manual and other documentation resources
online at:
    <http://www.gnu.org/software/gdb/documentation/>.
[New LWP 191743]
[New LWP 193054]
[Thread debugging using libthread_db enabled]
Using host libthread_db library "/lib64/libthread_db.so.1".
Core was generated by `/debugging_workshop/VH1-
debug/run/..'.
Program terminated with signal SIGSEGV, Segmentation fault.
#0  0x0000000000413d74 in flatten () at flatten.f90:29
29      do n = nmin-4, nmax+4
[Current thread is 1 (Thread 0x2b4e0268a5c0 (LWP 191743))]
(gdb) bt
#0  0x0000000000413d74 in flatten ( ) at flatten.f90:29
#1  0x0000000000412570 in sweepz ( ) at sweepz.f90:126
#2  0x0000000000000000 in ?? ( )
```

GDB RELATED SUPPORT IN GDB4HPC

- Supports (almost) all the commonly used gdb commands
- Gdb4hpc isn't a simple forwarder for gdb
  - Must handle all its special HPC related syntax
  - Understand data types to transmit data efficiently
  - Maintains its own state, like breakpoints
  - Does syntax checking and source look up on the client side
- Gives a "gdbmode" command to access any gdb commands it doesn't handle.
- Also, an escape for expression handling
  - Drawback is that gdb4hpc can only treat these as raw text
- No "convenience features", shell control structures and variables, auto completion, etc.

GDB4HPC HELP

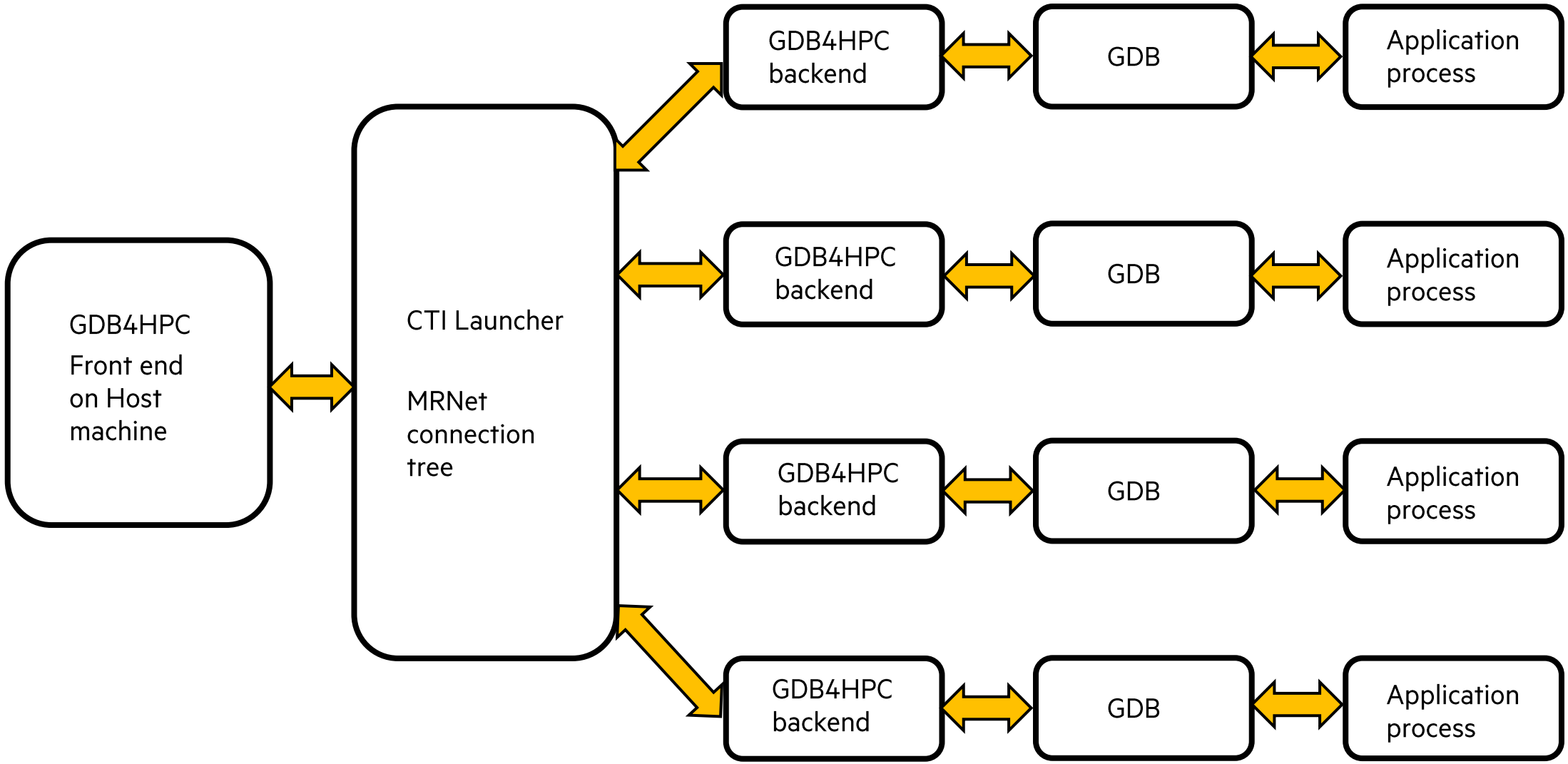
```
> module load gdb4hpc
> gdb4hpc
gdb4hpc 4.15.1 - Cray Interactive Parallel Debugger
With Cray Comparative Debugging Technology.
Copyright 2007-2023 Hewlett Packard Enterprise Development LP.
Copyright 1996-2016 University of Queensland. All Rights Reserved.

