TECHNISCHE UNIVERSITÄT DRESDEN

Center for Information Services and High Performance Computing (ZIH)

Flexible Workload Generation for HPC Cluster Efficiency Benchmarking

07.09.2011

Daniel Molka (daniel.molka@tu-dresden.de)

Daniel Hackenberg (daniel.hackenberg@tu-dresden.de)

Robert Schöne (robert.schoene@tu-dresden.de)

Timo Minartz (timo.minartz@informatik.uni-hamburg.de)

Wolfgang E. Nagel(wolfgang.nagel@tu-dresden.de)

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Motivation

- Varying power consumption of HPC systems
  - Depends on changing utilization of components over time (processors, memory, network, and storage)
  - Applications typically do not use all components to their capacity
  - Potential to conserve energy in underutilized components (DVFS, reduce link speed in network, etc.)
  - But power management can decrease performance
- HPC tailored energy efficiency benchmark needed
  - Evaluate power management effectiveness for different degrees of capacity utilization
  - Compare different systems

eeMark – Energy Efficiency Benchmark

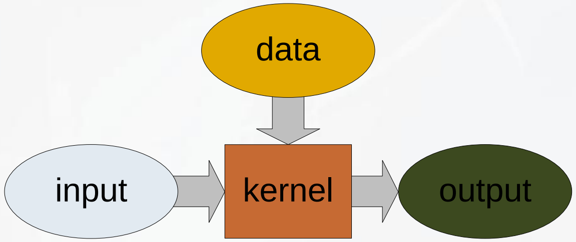
- Requirements
- Benchmark Design
  - Process groups and kernel sequences
  - Power measurement and reported result
- Kernel Design
  - compute kernels
  - I/O kernels
  - MPI kernels
- Initial results
- Summary

Requirements

- Kernels that utilize different components
- Arbitrary combinations of kernels
- Adjustable frequency of load changes
- Usage of message passing
- Parallel I/O
- Reusable profiles that scale with system size

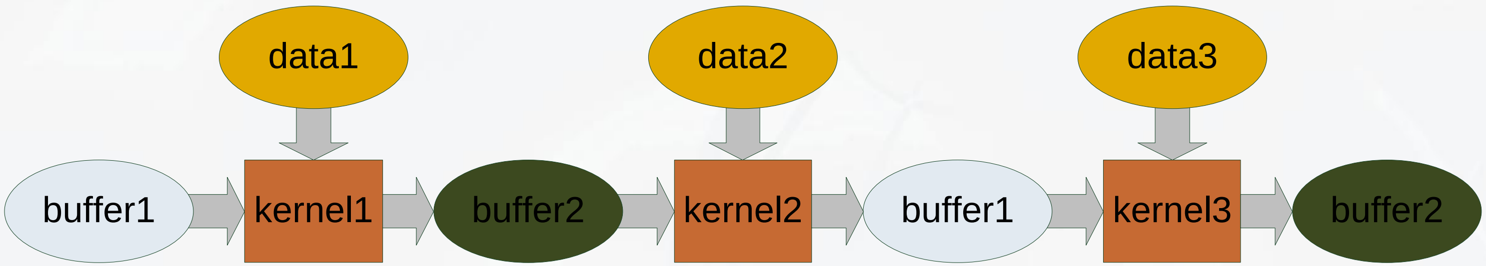
Benchmark Design - Kernels

- 3 types of kernels
  - Compute - create load on processors and memory
  - Communication - put pressure on network
  - I/O - stress storage system
- Same basic composition for all types of kernels
  - Three buffers available to each function
  - No guarantees about input other than
    - Data has the correct data type
    - No nan, zero, or infinite values
  - Kernel ensures that output satisfies these requirements as well
    - Buffer data initialized in a way that nan, zero, or infinite do not occur



