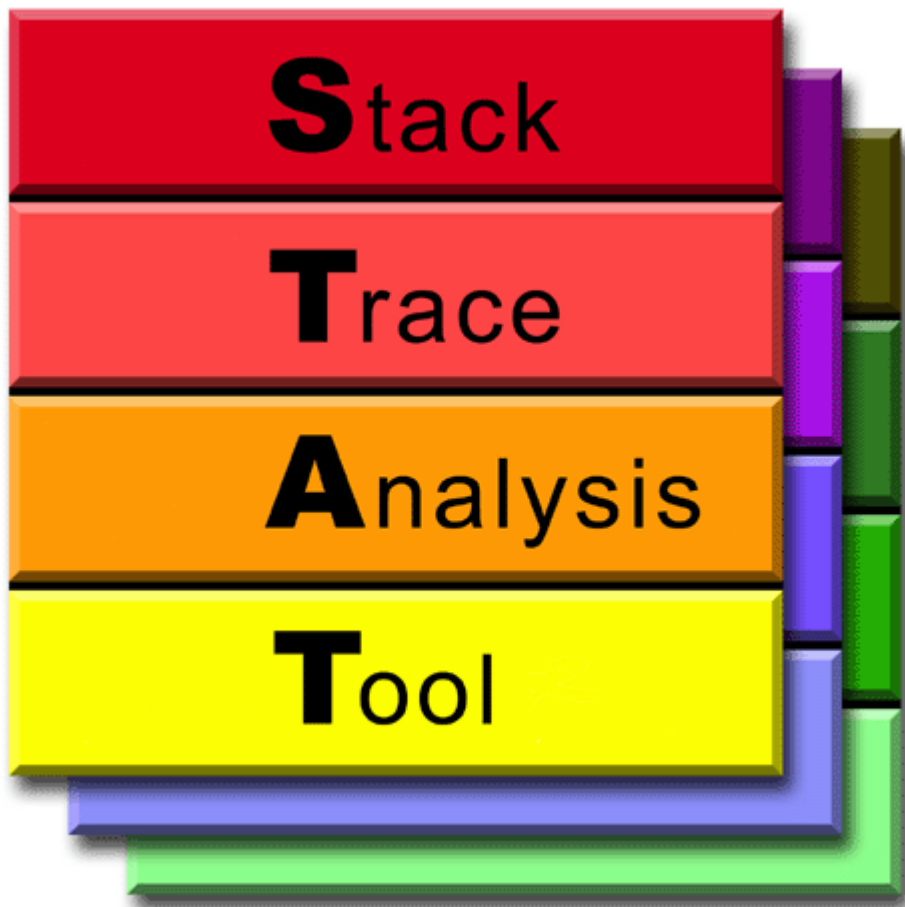


STAT: the Stack Trace Analysis Tool



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Chapter 1. Introduction

The Stack Trace Analysis Tool (STAT) is a highly scalable, lightweight debugger for parallel applications. STAT is developed as a collaboration between the Lawrence Livermore National Laboratory, the University of Wisconsin, and the University of New Mexico. It is currently open source software released under the Berkeley Software Distribution (BSD) license. It builds on a highly portable, open source infrastructure, including LaunchMON for tool daemon launching, MRNet for scalable communication, and StackWalker for obtaining stack traces.

STAT works by gathering stack traces from all of a parallel application's processes and merging them into a compact and intuitive form. The resulting output indicates the location in the code that each application process is executing, which can help narrow down a bug. Furthermore, the merging process naturally groups processes that exhibit similar behavior into process equivalence classes. A single representative of each equivalence can then be examined with a full-featured debugger like TotalView¹ or DDT² for more in-depth analysis.

STAT has been ported to several platforms, including Linux clusters, IBM's Bluegene/L, Bluegene/P, and Bluegene/Q machines, and Cray systems. It works for Message Passing Interface (MPI) applications written in C, C++, and Fortran and also supports threads. STAT has already demonstrated scalability over 1,000,000 MPI tasks and its logarithmic scaling characteristics position it well for even larger systems.

Notes

1. <http://www.totalviewtech.com/>
2. <http://www.allinea.com/index.php?page=48>

Chapter 2. Overview

STAT, the Stack Trace Analysis Tool, helps isolate bugs by gathering stack traces from each individual process of a parallel application and merging them into a global, yet compact representation. Each stack trace, as depicted in Figure 2-1, captures the function calling sequence of an individual process. The nodes are labeled with the function names and the directed edges show the function calling sequence from caller to callee. STAT's stack trace merging process forms a call graph prefix tree, which can be seen in Figure 2-1. The prefix tree groups together traces from different processes that have the same calling sequence and labels the edges with the count and set of tasks that exhibited that calling sequence. Nodes in the prefix tree that are visited by the same set of tasks are given the same color, providing the user with a quick means of identifying the various process equivalence classes.

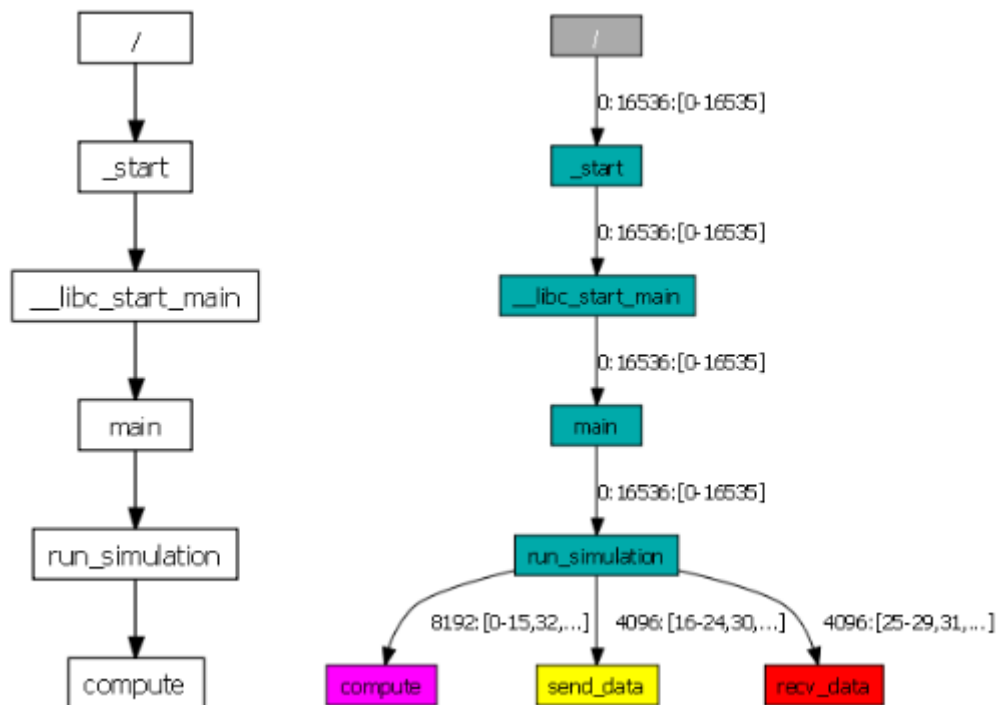


Figure 2-1. A single stack trace (left) and a STAT merged call prefix tree (right)

STAT merges stack traces into 2D spatial and 3D spatial-temporal call prefix trees. The 2D spatial call prefix tree (Figure 2-2) represents a single snapshot of the entire application. The 3D spatial-temporal call prefix tree (Figure 2-3) takes a series of snapshots from the application over time and is useful for analyzing time-varying behavior.