Type "help" for a list of commands.
Type "help <cmd>" for detailed help about a command.
dbg all> help
assign          Change the value of an application or debugger variable.
attach          Attach to an application.
backtrace       Print backtrace of all stack frames.
break           Set breakpoint at specified line or function.
build           Build an assertion script.
catch           Set catchpoint on specified event.
checkpoint      Fork program for restoration at a later point.
compare         Compare the contents of two variables.
condition       Stop only if a condition is met.
…
dbg all> help attach
Summary: Attach to an application.
Usage: attach <app_handle> <app_ident> [--gpu]
Additional options: [--debug] [--gdb=<gdbapp>] [--gdb-data-dir=<datadir>]
Example command: attach $a 9544773
…
dbg all> quit
```

List of all commands

Detailed information about a specific command

Launched applications are killed (execution terminated) and attached applications are released from the debugger's control but are allowed to continue execution. Applications can be killed or released from within gdb4hpc, prior to exiting, with the `kill` or `release` commands, respectively.

GDB4HPC ARCHITECTURE (LAUNCH OR ATTACH TO AN APPLICATION)



GDB4HPC USAGE: RUN A JOB

```
> module load gdb4hpc
```

- Load the module to access the gdb4hpc executable.
- Compile the application using either the `-g` or `–Gn` option of the relevant compiler

```
> salloc –N …
> gdb4hpc
dbg all> launch $p{<number of ranks>} --args=”<app_args>” app.exe
```

- Launch the application from gdb4hpc on a given number of ranks with arguments.
- Do this from an interactive session with enough resources.
- Typical scenario when you want to debug an application from the beginning.

GDB4HPC USAGE: ATTACH TO A RUNNING JOB

```
> sbatch job.slurm
> module load gdb4hpc
> gdb4hpc
dbg all> attach $p <slurm_jobid>.<slurm_stepid>
```

- gdb4hpc can attach to a running application (job step) from the login node
- Get the `<slurm_stepid>` with `sstat --format "JobID" <slurm_jobid>`, eg.

```
>sstat --format "JobID" 2053748
JobID
------------
2053748.0
```

DEADLOCK EXAMPLE

- The dollar sign and curly brackets are specific gdb4hpc syntax
  - `$p` is the process set name in this example
  - Each is identified by a unique process set identifier and the curly braces are used for indexing a process set
  - More typically it specifies the members of a subset, examples
    - $p{4}, $p{0..9}, $p{0,3,7}, $p{0,11..16}
  - `viewset $p` to see members

```
> gdb4hpc
gdb4hpc 4.14.2 - Cray Line Mode Parallel Debugger
With Cray Comparative Debugging Technology.
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Type "help" for a list of commands.
Type "help <cmd>" for detailed help about a command.
dbg all> attach $p 2053796.0
0/2 ranks connected... (timeout in 299 seconds)
2/2 ranks connected.
Created network...
Connected to application...
Current rank location:
p{0}: #0  0x000014bd843b5ee6 in MPIDI_SHMI_progress
p{0}: #1  0x000014bd82e68059 in MPIR_Wait_impl.part.0
p{0}: #2  0x000014bd82901fc0 in PMPI_Recv
p{0}: #3  0x0000000000201b74 in main at
/pfs/lustrep2/projappl/project_465000297/alfiolaz/work/debugging/d
eadlock/deadlock.c:25
p{1}: #0  0x000014561e7961e5 in MPIDI_CRAY_Common_lmt_progress
p{1}: #1  0x000014561e78b599 in MPIDI_SHMI_progress
p{1}: #2  0x000014561d23d059 in MPIR_Wait_impl.part.0
p{1}: #3  0x000014561ccd6fc0 in PMPI_Recv
p{1}: #4  0x0000000000201bc4 in main at
/pfs/lustrep2/projappl/project_465000297/alfiolaz/work/debugging/d
eadlock/deadlock.c:30
```

GDB4HPC EXTENSIONS: PROCESS SET

- We can use focus to set context
  - `focus $p{0..3}`
  - `focus $all`
- We can define a new process set with defset
  - `defset $few $p{0..3}`
  - `focus $few`
- Can also use sets in variable references, eg. printing a variable
  - `p $few::mycount`