Benchmark Design - Kernel Sequences

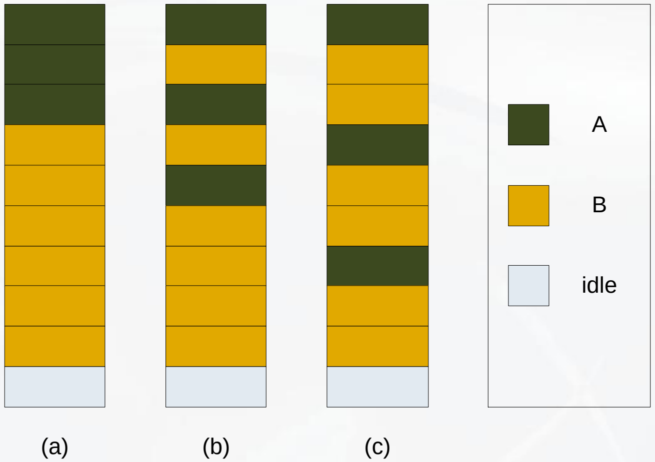
- 2 buffers per MPI process used as input and output
  - Output becomes input of next kernel
- data buffer per kernel



- Input and output used for communication and I/O as well
  - send(input), write(input): - send or store results
  - receive(output), read(output): - get input for next kernel

Profiles

- Define kernel sequences for groups of processes
  - Groups with dynamic size adopt to system size
    - E.g. half the available processes act as producers, the other half as consumers
    - Different group sizes possible
    - Multiple distribution patterns



  - Groups with fixed amount of processes for special purposes
    - E.g. a single master that distributes work
- Define the amount of data processed per kernel
- Define block size processed by every call of kernel

Example Profile

```
[general]
iterations=      3
size=            64M
granularity=     2M
distribution=    fine

[Group0]
size=            fixed
num_ranks=       1
function=        mpi_io_read_double, mpi_global_bcast_double-Group0,
                 mpi_global_reduce_double-Group0, mpi_io_write_double
[Group1]
size=            dynamic
num_ranks=       1
function=        mpi_global_bcast_double-Group0, scale_double_16,
                 mpi_global_reduce_double-Group0
```

Power Measurement

- No direct communication with power meters
- Use of existing measurement systems
  - Dataheap, developed at TU Dresden
  - PowerTracer, developed at University of Hamburg
  - SPEC power and temperature demon (ptd)
- Power consumption recorded at runtime
  - API to collect data at end of benchmark
- Multiple power meters can be used to evaluate large systems

Benchmark Result

- Kernels return type and amount of performed operations
  - workload heaviness = weighted amount of operations
    - Bytes accessed in memory: factor 1
    - Bytes MPI communication: factor 2
    - I/O Bytes: factor 2
    - Int32 and single ops: factor 4
    - Int64 and double ops: factor 8
- Performance Score = workload heaviness / runtime
  - billion weighted operations per second
- Efficiency Score = workload heaviness / energy
  - billion weighted operations per Joule
- Combined Score = sqrt(perf_score*eff_score)

Example Result file:

```
Benchspec: example.benchspec
  Operations per iteration:
    - single precision floating point operations:   1610612736
    - double precision floating point operations:   5737807872
    - Bytes read from memory/cache:                 33822867456
    - Bytes written to memory/cache:                18522046464
    - Bytes read from files:                        805306368
  Workload heaviness: 106.300 billion weighted operations
Benchmark started: Fri Jun 24 10:43:48 2011

[…] (runtime and score of iterations)

Benchmark finished: Fri Jun 24 10:44:00 2011
 average runtime: 2.188 s
 average energy:  492.363 J
 total runtime:   10.941 s
 total energy:    2461.815 J
 Results:
 - performance score:   48.58
 - efficiency score:     0.22
 - combined score:       3.24
```

eeMark – Energy Efficiency Benchmark

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- Summary and Outlook

Kernel Design - Compute Kernels

- Perform arithmetic operations on vectors
  - Double and single precision floating point
  - 32 and 64 Bit integer
- Written in C for easy portability
  - No architecture specific code (e.g. SSE or AVX intrinsics)
  - Usage of SIMD units depends on autovectorization by compiler
- Adjustable ratio between arithmetic operations and data transfers
  - Compute bound and memory bound versions of same kernel

Source Code Generation

- Source code created with python based generator
- config file
  - Compiler options
  - Source code optimizations
    - Block size used by kernels to optimize L1 reuse
    - Alignment of buffers
    - Usage of *restrict* keyword
    - Additional pragmas
  - Lists of available functions and respective templates
    - Few templates for numerous functions