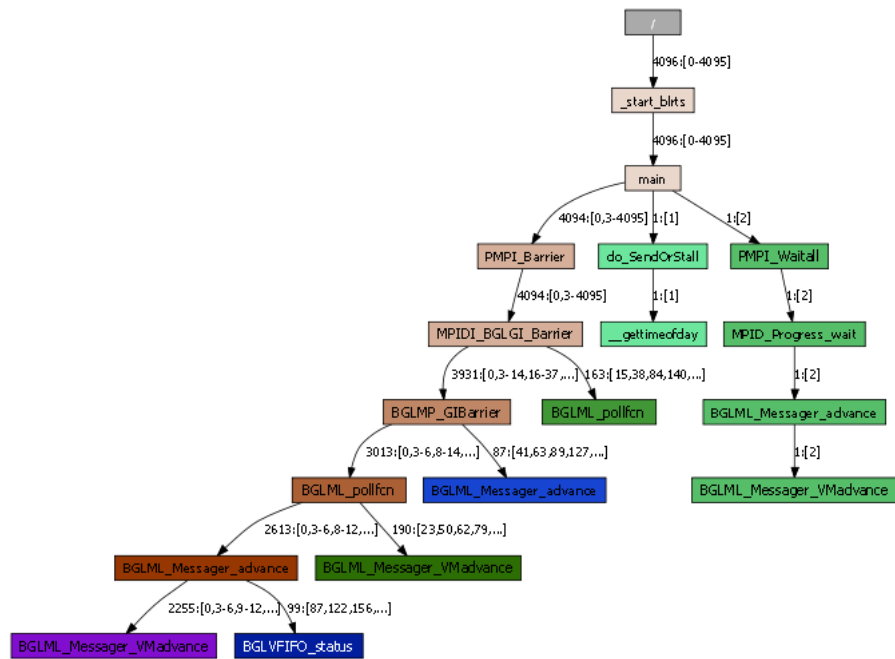


Figure 2-2. A 2D spatial call prefix tree

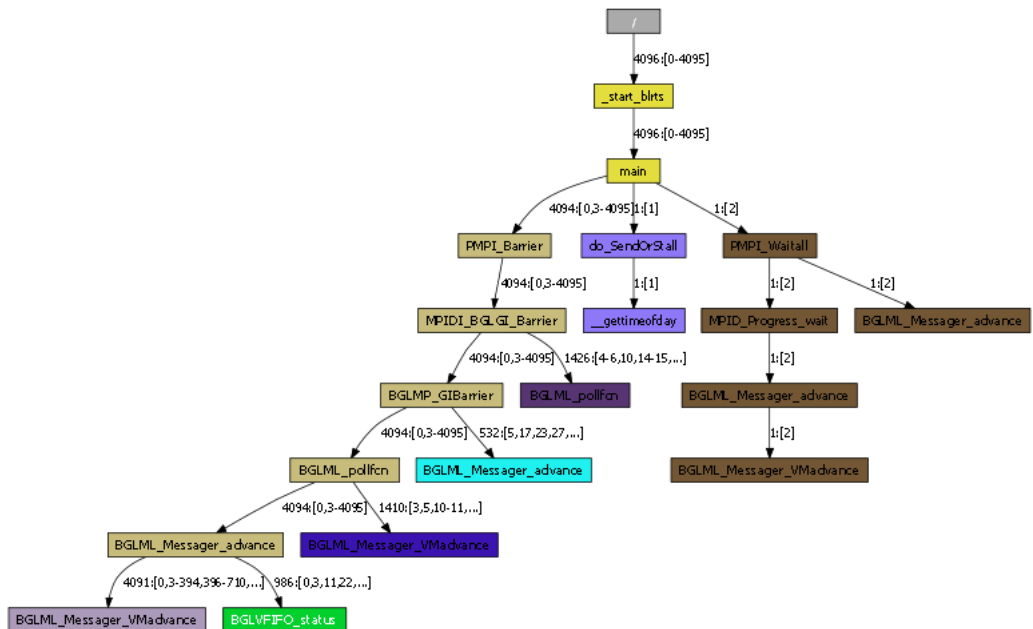


Figure 2-3. A 3D spatial call prefix tree

Stack traces based on function names only provide a high-level overview of the application's execution. However, for certain bugs this view may be too coarse-grained so STAT is also capable of gathering stack traces with more fine-grained information. In particular, STAT can also record the program counter of each frame or with the appropriate debug information compiled into the application (i.e., with the "-g" compiler flag), STAT can gather the source file and line number of each stack frame. Both of these refinements can further delineate processes and refine the process equivalence classes.

In addition, line number information can be fed into a static code analysis engine to derive the logical temporal order of the MPI tasks Figure 2-4. This analysis traverses from the root of the tree towards the leaves, at each step analyzing the

control flow of the source code and sorting sibling nodes by the amount of execution progress made through the code. For straight-line code, this simply means that one task has made more progress if it has executed past the point of another task, i.e., if it has a greater line number. This ordering is partial since two tasks in different branches of an if-else are incomparable. In cases where the program points being compared are within a loop, STAT can extract the loop ordering variable from the application processes and further delineate tasks by execution progress. This analysis is useful for identifying the culprit in a deadlocked or live-locked application, where the problematic task has often either made the least or most progress through the code, leaving the remaining tasks stuck in a barrier or blocked pending a message. Note, this feature is still a prototype.

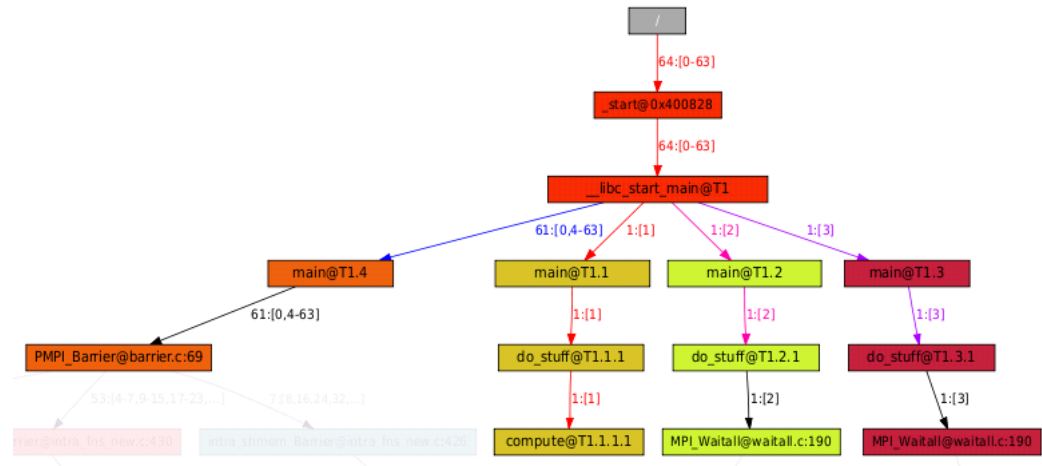


Figure 2-4. STAT's temporal ordering analysis engine indicates that task 1 has made the least progress. In this example, task 1 is stuck in a compute cycle, while the other tasks are blocked in MPI communication, waiting for task 1.

Chapter 3. Changelog

STAT version 2.1

- Added prototype DysectAPI
- Added prototype temporal ordering capability
- Improved Python wrapping, including new python-script command and a Python-based test script to run through STAT functionality
- Modified cut/hide interface to allow for user-defined programming models
- Modified dot file naming convention for easier sequencing. Also allow specification of dot filename on gather.
- New process table interface (via File->Properties)
- Added CP location policy
- Improved BG/Q support, including use of StackWalker timeouts.
- Improved FGFS support, including adding BG/Q support and re-enabling MRNet failure recovery when FGFS is in use
- Better labeling of error tasks in stack traces
- As always, numerous other bug fixes and minor enhancements (refer to ChangeLog file in top-level directory)

STAT version 2.0

- The capitalized STAT commands have been deprecated in favor of all lower-case commands. The **STAT** command is now **stat-cl**, **STATGUI** is now **stat-gui**, **STATview** is now **stat-view**, and **STATBench** is now **stat-bench**.
- Added optional build with Fast Global File Status plus target application binary file broadcasting
- Added Python-script-level debugging (Python must be built with -g and preferably -O0)
- Added ability to manually specify serial processes to attach to
- Added count + representative level of detail
- Added join equivalence class GUI feature
- Added cut text GUI feature
- Added GUI preferences menu item
- (old) DynInst support has been removed. STAT now strictly requires the Stack-walker component of DynInst.
- Graphlib 2.0 required (removed support for 1.X)
- MRNet version 3 or greater required (removed support for 1.X and 2.X)
- Added ability to manually specify list of processes
- Numerous other bug fixes and minor enhancements (refer to ChangeLog file in top-level directory)

Chapter 4. Installing STAT

Dependent Packages

STAT has several dependencies

Table 4-1. STAT Dependent Packages

Package Package Web Page	What It Does
Graphlib version 2.0 or greater https://github.com/lee218llnl/STAT/	Graph creation, merging, and export
Launchmon http://sourceforge.net/projects/launchmon/	Scalable daemon co-location
Libdwarf http://reality.sgiweb.org/davea/dwarf.html	Debug information parsing (Required by StackWalker)
MRNet version 3.0 or greater http://www.paradyn.org/mrnet/	Scalable multicast and reduction network
StackWalker http://www.paradyn.org/html/downloads.html	Lightweight stack trace sampling

In addition, the STAT GUI requires Python¹ with PyGTK², both of which are commonly preinstalled with many Linux operating systems. The Pygments³ Python module can optionally be installed to allow the STAT GUI to perform syntax highlighting of source code.