```
p{0..19}: Initial breakpoint, main at /mnt/lustre/a2fs-
work2/work/y02/y02/harveyr/examples/pi/C/pi_mpi.c:10
dbg all> l 18,19
p{0..19}: 18     MPI_Comm_rank(MPI_COMM_WORLD,&rank);
p{0..19}: 19     MPI_Comm_size(MPI_COMM_WORLD,&size);
dbg all> break 18
p{0..19}: Breakpoint 1: file /mnt/lustre/a2fs-
work2/work/y02/y02/harveyr/examples/pi/C/pi_mpi.c, line 18.
dbg all> cont
p{0..19}: Breakpoint 1, main at /mnt/lustre/a2fs-
work2/work/y02/y02/harveyr/examples/pi/C/pi_mpi.c:18
dbg all> focus $p{0..3}
dbg p_temp> next
p{0..3}: main at /mnt/lustre/a2fs-
work2/work/y02/y02/harveyr/examples/pi/C/pi_mpi.c:19
dbg p_temp> p rank
p{0}: 0
p{1}: 1
p{2}: 2
p{3}: 3
dbg p_temp> focus $all
dbg all> p rank
p{0,4..19}: 0
p{1}: 1
p{2}: 2
p{3}: 3
```

GDB4HPC WITH ROCGDB

- Running GDB4HPC on a GPU application
  - `export CTI_SLURM_DAEMON_GRES="gpu:4"` # required so that gdb4hpc can detect the GPUs
  - `export HIP_ENABLE_DEFERRED_LOADING=0` # useful for the GPU kernels
  - Run gdb4hpc
  - `launch $p{<number of ranks>} --gpu --args="<app_args>" app.exe`
  - --gpu enables the possibility to use rocgdb for GPU kernels
    - A single tool to debug MPI, CPU threads and GPU kernels
  - add `--env="MPICH_GPU_SUPPORT_ENABLED=1"` to enable GPU-aware communications

AN EXAMPLE GDB4HPC LAUNCH

```
faces-tests> gdb4hpc
gdb4hpc 4.13.10 - Cray Line Mode Parallel Debugger
With Cray Comparative Debugging Technology.
Copyright 2007-2021 Hewlett Packard Enterprise Development LP.
Copyright 1996-2016 University of Queensland. All Rights Reserved.

Type "help" for a list of commands.
Type "help <cmd>" for detailed help about a command.
dbg all> launch $a{16} --gpu --env="MPICH_GPU_SUPPORT_ENABLED=1" -g "-N 2 -p bp11" -i opt.in ./faces
Starting application, please wait...
Creating MRNet communication network...
sbcast: error: No compression library available, compression disabled.
sbcast: error: No compression library available, compression disabled.
Waiting for debug servers to attach to MRNet communications network...
Timeout in 400 seconds. Please wait for the attach to complete.
Number of dbgsrvs connected: [1];  Timeout Counter: [0]
Number of dbgsrvs connected: [1];  Timeout Counter: [1]
Number of dbgsrvs connected: [16];  Timeout Counter: [0]
Finalizing setup...
Launch complete.
a{0..15}: Initial breakpoint, main at /lus/cflus02/sabbott/faces/hip/gpu_subtle/main.cpp:103
dbg all>
```

Start the debugger

Launch command

Thread aggregation in GDB4HPC