Source Code Example

```
int work_mul_double_1 (void * input, void * output, void * data, uint64_t size) {
        int i,j;
        uint64_t count = (size / sizeof(double))/2048;
        double * RSTR src1_0 = (double *)input + 0;
        double * RSTR src2_0 = (double *)data + 0;
        double * RSTR dest_0 = (double *)output + 0;
        double * RSTR src1_1 = (double *)input + 512;
        double * RSTR src2_1 = (double *)data + 512;
        double * RSTR dest_1 = (double *)output + 512;
        double * RSTR src1_2 = (double *)input + 1024;
        double * RSTR src2_2 = (double *)data + 1024;
        double * RSTR dest_2 = (double *)output + 1024;
        double * RSTR src1_3 = (double *)input + 1536;
        double * RSTR src2_3 = (double *)data + 1536;
        double * RSTR dest_3 = (double *)output + 1536;

        for(i=0; i<count; i++){
           for(j=0;j<512;j++){
              dest_0[j] = src1_0[j] * src2_0[j];
              dest_1[j] = src1_1[j] * src2_1[j];
              dest_2[j] = src1_2[j] * src2_2[j];
              dest_3[j] = src1_3[j] * src2_3[j];
           }
           src1_0+=2048;
           src2_0+=2048;
           dest_0+=2048;
           src1_1+=2048;
           src2_1+=2048;
           dest_1+=2048;
           src1_2+=2048;
           src2_2+=2048;
           dest_2+=2048;
           src1_3+=2048;
           src2_3+=2048;
           dest_3+=2048;
        }
        return 0;
}
```

Simple loop form (i=0;i<n;i++)

