Performance Characterization and Benchmarking for High Performance Systems and Applications

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Our Starting Point

- To evaluate and compare application and system performances we need a frame of reference in the performance space.
- Right now only peak performance and Linpack are widely used.
- A reference can be established by a set of benchmarks.
- Users should be able to relate the performance of these benchmarks to their codes.
- To develop such benchmarks we first need a better understanding what the critical performance aspects of algorithms are.

General Approach

- Develop a new quantitative characterization of algorithms and codes focusing on performance aspects.
- Avoid using any specific hardware models or concepts for this characterization.
- Develop synthetic performance probes and benchmarks testing these characteristics.
- Relate benchmark performance with code performance.
- Our focus is initially the performance influence of global data-access.

Design Ideas

Performance Characterization:

- Hardware independent.
- Global data access as main focus.
- Random data access as starting point.

Benchmark probe:

- Reference implementations together with a pencil and paper description.
- Runtimes not tied to computational complexities of specific algorithms.
- System and generation scalable.
- Focus on sustainable rates using substantial fractions of available resources.

Characterizing Performance

- Characterize performance behavior of applications and algorithms independent from hardware.
  - Use most general architecture model possible.
- Based on von Neumann model we assume that the effects of data access and instruction stream are independent (first order approximation)

  - “Time to solution =
    f(Algorithmic Complexity) ‘*’
    (f(Data Access Characteristics),
    ‘+’f(Structure of Operations))”

Concepts for Performance Ch.

Code complexities:

- Computational complexity.
- Data access complexity.

Instruction stream:

- Computational granularity.
  - Ratio of instructions to data accesses.
- Length of basic instruction blocks.
  - Between branches.
- Number of “global” operations.
  - Coupling parallel instructions streams.
- Length of local instruction blocks.
  - Between global operations.

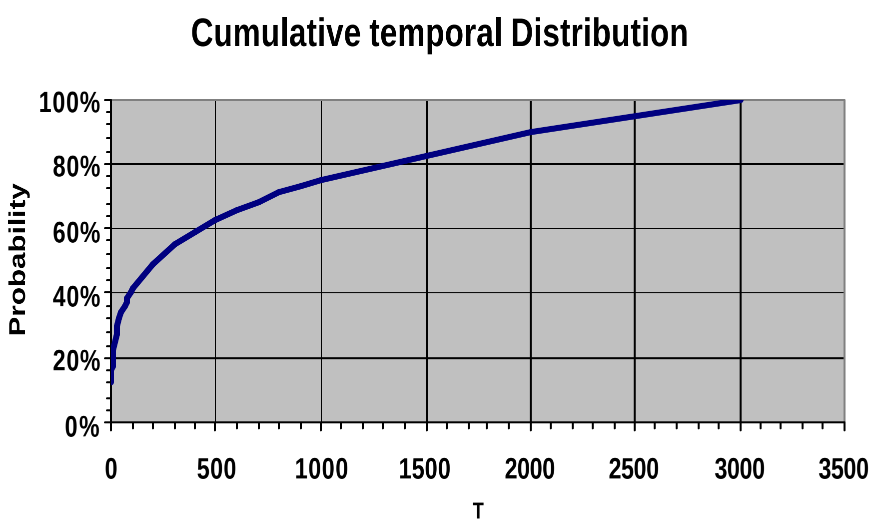
Data Access Characteristics

Data access pattern: What do we want to capture?

- *Re-use* of data by modern algorithm for improving locality – *Temporal locality.*
  - Hierarchical block-structured or recursive algorithms.
  - Hard to define hardware independent.
- Limitations of “vector”-length – *Granularity.*
  - Due to data-dependencies, communication, etc.
  - Becomes particularly important in parallel context.
- Regular contiguous memory access – *Regularity.*
  - stride 1 (n).

Temporal Locality

- How can we *quantitatively* describe data re-use?
- Look at temporal distribution function:
  - The probability distribution of how long ago I last used a data item.
    - At every access I have a *f(t)%* probability to hit a location I have visited within the last *t cycles*.



Temporal distance is similar to reuse distance, stack distribution, stack distance).

Re-use Number

Define a "re-use" number:

- *M* be the used memory in words.
- The re-use of a specific word is the number *k* of accesses to it during a window of *M* successive data accesses.
- The average re-use for the code is the average *k* during this window for all accessed words.