```
a{0..15}: Initial breakpoint, main at /lus/cflus02/sabbott/faces/hip/gpu_subtle/main.cpp:103
dbg all> c
<$a>: 0 with node rank 0 using device 0 (8 devices per node) (asked for 0)
<$a>: 8 with node rank 0 using device 0 (8 devices per node) (asked for 0)

dbg all> info thread
a{8}: Debugger error: Gdb get thread info failed.
a{0..5,7,9..10,13}: *** The application is running
a{11..12,14..15}:   Id    Frame
a{11..12,14..15}: * 1-3   "faces" (running)
a{11..12,14..15}:   4-2313 AMDGPU "faces" void gpuRun2x3<Faces::share(DArray<double, 6>&)::{lambda(int, int,
 int, int, int)#1}>(Faces::share(DArray<double, 6>&)::{lambda(int, int, int, int, int)#1}, int, int, int, in
t, int) [clone .kd] () from file:///lus/cflus02/sabbott/faces/hip/gpu_subtle/faces#offset=77824&size=267392
a{11..12,14..15}:
a{6}:   Id    Frame
a{6}: * 1-3   "faces" (running)
a{6}:   4-443 AMDGPU "faces" ?? ()
a{6}:
dbg all>
```

We're in non-stop mode by default, so some threads halting doesn't necessarily stop everything

gdb4hpc tries its best to aggregate information

(but sometimes aggregation does break down)

In non-stop mode you can halt the threads, e.g. `halt -a` for all threads

FINAL REMARKS FOR GDB4HPC

- More information with man page gdb4hpc
  - https://cpe.ext.hpe.com/docs/debugging-tools/index.html#gdb4hpc
- The key concept that gdb4hpc overlays on gdb (rocgdb)
  - A parallel harness and aggregator around gdb, rocgdb
  - Moving on from this you can use gdb to follow execution paths, view the state of variables etc. to trace more insidious bugs in an application