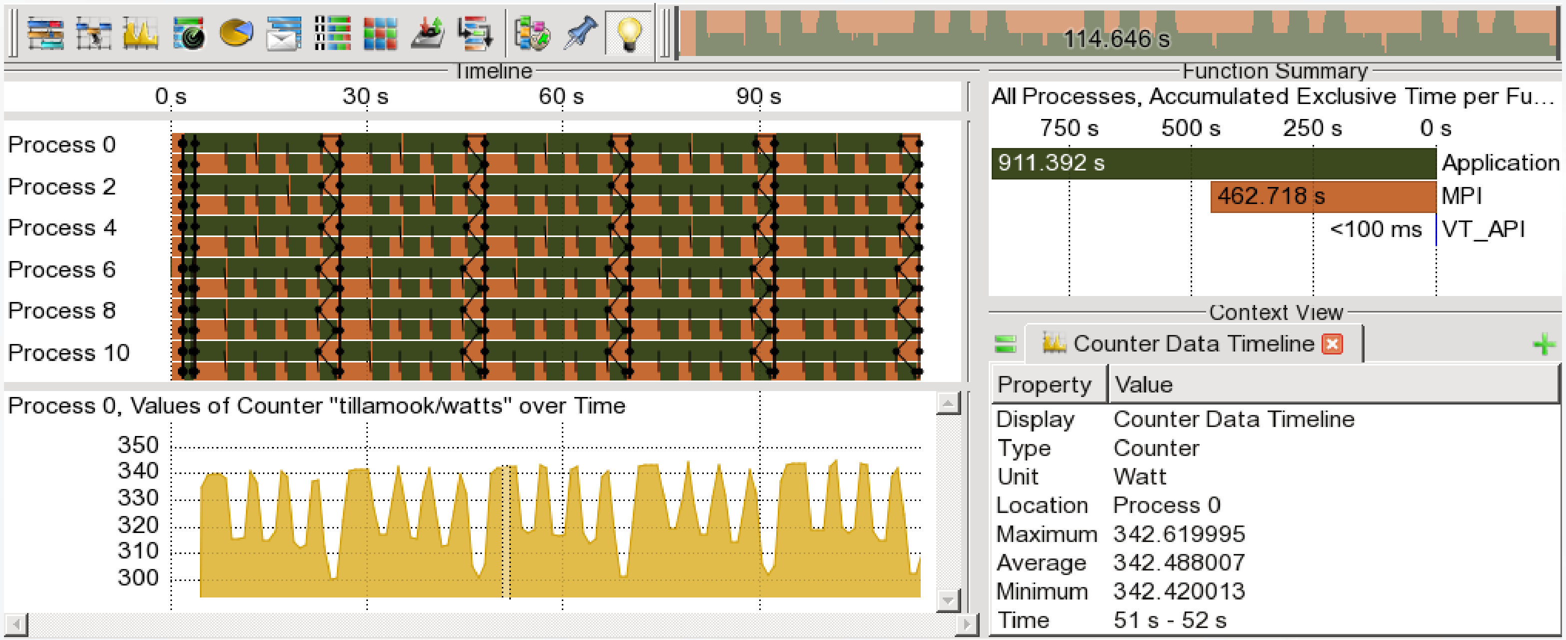
No calculation within array index

Coarse grained loop unrolling to provide independent operations

Kernel Design - Communication and I/O Kernels

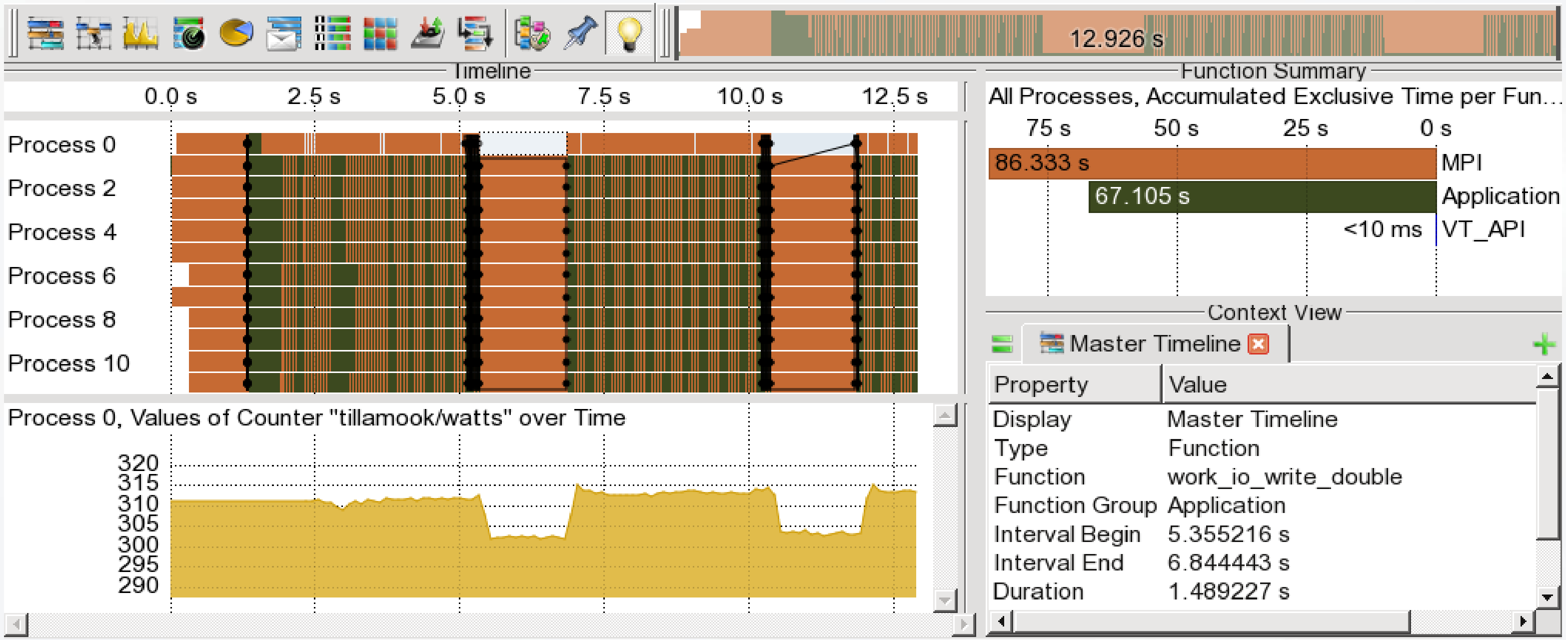
- MPI kernels
  - bcast/reduce involving all ranks
  - bcast/reduce involving one rank per group
  - bcast/reduce within a group
  - send/receive between groups
  - rotate within a group
- I/O kernels
  - POSIX I/O with one file per process
  - MPI I/O in with one file per group of processes

