It’s not my fault!
Finding errors in parallel codes

查找並行程序的錯誤

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State of the art in debugging?

printf("%f %f %f\n", a[i], b[i], c[i])

If debugging is the process of removing software bugs, then programming must be the process of putting them in.

--- Edsger Dijkstra ---

a.out > dumpfile; b.out > dumpfile1
diff dumpfile1 dumpfile2
Supercomputing requires extreme debugging

- **Titan**
  - 299,008 AMD Opteron cores
  - 18,688 Nvidia Tesla K20 GPU Accelerators
  - 710 TB system memory, 32 GB + 6 GB per node (w/accelerator)
  - 18,688 compute nodes

- **Sunway TaihuLight**
  - 40,960 SW26010 manycore 64-bit RISC processors
  - Each processor chip contains
    - 256 processing cores,
    - 4 auxiliary
  - 10,649,600 CPU cores
Debugging large codes

- **Cognitive challenge**
  - Large number of processes
    - Particular problems for UI
  - Large data structures
    - Infeasible to examine individual cells of multi-dimensional, floating point, structures.
  - Heterogeneity
    - A great source of errors
    - Hard to debug when do fail

- **Performance Challenge**
  - High level debugging is expensive
  - Debuggers generally don't use underlying parallel platform

- In the Exascale this just gets worse!
COMPARATIVE DEBUGGING
Debugging Evolved Applications

• Large codes are constantly evolving
  – User requirements
  – Underlying algorithms
  – New architectures

• Subtle errors occur often
  – Programmers spend lots of time debugging
  – Identify the source of a discrepancy
  – Follow it back to original source of deviation
Comparative Debugging

• What is comparative debugging?
  – Data centric approach
  – Two applications, same data
  – Key idea: The data should match
  – Quickly isolate deviating variables
  – Focus is on where deviations occur

• How does this help me?
  – Algorithm re-writes
  – Language ports
  – Different libraries/compilers
  – New architectures
Comparative Debugging

- Specify conditions for correct behavior prior to execution
- Debugger:
  - keeps track of breakpoints
  - performs comparison automatically
- Control returned to user:
  - examination of state
  - continuation of execution

```assert P1::big[100..199]@"file.c":240 = P2::small@"prog.f":300```
Why this works?

- Iterative refinement of problem area
Why this works?

• Iterative refinement of problem area
Why this works?

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Why this works?

- Iterative refinement of problem area
VISUALIZATION
Reporting Differences

Values of scalars, small arrays

Starting execution of processes
Comparing c and c.
Maximum difference between values: 1.15442e-23
Total difference between values: 4.37116e-23
Number of differences detected = 823
First 10 errors are:
At Index : ( 30) = (Diff, Value 1, Value2) 0.000488
At Index : ( 32) ( 32) = (Diff, Value 1, Value2) 0.

2-D pixel maps

Movies

Multi-dimensional visualisation
The power of visualization
The power of visualization

- Difference in physics of planetary boundary layer
  - Computation of steps suited to parallel execution
  - Evident in 3 dimensional visualisation
- Error in radiation time step computation
- More complete physics in long wave radiation
The power of visualization
SCALABILITY
CCDB ARCHITECTURE
Overall architecture

- Scalable broadcasts and reductions
- Switchable backends
- Result aggregation
The architecture of CCDB is illustrated using the Hash-based comparison.
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HETEROGENEITY AND IMPLEMENTATION TECHNIQUES
Assertion Engine

• Application processes run asynchronously
• Multiple assertions, can share same line numbers or variables
• Assertions specify breakpoint locations in processes
  – multiple breakpoints reached at any time
  – need to read data from process at breakpoint
• Comparison process is automated
• Stop execution when threshold reached

⇒DATAFLOW
Dataflow Engine

- Supports asynchronous behavior in debugged processes
- Flexible assertion structure
  - Single program assertions
  - Cross coupled assertions
  - Multi-process parallel programs

```
assert R($ref::large)@trusted.c:65 = S($sus::super)@ported.c:68
```
Architecture Independent Format

- Ability to represent data from different architectures in an architecture neutral way
- Need to perform numerical operations on data in this format
- Need to be able to convert to/from native formats