(This assumes that all windows give me the same answer)

- The probability at a temporal distance of *M* is then:

$$P(M) = (k-1)/k$$

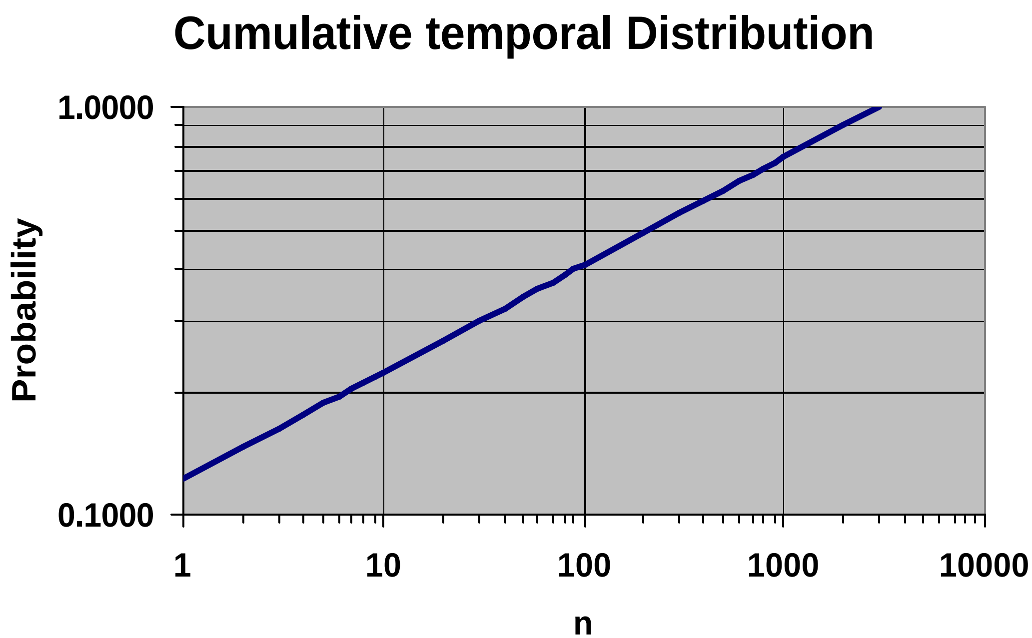
Temporal Distribution

- Approximate the temporal distribution function of codes by a simple generic function.
  - We try to capture the ‘main’ re-use effect by using a generic function with only a few numeric parameters.
  - For recursive algorithms the cumulative temporal distribution function should be self-similar and scale-invariant. (A recursive algorithm is self-similar.)

  - Power Function Distribution

Power Distribution

- Characterized by one number.
  - *Slope* in log-log related to the 'Re-use' factor.
- Concept does not use hardware concepts such as '*cache*'
- Distribution function is problem size and scale invariant.



Power Distribution

- All we need now is a synthetic pseudo-random algorithm which has a power distribution as temporal distribution function.
- Many algorithms generate the same temporal distribution, so we have some choices.
- The details of the chosen algorithm could produce artifacts if not selected carefully.
- In particular the temporal distribution function is independent of the selected data mapping!
  - Still (almost) any regularity possible!

Granularity

Limitation of “vector”-length due to data-dependencies.

- The amount of “pre-computable” addresses.
  - Access can be irregular (‘indirect’) or
  - Regular (‘strided’).
  - Limits the amount of dynamic reordering such as gather-scatter or message assembly.
- We focus on indirect as it becomes more important and represent more of a lower-bound for achievable performance.
- Granularity becomes very important for parallel version with explicit communication.
  - It (severely) limits message sizes .

Regularity

- A mapping of the data structure to the address space which permits stride 1 (n) access exposes regularity.
- Re-mapping during execution might be necessary for many algorithms to expose regularity.
  - This form of 'dynamic' regularity has associated re-mapping costs (gather-scatter operations).
  - This type of ("irregular") data access becomes more and more important and is usually not avoidable.
  - If irregular data access is present in a code it is likely to become the performance bottleneck (Amdahl's Law).
  - Irregular data access is "*our focus*".

Synthetic Benchmark Probe

- Measures sustainable rates.
  - Warm caches etc.
- Non-uniform random memory access for re-use.
  - Power-function as temporal distribution function.
  - Use indexed ("irregular") data access to measure a lower bound for performance.
- Granularity
  - Vector length for pre-computed addresses and organization of communication.
- Regularity for simulating data structures.
- We have (only) 3 parameters so far (Small enough?).