STAT can also be optionally built with the Fast Global File Status (FGFS)⁴ library. This library helps STAT identify when a file (target binary) resides on a shared file system that may become a bottleneck if all STAT daemons try to access that file at the same time. If so, STAT will access the file from the STAT frontend and distribute its contents to the daemons via the MRNet communication tree. The two necessary components of FGFS can be downloaded from <https://github.com/dongahn/MountPointAttributes> and <https://github.com/dongahn/FastGlobalFileStatus>

Installation

A script that downloads and install STAT and all its dependencies for BlueGene/Q has been created and can be downloaded at <https://github.com/lee218llnl/STAT/blob/master/script-stat-install> or can be found in the top-level directory of the STAT source. Note this script was developed for BlueGene/Q systems, but can be used as guidance for other systems as well.

When building STAT itself, first run `configure`. You will need to use the `--with-package` options to specify the install prefix for `mrnet`, `graphlib`, `launchmon`, `libdwarf`, and `stackwalker`. These options will add the necessary include and library search paths to the compile options. Refer to `configure --help` for exact options. You may also wish to specify the maximum number of communication processes to launch per node with the option `--with-procspernode=number`, generally set to the number of cores per node.

STAT creates wrapper scripts for the `stat-cl` and `stat-gui` commands. These wrappers set appropriate paths for the `launchmon` and `mrnet_commnode` executables, based on the the `--with-launchmon` and `--with-mrnet` configure options, thus it is important to specify both of these even if they share a prefix.

STAT will try to build the GUI by default. If you need to modify your PYTHONPATH environment variable to search for side installed site-packages, you can do this by specifying STAT_PYTHONPATH=path during configure. This will add the appropriate directory to the \$PYTHONPATH environment variable within the stat-gui script. To disable the building of the GUI, use the --enable-gui=no configure option.

On BlueGene systems, be sure to configure --with-bluegene. This will enable the BGL macro for BlueGene specific compilation. It is important to note that on BlueGene systems, you may need to use an alternate hostname for the front-end node in order to get MRNet to bind to the appropriate network interface that can communicate with the I/O nodes. By default, STAT will append "-io" to the hostname. Alternatively, you can specify the hostname with the STAT_FE_HOSTNAME environment variable. A script that downloads and install STAT and all its dependencies for BlueGene/Q has been created and can be downloaded at <https://github.com/lee218llnl/STAT/blob/master/script-stat-install> or can be found in the top-level directory of the STAT source. Due to system configurations, this may not completely work out of the box, but it provides good guidance on the steps required.

To compile on Cray systems, specify --with-cray-xt. An example configure line for Cray:

```
./configure --with-launchmon=/tmp/work/lee218/install \  
--with-mrnet=/tmp/work/lee218/install \  
--with-graphlib=/tmp/work/lee218/install \  
--with-stackwalker=/tmp/work/lee218/install \  
--with-libdwarf=/tmp/work/lee218/install \  
--prefix=/tmp/work/lee218/install --with-cray-xt \  
MPICC=cc MPICXX=CC MPIF77=ftn --enable-shared LD=/usr/bin/ld
```

Note that specifying LD=/usr/bin/ld may be required on Cray systems to avoid using the compute node linker. It is also worth noting that Cray includes a build of STAT as part of their system software stack. It is typically installed in /opt/cray/stat and can be loaded via modules.

After running configure you just need to run:

```
make  
make install
```

Note that STAT hardcodes the paths to its daemon and filter shared object, assuming that they are in \$prefix/bin and \$prefix/lib respectively, thus testing should be done in the install prefix after running "make install" and the installation directory should not be moved. The path to these components can, however, be overridden with the --daemon and --filter arguments. Further, the STAT_PREFIX environment variable can be defined to override the hardcoded paths in STAT. STAT will also, by default, add rpaths to dependent libraries. This behavior can be disabled by specifying "--with-rpath=no". However, when doing so, you must be sure to set LD_LIBRARY_PATH to point to the directories containing the dependent libraries.

Notes

1. <http://www.python.org/>
2. <http://www.pygtk.org/>
3. <http://pygments.org/>
4. <https://computation-rnd.llnl.gov/fgfs/>

Chapter 5. Using the stat-cl Command

Description

STAT (the Stack Trace Analysis Tool) is a highly scalable, lightweight tool that gathers and merges stack traces from all of the processes of a parallel application. After running the STAT command, STAT will create a `stat_results` directory in your current working directory. This directory will contain a subdirectory, based on your parallel application's executable name, with the merged stack traces in DOT format.

stat-cl Options

- `-a, --autotopo`
let STAT automatically create topology.
- `-f, --fanout width`
Sets the maximum tree topology fanout to *width*. Specify nodes to launch communications processes on with `--nodes`.
- `-d, --depth depth`
Sets the tree topology depth to *depth*. Specify nodes to launch communications processes on with `--nodes`.
- `-u, --usertopology topology`
Specify the number of communication nodes per layer in the tree topology, separated by dashes, with *topology*. Specify nodes to launch communications processes on with `--nodes`. Example topologies: 4, 4-16, 5-20-75.
- `-n, --nodes nodelist`
Use the specified nodes in *nodelist*. To be used with `--fanout`, `--depth`, or `--usertopology`. Example nodes lists: `host1; host1,host2; host[1,5-7,9]`.
- `-A, --appnodes`
Allow tool communication processes to be co-located on nodes running application processes.
- `-x, --exclusive`
Do not use the front-end or back-end nodes for communication processes.
- `-p, --procs processes`
Sets the maximum number of communication processes to be spawned per node to *processes*. This should typically be set to a number less than or equal to the number of CPU cores per node.
- `-j, --jobid id`
Append *id* to the output directory and file prefixes. This is useful for associating STAT results with a batch job.
- `-r, --retries count`
Attempt *count* retries per sample to try to get a complete stack trace.
- `-R, --retryfreq frequency`
Wait *frequency* microseconds between sample retries. To be used with the `--retries` option.

- `-P, --withpc`
Sample program counter values in addition to function names.
- `-i, --withline`
Sample source line number in addition to function names.
- `-c, --comprehensive`
Gather 4 traces: function only; function + line; function + PC; and 3D function only.
- `-U, --countrep`
Only gather edge labels with the task count and a single representative. This will improve performance at extreme (i.e., over 1 million tasks) scales.
- `-w, --withthreads`
Sample stack traces from helper threads in addition to the main thread.
- `-y, --withpython`
Where applicable, gather Python script level stack traces, rather than show the Python interpreter stack traces. This requires the Python interpreter being debugged to be built with `-g` and preferably `-O0`.
- `-t, --traces count`
Gather *count* traces per process.
- `-T, --tracefreq frequency`
Wait *frequency* milliseconds between samples. To be used with the `--traces` option.
- `-S, --sampleindividual`
Save all individual samples in addition to the 3D trace when using `--traces` option.
- `-C, --create arg_list`
Launch the application under STAT's control. All arguments after `-C` are used to launch the app. Namely, *arg_list* is the command that you would normally use to launch your application.
- `-I, --serial arg_list`
Attach to a list of serial processes. All arguments after `-I` are interpreted as processes. Namely, *arg_list* is a white-space-separated list of processes to attach to, where each process is of the form `[exe@[hostname:]]PID`.
- `-D, --daemon path`
Specify the full path *path* to the STAT daemon executable. Use this only if you wish to override the default.
- `-F, --filter path`
Specify the full path *path* to the STAT filter shared object. Use this only if you wish to override the default.
- `-s, --sleep time`
Sleep for *time* seconds before attaching and gathering traces. This gives the application time to get to a hung state.
- `-l, --log`

```
[FE | BE | CP]
```

Enable debug logging of the *FE* frontend, *BE* backend, *CP* communication process, *SW* Stackwalker, *SWERR* Stackwalker on error. Multiple log options may be specified (i.e., `-l FE -l BE`).

```
-L, --logdir log_directory
```

Dump logging output into *log_directory*. To be used with the `--log` option.

```
-M, --mrnetprintf
```

Use MRNet's `printf` for STAT debug logging.