- The tool can be used for investigating hanging or crashed applications
  - Such information is useful if you submit a helpdesk query

CCDB - COMPARATIVE DEBUGGER

Using the Cray Comparative debugger (ccdb)

DEMO 3D_CCDB

COMPARATIVE DEBUGGING

- What is comparative debugging?
  - Two applications, same data
  - Key idea: The output should match!
- When might comparative debugging be useful?
  - Algorithm re-writes
  - Language ports
  - Different libraries/compilers or optimization levels

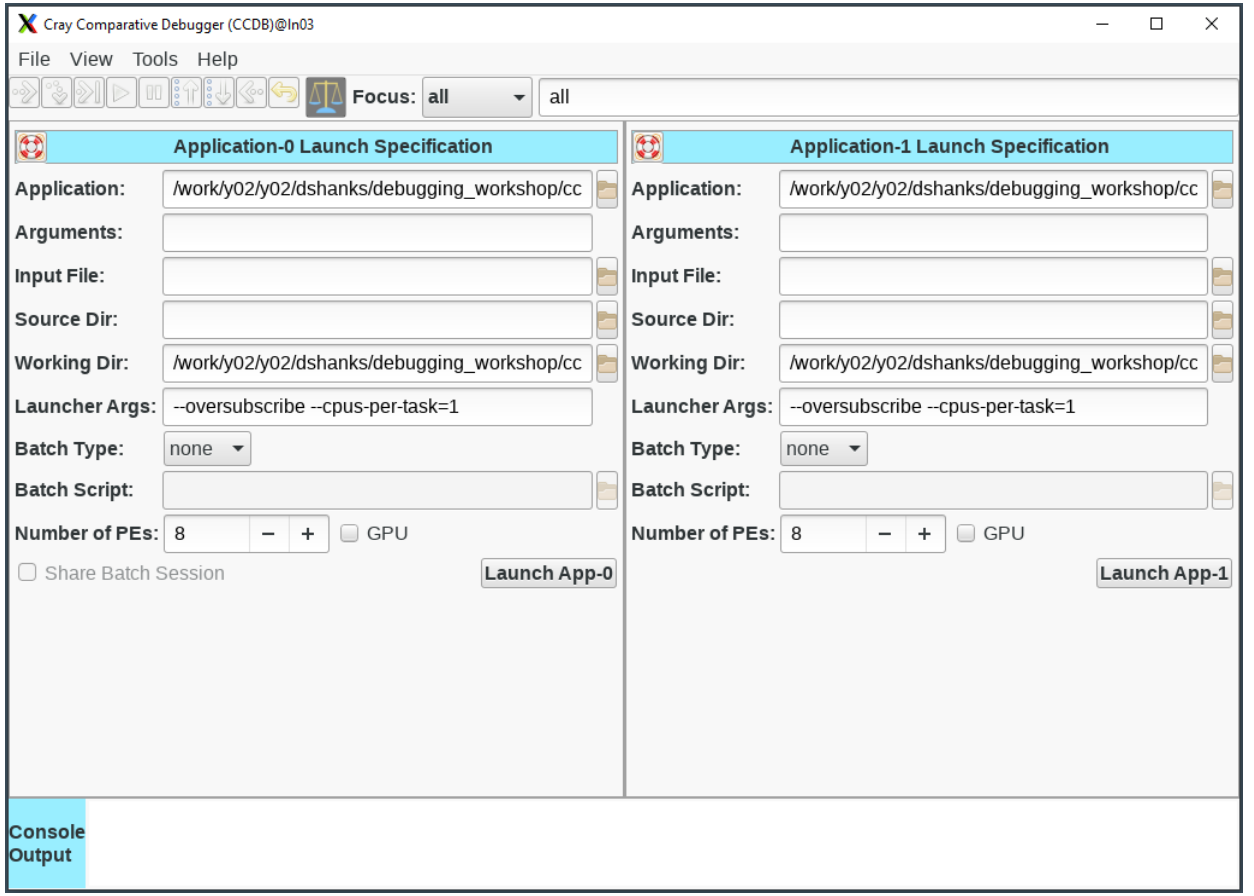
CRAY COMPARATIVE DEBUGGER

- Cray Comparative Debugger (**CCDB**)
  - Assists with comparative debugging
  - CCDB GUI hides the complexity and helps automate process
  - Allows user to create own comparisons
  - Error and warning epsilon tolerance
  - Scalable
- To compare data between two executables CCDB requires
  - **PE set**: The set of MPI processes for the variable
  - **MPI decomposition**: How a variable is distributed over the PE set
  - **Assertion script**: Relations (of variables) to be tested between two executables
- This is greatly simplified when using ccdb compared to gdb4hpc

CCDB USAGE

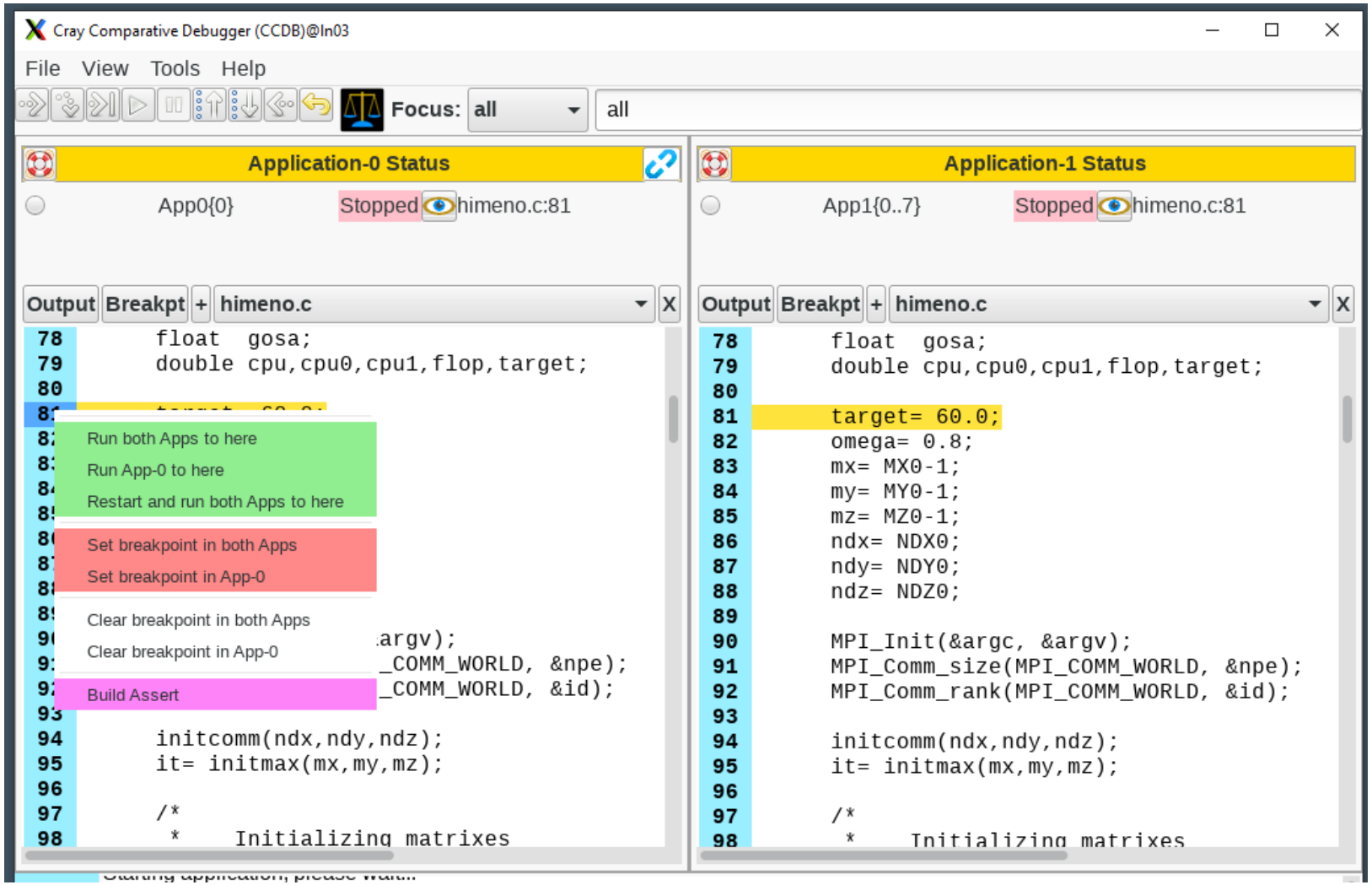
- Load the module to access `ccdb`
- Compile the applications using either the `-g` or `-Gn` option of the relevant compiler
- We suggest requesting resources via `salloc` before launching `ccdb`
- If resources have not been specified, then details will have to be entered in the GUI
- Populate the GUI with application details
- Now launch both applications