Producer Consumer Example



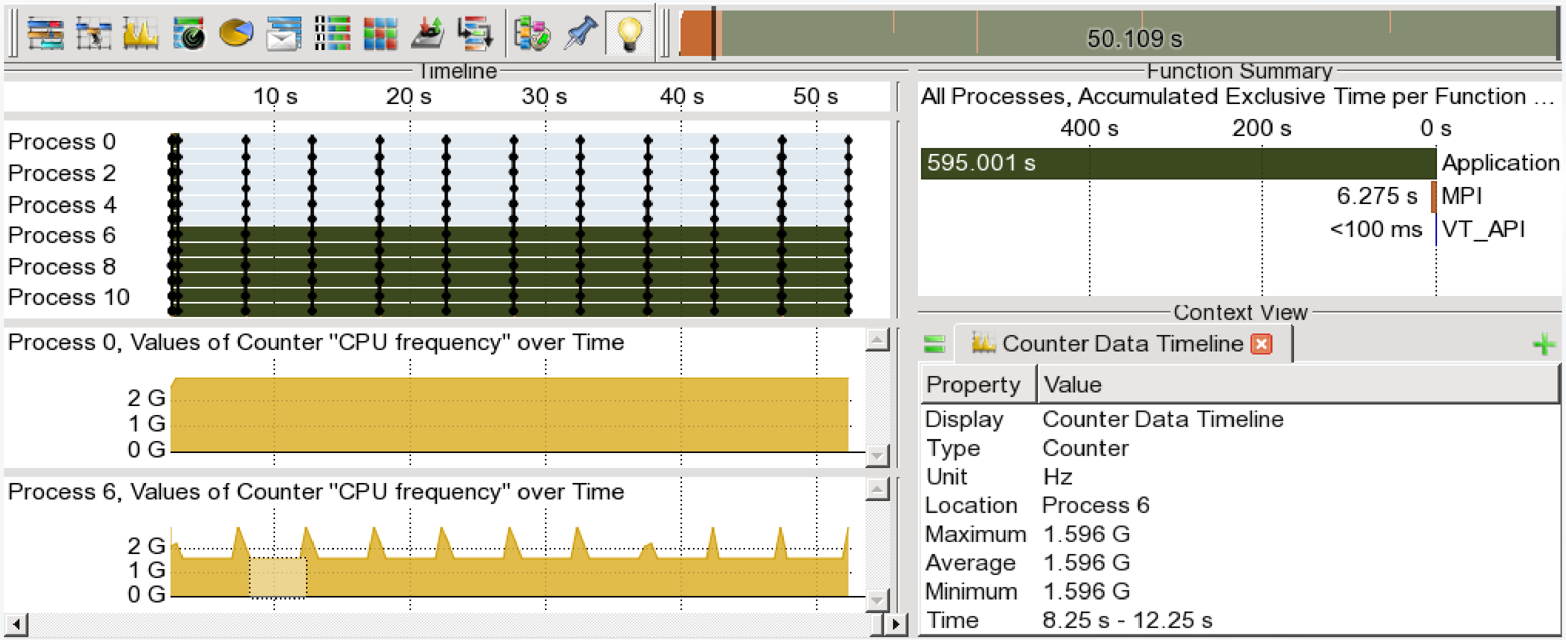
- Unbalanced workload
  - Consumers wait in MPI_Barrier
  - Higher power consumption during MPI_Barrier than in active periods of consumers