STAT Usage Example

The most typical usage is to invoke STAT on the job launcher's PID:

```
% srun mpi_application arg1 arg2 &
[1] 16482

% ps
  PID TTY          TIME CMD
16755 pts/0    00:00:00 bash
16842 pts/0    00:00:00 srun
16871 pts/0    00:00:00 ps

% stat-cl 16482
```

You can also launch your application under STAT's control with the `-C` option. All arguments after `-C` are used for job launch:

```
% stat-cl -C srun mpi_application arg1 arg2
```

With the `-a` option (or when automatic topology is set as default), STAT will try to automatically create a scalable topology for large scale jobs. However, if you wish you may manually specify a topology at larger scales. For example, if you're running on 1024 nodes, you may want to try a fanout of $\sqrt{1024} = 32$. You will need to specify a list of nodes that contains enough processors to accommodate the $\text{ceil}(1024/32) = 32$ communication processes being launched with the `--nodes` option. Be sure that you have login permissions to the specified nodes and that they contain the `mrnet_commnode` executable and the `STAT_FilterDefinitions.so` library.

```
% stat-cl --fanout 32 --nodes atlas[1-4] --procs 8 16482
```

Upon successful completion, STAT will write its output to a `stat_results` directory within the current working directory. Each run creates a subdirectory named after the application with a unique integer ID. STAT's output indicates the directory created with a message such as:

```
Results written to /home/user/bin/stat_results/mpi_application.6
```

Within that directory will be one or more files with a `.dot` extension. These `.dot` files can be viewed with `stat-view`.

Chapter 6. Using the stat-view GUI

Description

stat-view (Figure 6-1) is a GUI for viewing STAT-outputted dot files. stat-view provides easy navigation of the call prefix tree and also allows manipulation of the call tree to help focus on areas of interest. Each node in the STAT call prefix tree represents a function call and the directed edges denote the calling sequence. Further, the edges are labeled by the set of tasks that have taken that call path. For simplification, stat-view will display the number of tasks in the set and truncate long task lists in the main display with "..." notation. Similarly, long function node label names will be truncated with "..." notation. The truncation length can be modified via the File->Preferences menu (this requires clicking the **Layout** button to rerender any already loaded graphs). Nodes are colored based on the set of tasks of the incoming edge, providing a visual distinction when different tasks take different branches.

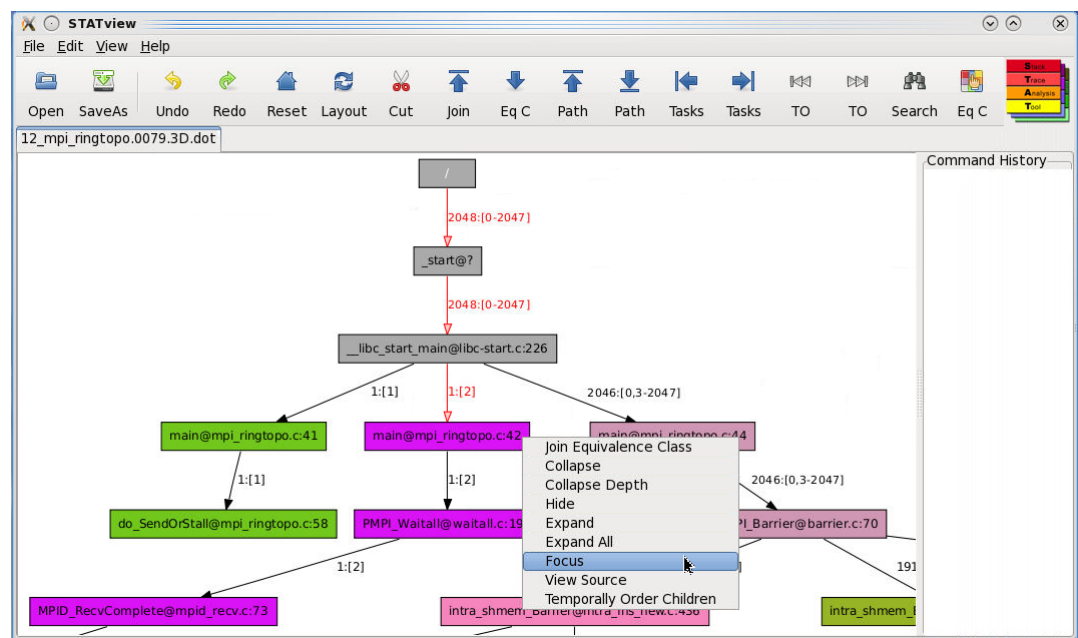


Figure 6-1. A screenshot of the stat-view GUI.

The stat-view Node Menu

By left clicking on a node in the call prefix tree you will get a window displaying the full list of tasks and the full frame label (Figure 6-2). This window also contains buttons that allow for the manipulation of the graph from that node. Right clicking on a node provides a pop-up menu with the same options. Note all of these operations are performed on the current visible state of the call prefix tree.

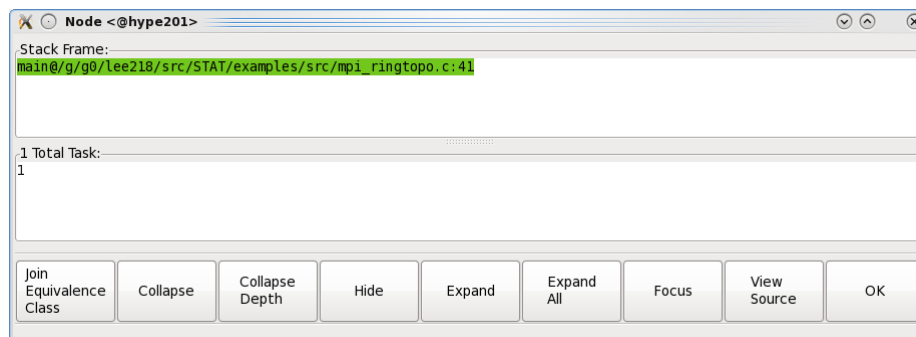


Figure 6-2. The node pop-up window

The node operations are defined as follows:

Join Equivalence Class

collapses all of the descendent nodes with the same equivalence class into the current node and renders in a new tab.

Collapse

hide all of the descendents of the selected node.

Collapse Depth

collapse the entire tree to the depth of the selected node.

Hide

the same as **Collapse**, but also hides the selected node.

Expand

show (unhide) the immediate children of the selected node.

Expand All

show (unhide) all descendents of the selected node.

Focus

hide all nodes that are neither ancestors nor descendents of the selected node. (Note: This will not unhide any hidden ancestors.)

View Source

creates a popup window (Figure 6-3) displaying the source file (only for stack traces with line number information). This may require the source file's path to be added to the search path, through **File -> Add Search Paths**.

Temporally Order Children

(prototype only) determine the temporal order of the node's children (only for stack traces with line number information). Requires the source file's path and all include paths to be added to the search path, through **File -> Add Search Paths**.

OK

closes the pop-up window.

```

039 |
040 | do_Receive(prev, tag, &buf[0], &reqs[0]);
==>041 | do_SendOrStall(next, tag, rank, &buf[1], &reqs[1], numtasks);
->042 | MPI_Waitall(2, reqs, stats);
043 |
==044 | MPI_Barrier(MPI_COMM_WORLD);
045 | MPI_Finalize();
046 | return 0;
047 | }
048 |
049 | void do_SendOrStall(int to, int tag, int rank, int* buf, MPI_Request
050 | {
051 |     int i;
052 |     if (rank == 1)
053 |     {
054 |         if (sleeptime == -1)
055 |         {
056 |             printf("%s, MPI task %d of %d stalling\n", hostname, ran
057 |                 fflush(stdout);
==058 |                 while(1) ;
059 |         }
060 |     }
061 |     else
062 |     {
         for (i = sleeptime/10; i > 0; i = i - 1)

```

Figure 6-3. The source view window. The colored arrows correspond to the nodes in the call prefix tree.

The stat-view Toolbar

The main window also has several tree manipulation options (Figure 6-4). Note the initial click of a traversal operation operates on the original call prefix tree, while the remaining operations are performed on the current visible state of the call prefix tree.



Figure 6-4. The stat-view tree manipulation toolbar.

The toolbar operations are defined as follows:

Open

Open a STAT generated .dot file

Save As

Save the current graph in .dot format, which can be displayed by stat-view or in an image format, such as PNG or PDF, which can be viewed on any computer with an image viewer

Undo

Undo the previous operation

Redo

Redo the undone operation

Reset

Revert to the original graph

Layout

Reset the layout of the current graph and open in a new tab. This is useful for compacting wide trees after performing some pruning operations.