```
> module load cray-ccdb
> ccdb &
```



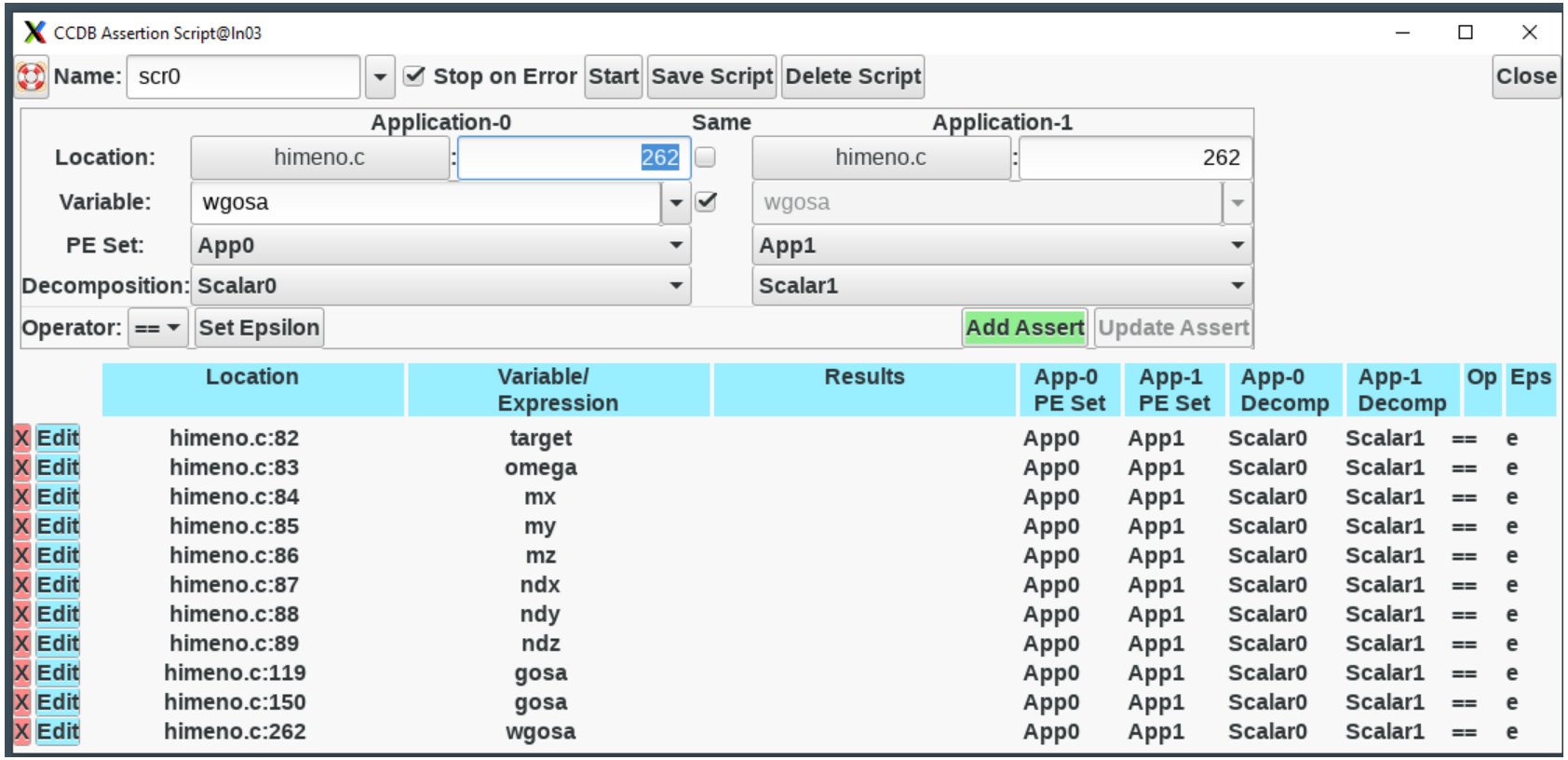
GENERATING AN ASSERTION SCRIPT (1)

- The script defines how variables in each application should be compared
- Will report on all differences in variables
- First double click on source file to view source code
- Left click a line number to generate an assertion script



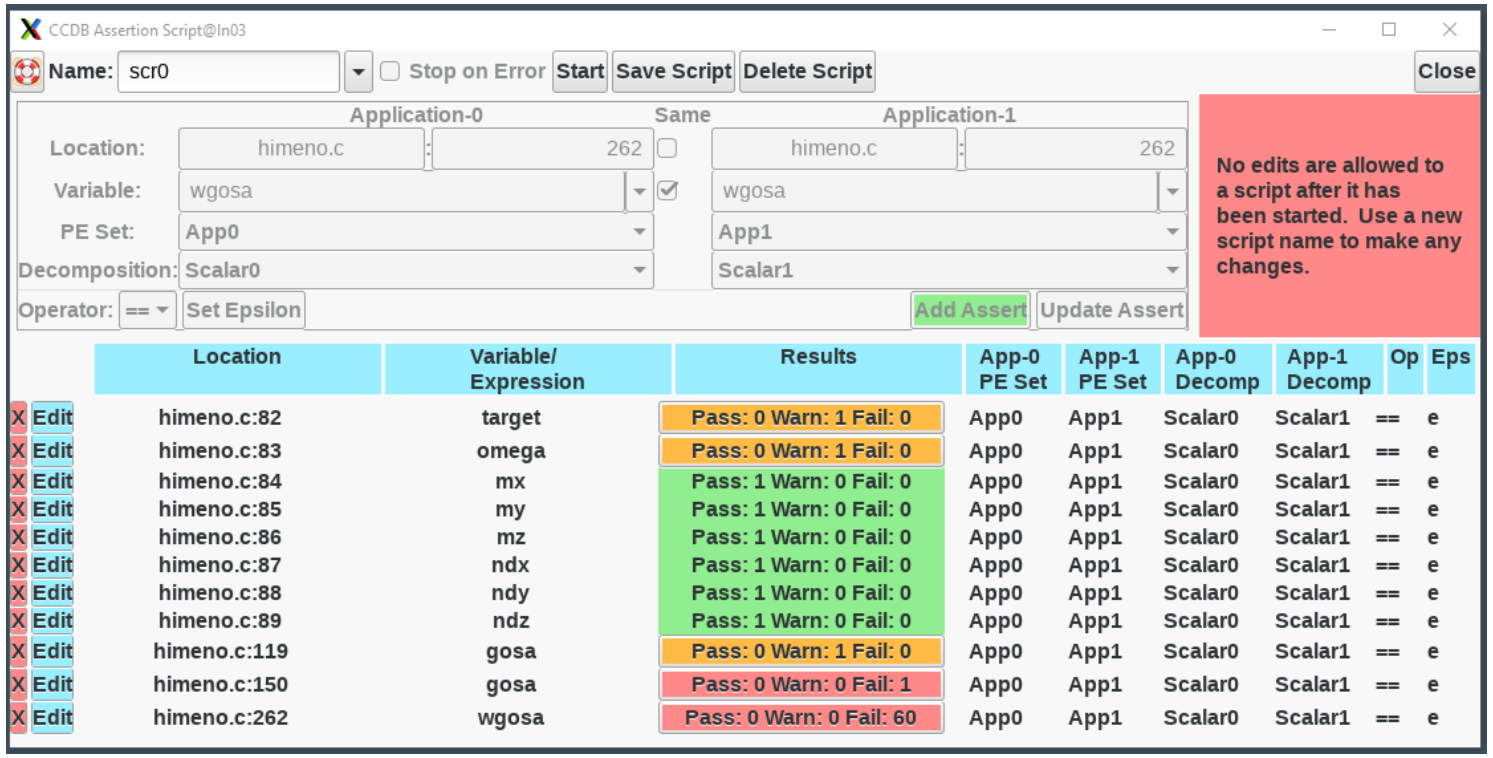
GENERATING AN ASSERTION SCRIPT (2)

- Now populate assertion script
  - Name of source
  - Line number
  - Variable
  - Decomposition
- Click “Add Assert”
- Enter more checks
- “Save Script”



RUNNING AN ASSERTION SCRIPT

- Accessed through
  View -> Assertion Scripts
- Can choose to stop on first error or run through showing all errors
- Custom “epsilon” can be set for warnings and errors
- Run by clicking start
- Click on **Warn** and **Fail** boxes to examine details



CCDB PROS AND CONS

- A lot easier to set up an assertion script than via gdb4hpc
- Relatively simple to set up quick comparison and narrow down difference before using a more in-depth debugger like gdb4hpc
- Not as polished as some other GUIs
- Not a general-purpose graphical debugger
- X11 forwarding requires patience over a slow connection

VALGRIND4HPC

Valgrind-based debugging tool for parallel applications

VALGRIND4HPC