POSIX I/O Example



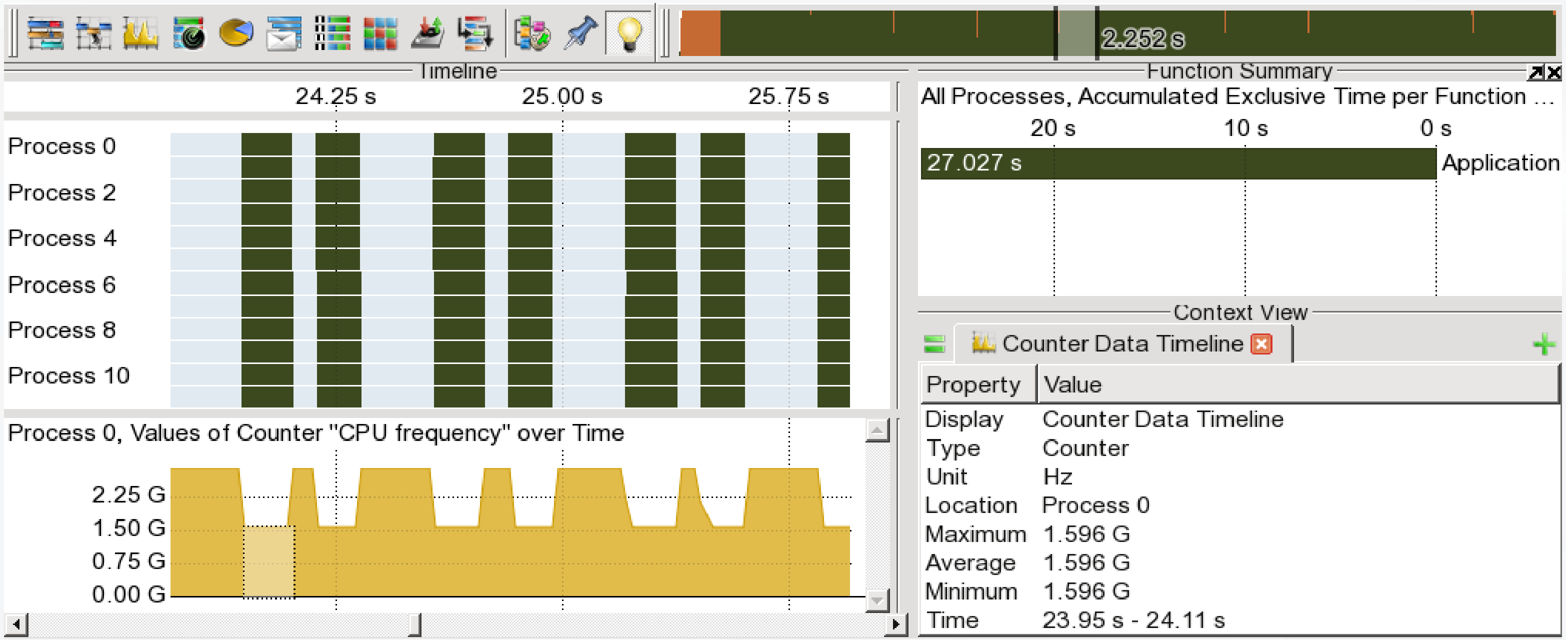
- Process 0 collects data from workers and writes to file
  - Usually overlapping I/O and calculation
  - Stalls if file system buffer needs to be flushed to disk

Frequency Scaling with pe-Governor



- Process 0-5 compute bound: highest frequency
- Process 6-11 memory bound: lowest frequency
  - High frequency during MPI functions

Frequency Scaling with pe-Governor



- Compute bound and memory bound phases in all processes
- Frequency dynamically adjusted by pe-Governor

Frequency Scaling Governor Comparison

Workload	ondemand governor		pe-Governor	
	runtime [ms]	energy [J]	runtime	energy
All ranks compute bound	4911	1195	+0.6%	+1.8%
All ranks memory bound	4896	1299	+0.8%	-10.7%
Compute bound and memory bound group	4939	1267	-0.4%	-6.1%
Each rank with compute and memory bound kernels	4856	1273	+4.4%	-2.3%

- pe-Governor decides based on performance counters
  - Significant savings possible for memory bound applications
  - Overhead can increase runtime and energy requirements

Summary

- Flexible workload
  - Stresses different components in HPC systems
  - Scales with system size
- Architecture independent
  - Implemented in C
  - Uses only standard interfaces (MPI, POSIX)
  - Simple code that enables vectorization by compilers
- Report with performance and efficiency rating
  - Evaluate effectiveness of power management
  - Compare different systems

Thank you

- Further Information at eeClust homepage
  - www.eeClust.de

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