Cut

This feature (Figure 6-5) allows you to collapse the prefix tree below the implementation frames for various programming models. For

instance, a user may wish to hide all calls that happen within the MPI library. The programming models may be entered in a configuration file or added by the user. STATview looks for configuration files in \$prefix/etc/STAT/STATview_models.conf and in \$HOME/.STATview_models.conf. Programming models are specified as regular expressions, using Python's `re` module syntax, and the `re.search` function is used in favor of `re.match`.

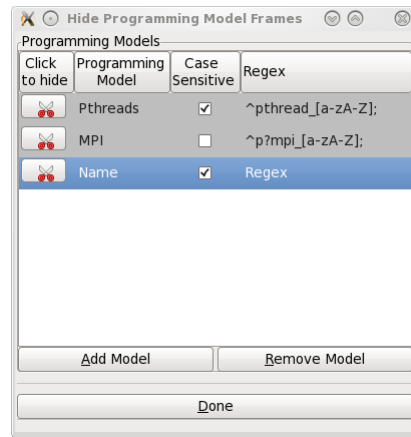


Figure 6-5. The stat-view programming model cutting interface.

[Cut] MPI

Collapse the MPI implementation frames below the MPI function call.

[Cut] Pthreads

Collapse the Pthread implementation frames below the Pthread function call.

Join

Join consecutive nodes of the same equivalence class into a single node and render in a new tab. This is useful for condensing long call sequences.

[Traverse] Eq C

Traverse the prefix tree by expanding the leaves to the next equivalence class set. The first click will display the top-level equivalence class.

[Traverse Longest] Path

Traversal focus on the next longest call path(s). The first click will focus on the longest path.

[Traverse Shortest] Path

Traversal focus on the next shortest call path(s). The first click will focus on the shortest path.

[Traverse Least] Tasks

Traversal focus on the path(s) with the next least visiting tasks. The first click will focus on the path with the least visiting tasks.

[Traverse Most] Tasks

Traversal focus on the path(s) with the next most visiting tasks. The first click will focus on the path with the most visiting tasks.

[Traverse Least] TO

Temporal Order traversal focus on the path(s) that have made the least execution progress in the application. The first click will focus on the path that has made the least progress.

[Traverse Most] TO

Temporal Order traversal focus on the path(s) that have made the most execution progress in the application. The first click will focus on the path that has made the most progress.

Search

Search for call paths containing specified text, taken by specified tasks, or from specified hosts. Search text may be a regular expression, using the syntax described in <http://docs.python.org/library/re.html>.

[Identify] Eq C

Identify the equivalence classes of the visible graph. After clicking on this button, a window will pop up showing the complete list of equivalence classes.

Chapter 7. Using the stat-gui GUI

Description

STAT includes a graphical user interface (GUI) to run STAT and to visualize STAT's outputted call prefix trees (Figure 7-1). This GUI provides a variety of operations to help focus on particular call paths and tasks of interest. It can also be used to identify the various equivalence classes and includes an interface to attach a heavyweight debugger to the representative subset of tasks.

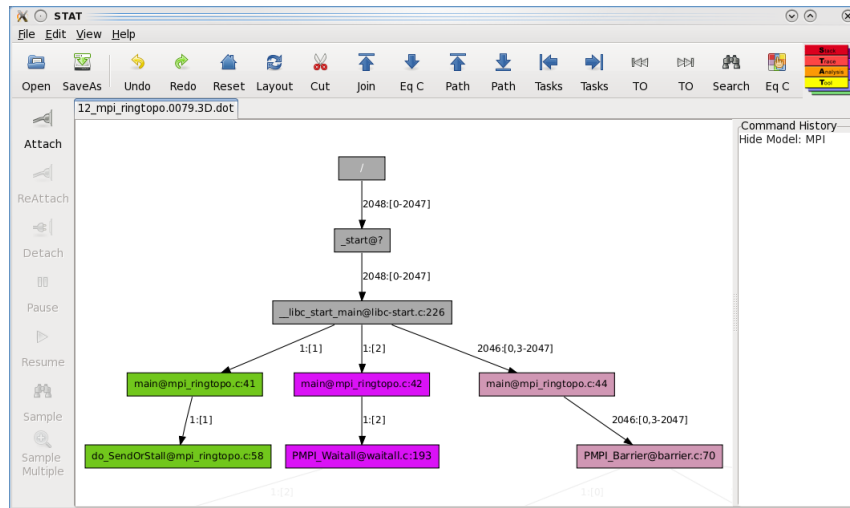


Figure 7-1. A screenshot of the STAT GUI

The stat-gui GUI Toolbar

In addition to the operations provided by stat-view, stat-gui provides a toolbar (Figure 7-2) to control STAT's operation.



Figure 7-2. The STAT GUI toolbar.

Attach

Attach to your application and gather an initial sample.

ReAttach

Reattach to the parallel application and gather an initial sample.

Detach

Detach from your application.

Pause

Put the application in a stopped state.

Resume

Set the application running.

Sample

Gather and merge a single stack trace from each task in your parallel application. The application is left in a stopped state after sampling.

Sample Multiple

Gather and merge multiple stack traces from each task in your parallel application over time. The application is left in a stopped state after sampling.

Sample Options

STAT has several options for stack trace sampling (Figure 7-3).

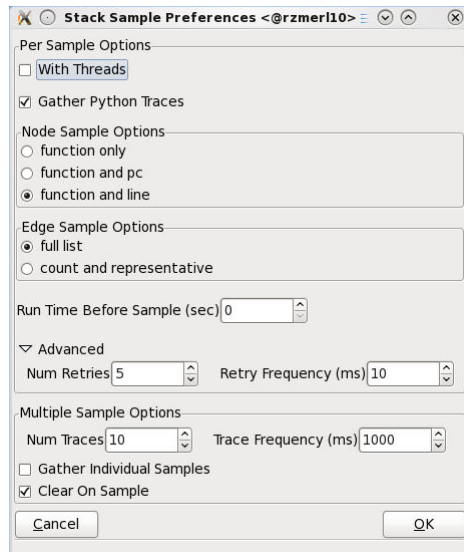


Figure 7-3. The stat-gui operation toolbar.

These options are defined as follows:

With Threads

Sample helper threads in addition to the main thread.

Gather Python Traces

Where applicable, gather Python script level stack traces, rather than show the Python interpreter stack traces. This requires the Python interpreter being debugged to be built with `-g` and preferably `-O0`.

function only | function and pc | function and line

Sample traces with function name only, or function name with the CPU program counter, or function name with the source file and line number.

full list | count and representative

Sample traces with the full task list or just the count and a single representative. When gathering the count and representative, you can actually query an individual STAT graph node (through the left-click menu) for the full edge label, as long as the STAT session is still attached.

Run Time Before Sample

Resume the application and let it run for the specified amount of time before gathering the sample

Retries/Retry Frequency (Advanced)

Sometimes a process may be in a state (i.e., function prologue or epilogue) such that a complete stack trace may not be obtainable. This option controls how many times to retry sampling and how often to wait (in microseconds) between retries to try and get a complete trace.

Traces/Trace Frequency

When sampling multiple traces over time, these options specify how many traces to gather per process and how long to wait between samples.

Gather Individual Samples

When sampling multiple traces over time, this option enables STAT to gather all of the intermediate 2D prefix trees in addition to the fully merged 3D prefix tree. The traces will be displayed in individual tabs.

Clear On Sample

When sampling multiple traces over time, STAT accumulates the traces that are gathered. This option determines whether to clear the accumulated traces when gathering additional traces.

Process Table

The application process table can be accessed through the stat-gui File->Properties menu item. This window (Figure 7-4) lists the properties of the application, including the number of nodes, processes, the job launcher host and PID and a 4-tuple list of application process rank, host, PID, and executable. The executable path in the 4-tuple is an index into the executable list at the top of the window in order to reduce duplication of text. The 4-tuple process table list can be filtered by ranks or hosts.