Status: Concept

- Went through a few iterations with the concept.
  - Still have not figured out the details of the non-uniform random distribution necessary to generate a power function as temporal distribution (math problem).
  - Are 3 parameters too many already?
- Extending the concept to parallel systems.
  - Details of the random process – homogeneous or inhomogeneous memory-access?
    (Do we access all words the same number or do we allow different access numbers?)
  - Detail of data-mapping – organized or pseudo-random?
    (Do we group frequent accessed words together?)

Status: Benchmark Probe

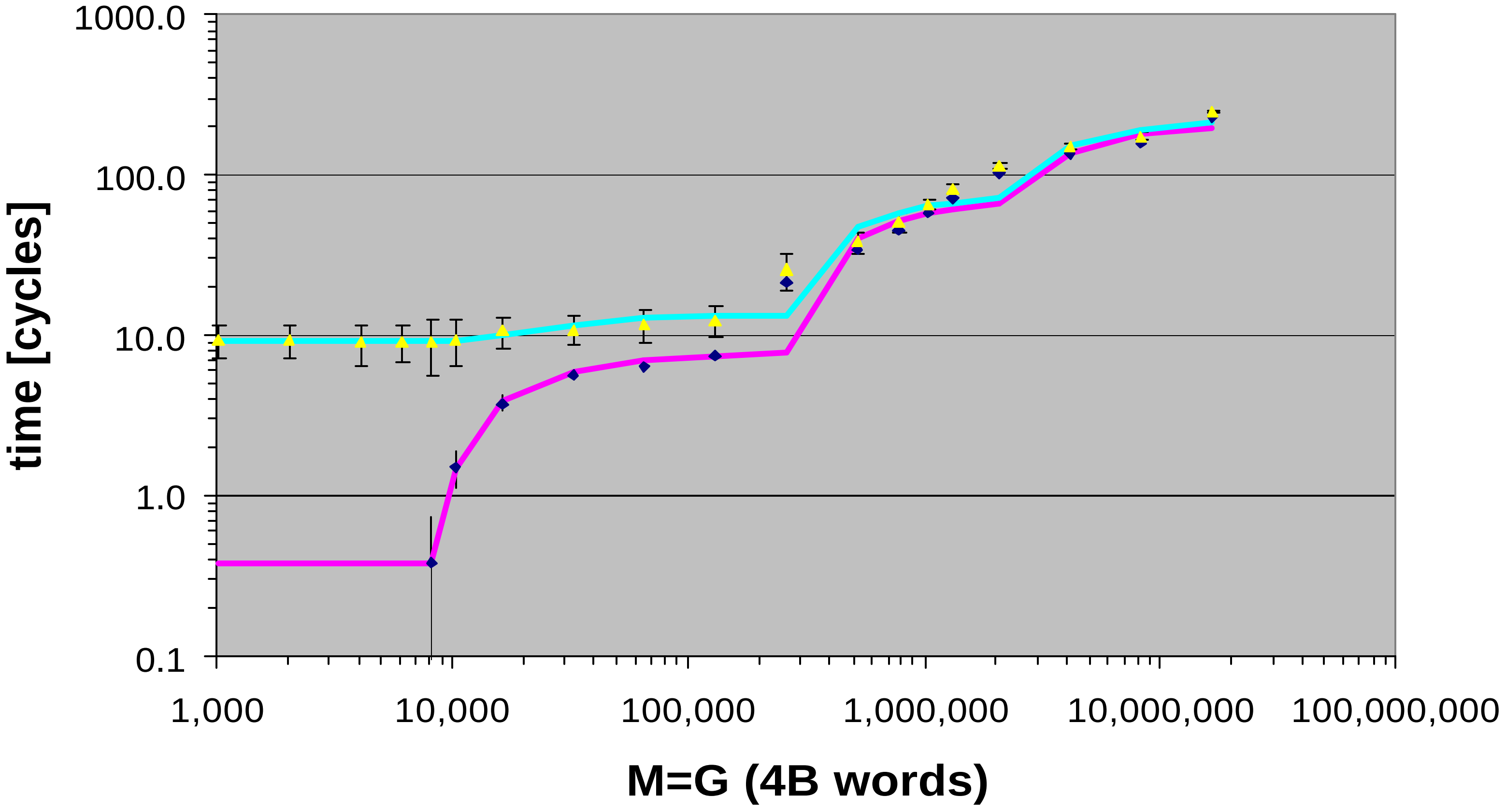
- Implemented several (sequential) test-codes.
  - Which kernel – DAXPY (again)?
  - How many different index vectors?
    - Impacts also data structures and regularity.