```
> module load valgrind4hpc
```

- Load the module to access the valgrind4hpc executable
- Target executables must be built dynamically and contain debug symbols (`-g` option).

```
> salloc …
> valgrind4hpc -n4 --launcher-args="-N2" --valgrind-args="--track-origins=yes
--leak-check=full" ./a.out -- arg1 arg2
```

- get an interactive session via `salloc`
- `-n` to specify the number of ranks
- `--launcher-args` to specify other SLURM flags
- `valgrind4hpc` and target program arguments should be separated by two dashes, `--`
- Many suppressions by default: `/opt/cray/pe/valgrind4hpc/<version>/share/suppressions/`

VALGRIND4HPC EXAMPLE

```
19: int *test = (int*)malloc(4*sizeof(int));
20:
21: if(rank==0)
22: {
23:         test[6] = 1;
24:         test[10] = 2;
25: }
```

```
RANKS: <0>

Invalid write of size 4
  at main (in hello.c:23)
Address is 8 bytes after a block of size 16 alloc'd
  at malloc (in vg_replace_malloc.c:306)
  by main (in hello.c:19)
```

- Man page valgrind4hpc for more info

SANITIZERS4HPC

Use several tools to check program correctness at run-time for parallel applications

PERFORM DYNAMIC ANALYSIS OF PARALLEL PROGRAMS WITH SANITIZERS4HPC

- Sanitizers4hpc is a debugging tool to aid in the detection of memory leaks and errors in parallel applications
  - Static instrumentation at compile time via `-fsanitize=<sanitizer>`
    - Sanitizers are: Address, Leak, Thread (https://github.com/google/sanitizers)
  - It aggregates any duplicate messages across ranks to help provide an understandable picture of program behaviour
- Sanitizers4hpc supports the Sanitizer libraries included with both the Cray CCE and the GNU GCC compilers
  - Cray Fortran only supports Address and Thread sanitizers
  - Note: Address Sanitizer and Thread Sanitizer cannot be used simultaneously
- More info: `man sanitizers4hpc`

SANITIZERS4HPC

- Compile the application with `-f sanitize=<sanitizer>`, e.g.

```
cc -g -fsanitize=leak leak.c -o leak
```

- Load the module to access the sanitizers4hpc executable
- Get an interactive session via salloc

```
> salloc …
> sanitizers4hpc -l “-n4” -- ./a.out arg1 arg2
```

- -l
- The target binary and its arguments are listed after the double dash -
- More info and examples: `man sanitizers4hpc`

SANITIZERS4HPC EXAMPLE: ADDRESS SANITIZER

```
 1: program address
 2:   implicit none
 3:
 4:   integer, dimension(10) :: array
 5:
 6:   array = 2
 7:
 8:   array(12) = 3
 9:
10:  print *, array
11:
12: end program address
```

```
RANKS: <0>
AddressSanitizer: global-buffer-overflow on address 0x000000551eec at pc 0x00000041f95c bp 0x7ffd3da8b890 sp
0x7ffd3da8b888
WRITE of size 4 at 0x000000551eec thread T0
    #0 0x41f95b in address_ /home/users/alazzaro/lumi_coe/sanitizers/fortran/address.f90:8
    #1 0x7f8ba5aad2bc in __libc_start_main (/lib64/libc.so.6+0x352bc) (BuildId:
28910b266cdd8f0c54c7830b758e4a1339f255c1)
    #2 0x41f429 in _start /home/abuild/rpmbuild/BUILD/glibc-2.31/csu/../sysdeps/x86_64/start.S:120
```

QUESTIONS?

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