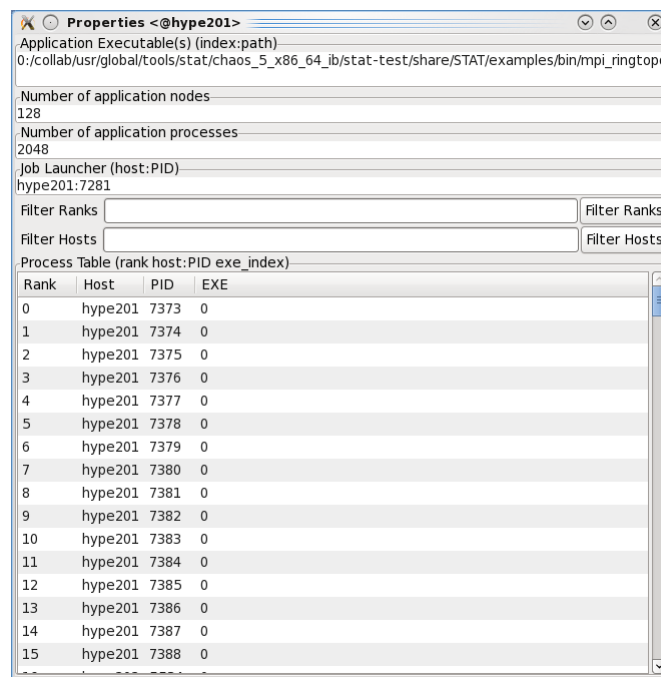


Figure 7-4. The properties window shows the application properties and lists the individual application processes.

Equivalence Classes and Subset Debugging

stat-gui can also serve as an interface to attach a full-featured debugger such as TotalView or DDT to a subset of application tasks. This interface can be accessed through the "identify equivalence classes" Eq C button, which will pop up the equivalence classes window (Figure 7-5). You can then select a single representative, all, or none of an equivalence classes' tasks to form a subset of tasks. The **Attach to Subset** buttons will launch the specified debugger and attach to the subset of tasks (note, this detaches STAT from the application). The **Debugger Options** button allows you to modify the debugger path.

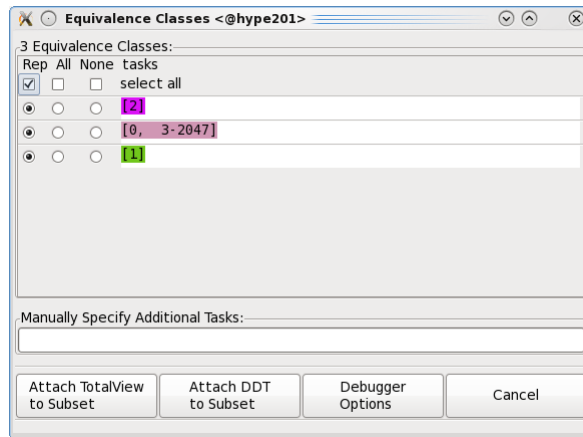


Figure 7-5. The equivalence classes window. The colored task lists correspond to the nodes in the prefix tree.

Availability

The STAT GUI is available on all TLCC systems (i.e., x86_64 machines) and Blue-Gene systems in `/usr/local/bin/stat-gui`. Man pages are also available (`man stat-gui`).

Chapter 8. Setting STAT Preferences and Options

Preference Files

Several files can influence how STAT runs. The first such file is `$prefix/etc/STAT/nodes.txt`, which specifies a list of hostnames, one hostname per line, on which to launch MRNet communication processes. This file is designed to be shared by all users and should point to shared resources that all users have remote shell access to, such as login nodes. Note that by default STAT will not test access to a node before trying to launch communication processes. If the `STAT_CHECK_NODE_ACCESS` environment variable is set to any value, then STAT will try to run (via remote shell) a simple test to see if the node is accessible before adding it to the MRNet tree. Also note that `nodes.txt` will not be used if the `-A` or "Share App Nodes" option is enabled.

STAT GUI preferences can be set with an installation specific `STAT.conf` or user specific `.STATrc` file. The installation specific file should be placed in `$prefix/etc/STAT/STAT.conf`, while the user specific file should be placed in `$HOME/.STATrc`. Options specified in the user's `.STATrc` file will always take precedence over the STAT installation's `.STATrc` file. Each preference file specifies one option per line of the format:

Option = Value

Here is a list of options:

Remote Host = *hostname*

Sets the default remote host to *hostname* to search for the job launcher process.

Remote Host Shell = *rsh/ssh*

Sets the default remote host shell to *rsh* or *ssh* to get a process listing on remote hosts.

Job Launcher = *regex*

Sets the default regular expression to *regex* (i.e., "mpirun | srun") for filtering the process listing for the job launcher process.

Tool Daemon Path = *path*

Use the STAT daemon executable installed in *path* instead of the default.

Filter Path = *path*

Use the STAT filter shared object installed in *path* instead of the default.

Topology Type = *automatic|depth|max_fanout|custom*

Use the specified topology type when building the MRNet communication tree. The *automatic* topology is typically recommended and set by default.

Topology = *topology*

Use *topology* for the specific topology configuration. This should be used with the Topology Type option. Refer to the `stat-cl` options to see valid Topology specifications for a given Topology Type.

Communication Nodes = *odelist*

Use the nodes listed in *odelist* for MRNet communication processes.

Check Node Access = *true/false*

Controls whether to check access to a node before trying to launch MRNet communication processes on it.

CP policy = *none/share app nodes/exclusive*

Controls where to launch communication processes. When set to *share app nodes*, they will be launched on nodes running application processes. On BlueGene systems, this will actually place them on the I/O nodes, and requires users to be able to access the I/O nodes via a remote shell. When set to *exclusive*, then the communication processes will only be run on specified nodes that do not run other STAT tool processes (e.g., the STAT frontend and the back-end daemons).

Communication Processes per Node = *count*

Launch no more than *count* MRNet communication processes per node.

Num Traces = *count*

Gather *count* stack traces when sampling multiple.

Trace Frequency (ms) = *count*

Let the process run *count* milliseconds between multiple samples.

Num Retries = *count*

Attempt *count* retries to try to obtain a complete stack trace.

Retry Frequency (ms) = *count*

Let the process run *count* milliseconds between stack sample retries.

With Threads = *true/false*

Controls whether to gather stack traces from threads.

Gather Python Traces = *true/false*

Controls whether to gather Python script level stack traces, rather than show the Python interpreter stack traces.

Sample Type = *function only/function and pc/function and line*

Controls the granularity of the nodes in the gathered stack traces.

Edge Type = *full list/count and representative*

Controls the granularity of the edges in the gathered stack traces.

DDT Path = *path*

Use the DDT executable installed in *path* for subset debugging.

DDT LaunchMON Prefix = *path*

Use the LaunchMON installation in *path* for improved DDT subset attaching, otherwise attach via hostname:PID pairs.

TotalView Path = *path*

Use the TotalView executable installed in *path* for subset debugging.

Additional Debugger Args = *args*

Add *args* to the argument list when launching TotalView or DDT.

Log Dir = *directory*

Write STAT debug logs to *directory*.

Log Frontend = *true/false*

Controls whether to enable debug logging of the STAT frontend.

Log Backend = *true/false*

Controls whether to enable debug logging of the STAT backend.

Log CP = *true/false*

Controls whether to enable debug logging of the STAT communication processes.

Log SW = *true/false*

Controls whether to enable debug logging of Stackwalker by the STAT backend.

Log SWERR = *true/false*

Controls whether to enable debug logging of Stackwalker by the STAT backend when a Stackwalker error is detected.

Use MRNet Printf = *true/false*

Controls whether to use MRNet's printf when writing debug logs. This is helpful to correlate timing between STAT log messages and MRNet debug log messages, when MRNet logging is being logged (via the STAT_MRNET_OUTPUT_LEVEL environment variable).

Loading and Saving Preferences

Options from a STAT session can be saved to a preferences file that can be loaded on subsequent sessions. This can be accessed through the **File -> Load Preferences** and **File -> Save Preferences** menu items.

Environment Variables

Several environment variables influence STAT and its dependent packages. Note that dependent package environment variables are prefixed with "STAT_" to avoid conflict with other tools using that package. The STAT process will then set the appropriate (i.e., without "STAT_") environment variable to pass the value to the dependent package.

STAT_PREFIX=*directory*

Use *directory* as the installation prefix instead of the compile-time STAT_PREFIX macro when looking for STAT components and configuration files.

STAT_CONNECTION_TIMEOUT=*time*

Wait *time* seconds for daemons to connect to MRNet. Upon timeout, run with the available subset.

STAT_DAEMON_PATH=*path*

Use the STAT daemon executable *path* instead of the default. *path* must be set to the full path of the STATD executable.