```c
struct {
    int a;
    float b[3];
};
```

```plaintext
{a:is4,b:[r0..2is4]f4}
```

```
<table>
<thead>
<tr>
<th>byte 1</th>
<th>byte 2</th>
<th>byte 3</th>
<th>byte 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>s</td>
<td>exponent</td>
<td>mantissa</td>
<td></td>
</tr>
<tr>
<td>s</td>
<td>exponent</td>
<td>mantissa</td>
<td></td>
</tr>
<tr>
<td>s</td>
<td>exponent</td>
<td>mantissa</td>
<td></td>
</tr>
</tbody>
</table>
```
Flexibility in Comparisons

• Tolerances used for inexact equality
• Data structures should be:
  – type conformant (with conversion)
  – same size, but can be differing shapes
• Arrays
  – Differences allowed are:
    • offset ranges in arrays
    • ordering of indexes
    • Number of indexes
    • Language
• Dynamic data
  – Linked lists
  – Objects
Programming Languages other than C/F

- **OpenACC/OpenMP**
  - Sequential regions executed on CPU
  - Parallel regions offloaded to GPU
  - Data dynamically moves between CPU and GPU
  - Separated address spaces for CPU and GPU codes
  - Inconsistent precision of floating numbers across CPU and GPU

- **UPC: a virtual global memory space**
  - Automatically decomposing the global data across a number of SPMD threads
  - Exchanging data between threads is managed by the UPC runtime system
Implementation

• Modification of CUDA-GDB
  – Automatically identify the variables residing on the GPU device attached to a Cray system
  – Move the data of a targeted GPU variable into the memory space of CUDA-GDB (in the memory of the host)
    • This enhancement is implemented using the debugger API provided by NVIDIA for GDB

• Tolerance threshold for comparing floating numbers
  – Truncate floating numbers to the same precision before they are converted into AIF.
The CCDB server on a hybrid node
Supporting UPC

• Affinity in UPC
  – Describes different domain decompositions
  – A user can provide a blocking-factor to achieve different decomposition schemas

• Implementation
  – Retrieve affinity metadata
  – Automatically generating a blockmap function, called auto-blockmap
  – Reconstruct a UPC global-shared array using the auto-blockmap function
CCDB on Cray supercomputers

• Supporting Cray XE, XK, and XC supercomputers
• CCDB client: a comparative debugging interface
  – Launching parallel applications onto the back-end
  – Controlling the execution of the programs remotely
  – Compare key data structures between different applications
• CCDB server: a pluggable architecture
  – GDB: C, Fortran, and UPC programs
  – CUDA-GDB: OpenACC, OpenMP
  – MRNet
  – Scalable communication between the CCDB client and servers
  – AIF(Architecture Independent Format)
  – ‘Normalizing’ the data across platforms and languages
TO INFINITY AND BEYOND?
Exascale

- Probably big!
- Heterogeneous
- Mixed precision
- Hierarchical memories
- Algorithms
  - Loose synchronization
  - Fault tolerant
Debugging and Correctness

Scaling Debugging Techniques
Debugging Hybrid and Heterogeneous Architectures
Specialized Memory Systems
Domain Specific Languages
Mixed Precision Arithmetic
Adaptive Systems
Correctness Tools
Debugging and Correctness

- Scaling Debugging Techniques ✔
- Debugging Hybrid and Heterogeneous Architectures ✔
- Specialized Memory Systems ✔
- Domain Specific Languages ✔
- Mixed Precision Arithmetic ✔
- Adaptive Systems ?
- Correctness Tools ?

✔ means some progress
Statistical Assertions

• Asserting descriptive statistics of a given dataset
  – Mean, standard deviation …
• Asserting statistical hypotheses
  – Distribution functions
  – Statistical tests
• Adjacent time steps show high data correlation
  – Can help identifying potential errors and outliers
• Asserting program states across time steps

  history etot $a::dvalue@“thermo.cpp”:1521 10 100
  set reduce stdev; compare etot < 0.1
Statistical Assertions

- **Statistical parameters** (*mean, SD, etc*)
- **Statistical tests** (*T, χ², etc*)
- **Distributions**

![Speed histogram for incorrect code](image1)

![Speed histogram for correct code](image2)

Many high speed particles
Conclusion

• Comparative Debugging
  – Focuses on errors during code and platform evolution
    • Very rapid convergence
  – Large machines and programs are challenging
  – Techniques that scale to hundreds of thousands of cores
  – Commercial release from Cray