Early Kernel

```
for (i = 0+off; i < IdxSize+off+0; i+=8) {
        tmp  += data[ind[i]];
        tmp1 *= data[ind[i+1]];
        …
        …
}
```

Test Results – IBM Power3

R=1; no re-use (k=1)

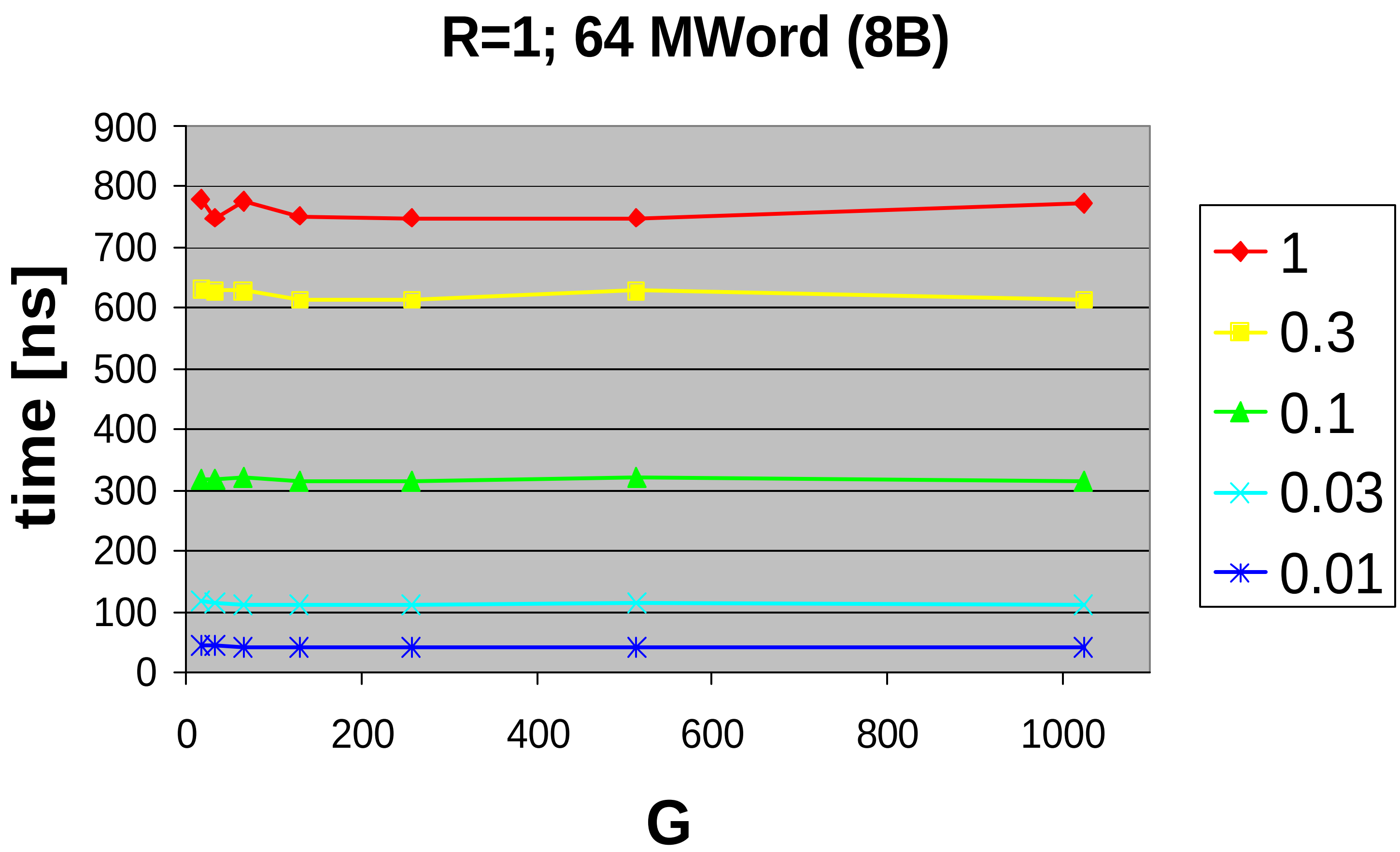


Current Kernel

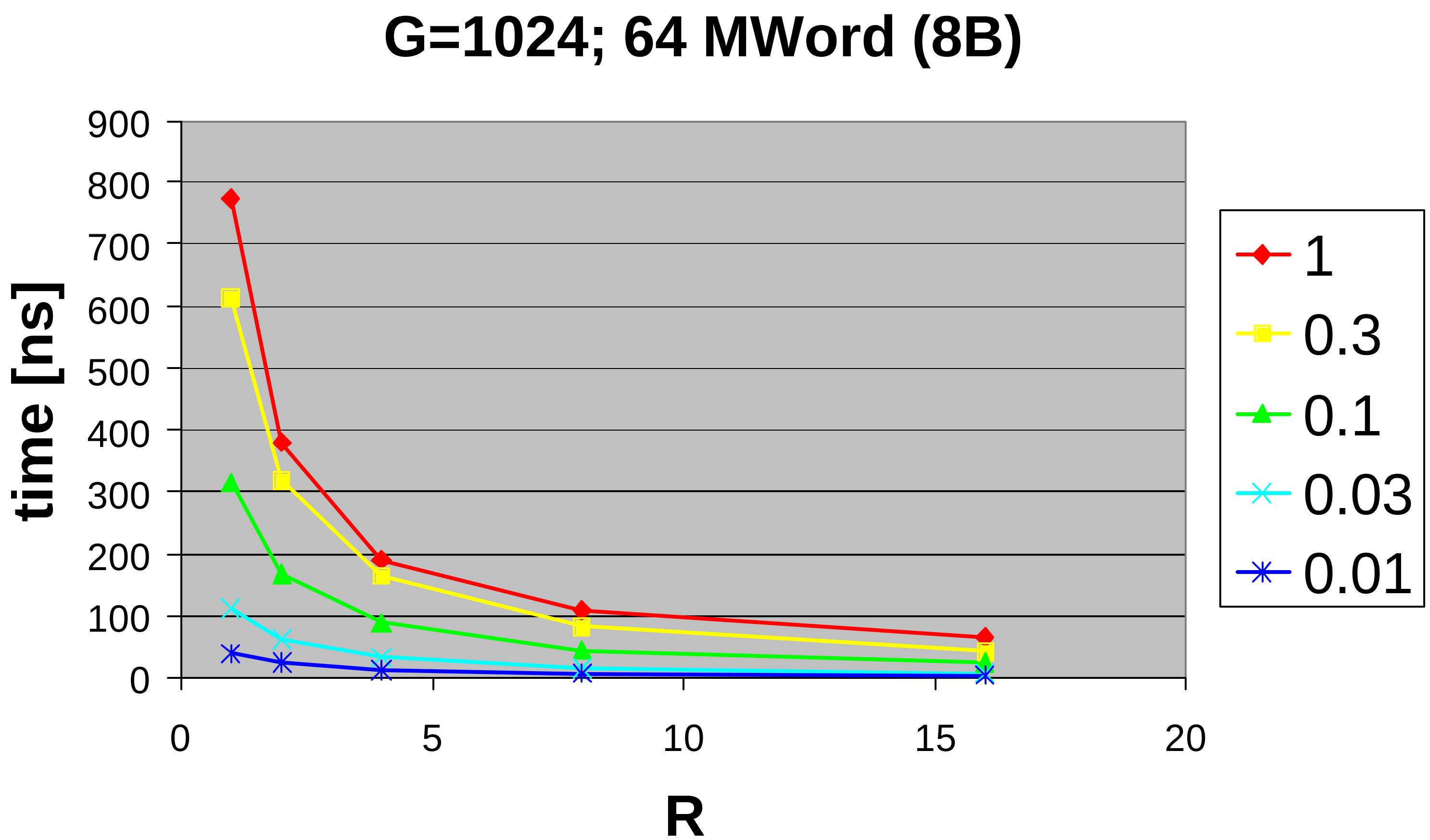
- Distribution: power(random(), 1/A) * (N/R -1);
- if (R == 1) {

```
if (R == 1) {
    for (j = 0; j < G; j++) {
        res[j] += weight[j] * data[ind[j]];
    }
}
else {
    for (j = 0; j < G/R; j++) {
        pos = ind[j] * R;
        for (k = 0; k < R; k++) {                    unroll?
            res[j] += weight[j*R+k] * data[pos + k];
        }
    }
}
```

Test Results – IBM Power3



Test Results – IBM Power3



Future

- Finish concept and benchmarking probe (parallel).
- Determine the re-use factors and granularities for actual codes (with paper and pencil) for making some meaningful choices.
- ‘Fix’ some values for parameters to be used as “The Benchmark”.
- Need to test the correlation between benchmark probe performance and code performance for the same re-use factors, granularities, and regularities.