STAT_FILTER_PATH=*path*

Use the STAT filter shared object *path* instead of the default. *path* must be set to the full path of the STAT_FilterDefinitions.so shared object file.

STAT_FGFS_FILTER_PATH=*path*

Use the STAT FGFS filter shared object *path* instead of the default. *path* must be set to the full path of the STAT_FilterDefinitions.so shared object file.

STAT_MRNET_OUTPUT_LEVEL=*level*

Enable MRNet debug logging at *level* (0-5).

STAT_MRNET_PORT_BASE=*port*

Set the MRNet base port number to *port*.

STAT_MRNET_STARTUP_TIMEOUT=*seconds*

Set the MRNet connection timeout to *seconds*.

STAT_CONNECT_TIMEOUT=*seconds*

Set the STAT connection timeout to *seconds*, after which STAT will try to continue with any subset of daemons that have connected.

STAT_MRNET_DEBUG_LOG_DIRECTORY=*directory*

Write MRNet debug log files to *directory*.

STAT_OUTPUT_REDIRECT_DIR=*directory*

Redirect stdout and stderr to a set of hostname specific files in *directory*.

STAT_MRN_COMM_PATH=*path*

Use the `mrnet_commnode` executable *path*. *path* must be set to the full path of the `mrnet_commnode` executable. (Deprecated along with MRNet's MRN_COMM_PATH)

STAT_MRNET_COMM_PATH=*path*

Use the `mrnet_commnode` executable *path*. *path* must be set to the full path of the `mrnet_commnode` executable.

STAT_XPLAT_RSH=*path*

Use the remote shell *path* for launching `mrnet_commnode` processes.

STAT_PROCS_PER_NODE=*count*

Allow up to *count* communication processes to be launched per node.

STAT_FE_HOSTNAME=*value*

Set the STAT Front End hostname to *value*. This may be necessary for example on BlueGene systems to use the proper network interface for the I/O nodes to connect back to.

STAT_CHECK_NODE_ACCESS=*value*

Set to any value to have STAT check user access to any specified nodes before launching communication processes.

STAT_GROUP_OPS=*value*

Set to any value to enable Stackwalker's group operations. Group operations may help with performance when a single daemon needs to manage a large number of target processes. This is on by default on BG/Q systems.

STAT_LMON_PREFIX=*path*

Sets the LaunchMON installation prefix to *path*.

STAT_LMON_LAUNCHMON_ENGINE_PATH=*path*

Use the `launchmon` executable *path*. *path* must be set to the full path of the `launchmon` executable.

STAT_LMON_REMOTE_LOGIN=*command*

Use the remote shell *command* for LaunchMON remote debugging.

STAT_LMON_DEBUG_BES=*value*

Launch the backends under a debugger's control if *value* is set (must be enabled in LaunchMON configuration).

`STAT_USAGE_LOG=`*path*

Record usage of STAT in the file located in *path*. *path* must be writeable by user.

`STAT_GROUP_OPS=`*value*

If this environment variable is set on the daemons, STAT will use Stack-walker's group operations instead of operating on individual processes. This is set by default on BG/Q systems.

Chapter 9. Tips and Tricks Using STAT

Using STAT with IO Watchdog and SLURM

STAT can be used in conjunction with the IO Watchdog¹ utility, which monitors application output to detect hangs. To enable STAT with the IO Watchdog, add the following to the file `$HOME/.io-watchdogrc`

```
search /usr/local/tools/io-watchdog/actions
timeout = 20m
actions = STAT, kill
```

You will then need to run your application with the `--io-watchdog srun` option:

```
% srun --io-watchdog mpi_application
```

When STAT is invoked, it will create a `stat_results` directory in the current working directory, as it would in a typical STAT run. The outputted `.dot` files can then be viewed with `stat-view`. For more details about using IO Watchdog, refer to the IO Watchdog README file in `/usr/local/tools/io-watchdog/README`.

Running STAT in a Batch Script

A good way to run STAT is at the end of a batch script. For example, if an application is estimated to take 10 hours to run and 12 hours are allocated, then you may consider your application hung if it is still running up to the 12th hour. In such a situation, one may choose to run STAT in the last 10 minutes of the allocation to get diagnostic information about the job.

The following example script demonstrates how one might setup STAT to catch a hung job in a batch script.

```
#!/bin/sh

# perform your batch script prologue/setup here

stat_wait_time_minutes=120
application_exited=0

#run the application and get the launcher PID
srun mpi_ringtopo &
pid=$!

# periodically check for application exit
for i in `seq ${stat_wait_time_minutes}`
do
    sleep 60
    ps -p ${pid}
    if test $? -eq 1
    then
        # the application exited, so we're done!
        application_exited=1
        break
    fi
done

# if the application is still running then invoke STAT
if test ${application_exited} -eq 0
then
    /usr/local/bin/stat-cl -c ${pid}
    waitpid ${pid} # alternatively you may want to `kill -TERM ${pid}`
fi
```

```
# perform your batch script epilogue/cleanup here
```

Within the for loop, the script will check every minute (sleep for 60 seconds between checks) to see if the application is still running by running 'ps' on the PID of the job launcher. If the application has exited, the script will break from the loop and perform any remaining operations in the batch script. If the wait time, 120 minutes in this example, expires then STAT will be run to gather stack traces from the application. The wait time should be set such that STAT has enough time to run (i.e., 10 minutes to be safe) within the batch script's allocated time. Note the -c option to STAT gathers a "comprehensive" set of stack traces, with varying levels of detail. After STAT completes, the script then waits for the application to exit. Alternatively, you may want to kill the application if it isn't making any progress.

Notes

1. <http://code.google.com/p/io-watchdog/>

Chapter 10. Using the stat-bench Emulator

Description

The Stack Trace Analysis Tool is a highly scalable, lightweight tool that gathers and merges stack traces from all of the processes of a parallel application. stat-bench is a benchmark that can emulate STAT's performance. By utilizing your entire parallel allocation (launching one stat-bench daemon emulator per core) and generating artificial stack traces, stat-bench is able model STAT's performance using less resources than an actual STAT run requires. With various options, you can also map stat-bench to your target machine architecture and target application. After completion, stat-bench will create a stat_results directory in your current working directory. This directory will contain a subdirectory for the current run, with the merged stack traces in DOT format as well as a performance results text file. An example stat-bench generated prefix tree emulating 1M (1024*1024) tasks can be seen in Figure 10-1.

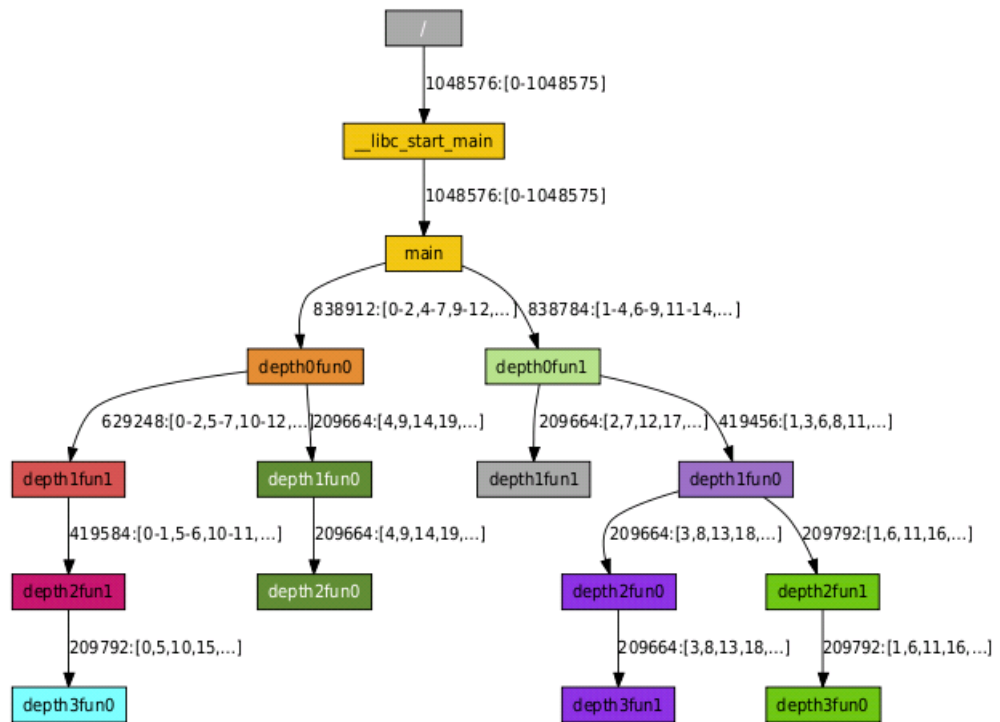


Figure 10-1. A stat-bench generated prefix tree emulating over 1 million tasks.

stat-bench Options

-a, --autotopo

let STAT automatically create topology.

-f, --fanout *width*

Sets the maximum tree topology fanout to *width*. Specify nodes to launch communications processes on with `--nodes`.

-d, --depth *depth*

Sets the tree topology depth to *depth*. This option takes precedence over the `--fanout` option. Specify nodes to launch communications processes on

- with `--nodes`.
- `-u, --usertopology topology`
Specify the number of communication nodes per layer in the tree topology, separated by dashes, with `topology`. This option takes precedence over the `--fanout` and `--depth` options. Specify nodes to launch communications processes on with `--nodes`. Example topologies: 4, 4-16, 5-20-75.
- `-n, --nodes nodelist`
Use the specified nodes in `nodelist`. To be used with `--fanout`, `--depth`, or `--usertopology` options. Example nodes lists: `host1`; `host1,host2`; `host[1,5-7,9]`.
- `-A, --appnodes`
Allow tool communication processes to be co-located on nodes running application processes.
- `-p, --procs processes`
Sets the maximum number of communication processes to be spawned per node to `processes`. This should typically be set to the number of CPUs per node.
- `-D, --daemon path`
Specify the full path `path` to the STATBenchD daemon executable. Use this only if you wish to override the default.
- `-F, --filter path`
Specify the full path `path` to the stat-bench filter shared object. Use this only if you wish to override the default.
- `-t, --traces count`
Gather `count` traces per process.
- `-i, --iters count`
Perform `count` gathers.
- `-n, --numtasks count`
Emulate `count` tasks per daemon.
- `-m, --maxdepth depth`
Generate traces with a maximum depth of `depth`.
- `-b, --branch width`
Generate traces with a max branching factor of `width`.
- `-e, --eqclasses count`
Generate traces within `count` equivalence classes.
- `-U, --countrep`
Only gather edge labels with the task count and a single representative.
- `-l, --log`
`[FE | BE | CP]`

Enable debug logging of the `FE` frontend, `BE` backend, or `CP` communication process. Multiple log options may be specified (i.e., `-l FE -l BE`).

`-L, --logdir log_directory`

Dump logging output into *log_directory*. To be used with the `--log` option.

`-M, --mrnetprintf`

Use MRNet's printf for STAT debug logging.

stat-bench Usage Example

In the simplest form, you can invoke stat-bench, from within a parallel allocation, with no arguments. This will run through with the default settings:

```
% stat-bench
```

To model your target machine architecture, you can specify the number of tasks to emulate per daemon. For instance if your target machine has 16-way SMP compute nodes:

```
% stat-bench --numtasks 16
```

You may also want to model a specific application. For instance, you may have a climate modeling code with 5 distinct task behaviors, or equivalence classes. You can also specify the maximum call depth of your application, the average branching factor from a given function, and the number of distinct traces expected per task:

```
% stat-bench --eqclasses 5 --maxdepth 17 --branch 5 --traces 4
```

At larger scales, you may want to employ a more scalable tree topology. For example, if you're running 1024 daemon emulators, you may want to try a fanout of $\sqrt{1024} = 32$. You will need to specify a list of nodes that contains enough processors to accommodate the $\text{ceil}(1024/32) = 32$ communication processes being launched. Be sure that you have login permissions to the specified nodes and that they contain the `mrnet_commmnode` executable and the `STAT_FilterDefinitions.so` library:

```
% stat-bench --fanout 32 --nodes atlas[1-4] --procs 8
```


Chapter 11. Troubleshooting Guide

Troubleshooting

stack walks not making it to `_start`

Processes can be in portions of code from which a debugger cannot walk the stack (i.e., function prologue or epilogue). Try the `-r` option to enable STAT to let the process run a bit and then retry the stack sample.

stack walks with line number information returning ??

Stack traces with line number information requires your code to be compiled with debug information (i.e., with the `-g` flag).

`/usr/lib/python2.6/site-packages/gtk-2.0/gtk/__init__.py :72: GtkWarning: could not open display`

Be sure to enable X-forwarding and to set your `$DISPLAY` environment variable.

STATview requires gtk

STAT requires the `pygtk` module to be installed. If it is side-installed, but sure to set your `$PYTHONPATH` environment variable to the directory containing the `pygtk` module.

ImportError: No module named STAT

Make sure to run 'make install' to install `STAT.py` in the `lib/python[version]/site-packages` directory or set your `$PYTHONPATH` environment variable to the directory containing `STAT.py`

(ERROR): LaunchMON Engine invocation failed, exiting: No such file or directory

Make sure the `launchmon` executable is in your `$PATH` or set the `$STAT_LMON_LAUNCHMON_ENGINE_PATH` engine path to the full path to the executable.

OptionParsing (ERROR): unknown launcher: a.out

You need to attach to your `mpirun` or equivalent parallel job launch process.

OptionParsing (ERROR): the path[`/usr/local/bin/STATD`] does not exit.

STAT looks for its components in the configured `$prefix`. Be sure to run 'make install' or set `STAT_DAEMON_PATH` to the full path to the `STATD` executable.

LaunchMON prints a usage message.

This is typically a mismatch in versions of the LaunchMON API and the LaunchMON engine. Make sure to set your `$STAT_LMON_LAUNCHMON_ENGINE_PATH` environment variable to the full path to the appropriate `launchmon` executable.

(ERROR): accepting a connection with an engine timed out

STAT may need additional time to launch all of its daemons. You may need to set your `$LMON_FE_ENGINE_TIMEOUT` to a larger value, such as 600.

Bibliography

- Dong H. Ahn, Michael J. Brim, Bronis R. de Supinski, Todd Gamblin, Gregory L. Lee, Matthew P. Legendre, Barton P. Miller, Adam Moody, and Martin Schulz, "Efficient and Scalable Retrieval Techniques for Global File Properties," *International Parallel & Distributed Processing Symposium*, Boston, Massachusetts, May 2013.
- Dong H. Ahn, Bronis R. de Supinski, Ignacio Laguna, Gregory L. Lee, Ben Liblit, Barton P. Miller, and Martin Schulz, "Scalable Temporal Order Analysis for Large Scale Debugging," *Supercomputing 2009*, Portland, Oregon, November 2009.
- Gregory L. Lee, Dorian C. Arnold, Dong H. Ahn, Bronis R. de Supinski, Matthew Legendre, Barton P. Miller, Martin Schulz, and Ben Liblit, "Lessons Learned at 208K: Towards Debugging Millions of Cores," *Supercomputing 2008*, Austin, Texas, November 2008.
- Dong H. Ahn, Dorian C. Arnold, Bronis R. de Supinski, Gregory L. Lee, Barton P. Miller, and Martin Schulz, "Overcoming Scalability Challenges for Tool Daemon Launching," *37th International Conference on Parallel Processing (ICPP-08)*, Portland, Oregon, September, 2008.
- Gregory L. Lee, Dorian C. Arnold, Dong H. Ahn, Bronis R. de Supinski, Barton P. Miller, and Martin Schulz, "Benchmarking the Stack Trace Analysis Tool for BlueGene/L," *International Conference on Parallel Computing (Parco) 2007*, Aachen and Julich, Germany, September 2007.
- Dorian C. Arnold, Dong H. Ahn, Bronis R. de Supinski, Gregory L. Lee, Barton P. Miller, and Martin Schulz, "Stack Trace Analysis for Large Scale Applications," *International Parallel & Distributed Processing Symposium*, Long Beach, California, March 2007.

Notes

1. <ftp://ftp.cs.wisc.edu/paradyn/papers/FGFS-IPDPS13-Ahn-validated.pdf>
2. <ftp://ftp.cs.wisc.edu/paradyn/papers/Miller09ScalableDebugging.pdf>
3. <ftp://ftp.cs.wisc.edu/paradyn/papers/Lee08ScalingSTAT.pdf>
4. <ftp://ftp.cs.wisc.edu/paradyn/papers/Ahn08LaunchMON.pdf>
5. <ftp://ftp.cs.wisc.edu/paradyn/papers/Lee07STATBench.pdf>
6. <ftp://ftp.cs.wisc.edu/paradyn/papers/Arnold06STAT.pdf>

