Performance measurements of computer systems: tools and analysis
Master 2R SL module MD

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1 Introduction, Definitions, Classifications
   - Performance Metric
   - Monitors & Measurements

2 Monitoring Examples
   - Measuring Time: Practical Considerations
   - Sequential Program Execution Monitoring: Profiling
   - “API-based” Monitoring Examples
   - Indirect Metrics
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Metrics are criteria to compare the performances of a system. In general, the metrics are related to speed, accuracy, reliability and availability of services.

The basic characteristics of a computer system that we typically need to measure are:

- a count of how many times an event occurs,
- the duration of some time interval, and
- the size of some parameter.

From these types of measured values, we can derive the actual value that we wish to use to describe the system: the performance metric.
Reliability  A system \(A\) always outperforms a system \(B\) ⇔ the performance metric indicates that \(A\) always outperforms \(B\).

Repeatability  The same value of the metric is measured each time the same experiments is performed.

Consistency  Units of the metrics and its precise definition are the same across different systems and different configurations of the same system.

Linearity  The value of the metric should be linearly proportional to the actual performance of the machine.

Easiness of measurement  If a metric is hard to measure, it is unlikely anyone will actually use it. Moreover it is more likely to be incorrectly determined.

Independence  Metrics should not be defined to favor particular systems.

Many metrics do not fulfill these requirements.
Performance as Time

- Time between the start and the end of an operation
  - Also called running time, elapsed time, wall-clock time, response time, latency, execution time, ...
  - Most straightforward measure: “my program takes 12.5s on a Pentium 3.5GHz”
  - Can be normalized to some reference time
- Must be measured on a “dedicated” machine
Used often so that performance can be independent on the “size” of the application (e.g., compressing a 1MB file takes 1 minute, compressing a 2MB file takes 2 minutes → the performance is the same).

MIPS Millions of instructions / sec = \frac{\text{instruction count}}{\text{execution time} \times 10^6} = \frac{\text{clock rate}}{\text{CPI} \times 10^6}.

But Instructions Set Architectures are not equivalent

- 1 CISC instruction = many RISC instructions
- Programs use different instruction mixes
- May be ok for same program on same architectures

MFlops Millions of floating point operations / sec

- Very popular, but often misleading
- e.g., A high MFlops rate in a stupid algorithm could have poor application performance

Application-specific

- Millions of frames rendered per second
- Millions of amino-acid compared per second
- Millions of HTTP requests served per seconds

Application-specific metrics are often preferable and others may be misleading
Resource vendors always talk about *peak performance* rate

- Computed based on specifications of the machine
- For instance:
  - I build a machine with 2 floating point units
  - Each unit can do an operation in 2 cycles
  - My CPU is at 1GHz
  - Therefore I have a $1 \times 2/2 = 1$GFlops Machine
- Problem:
  - In real code you will never be able to use the two floating point units constantly
  - Data needs to come from memory and cause the floating point units to be idle

Typically, real code achieves only an (often small) fraction of the peak performance
Since many performance metrics turn out to be misleading, people have designed benchmarks.

Example: SPEC Benchmark
- Integer benchmark
- Floating point benchmark

These benchmarks are typically a collection of several codes that come from “real-world software”

The question “what is a good benchmark” is difficult
- A benchmark is representative of a given workload.
- If the benchmarks do not correspond to what you’ll do with the computer, then the benchmark results are not relevant to you.

Other typical benchmarks
- Livermore loops, NAS kernels, LINPACK, …
- SPEC SFS, SPECWeb, …
How About GHz?

- This is often the way in which people say that a computer is better than another
  - More instruction per seconds for higher clock rate
- Faces the same problems as MIPS

<table>
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<tr>
<th>Processor</th>
<th>Clock Rate</th>
<th>SPEC FP2000 Benchmark</th>
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<td>1356</td>
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</table>

- But usable within a specific architecture
1 Introduction, Definitions, Classifications
   • Performance Metric
   • Monitors & Measurements

2 Monitoring Examples
   • Measuring Time: Practical Considerations
   • Sequential Program Execution Monitoring: Profiling
   • “API-based” Monitoring Examples
   • Indirect Metrics
A **Monitor** is a tool to observe the activities on a system. In general, a monitor:

1. makes measurements on the system (**Observation**)
2. collects performance statistics (**Collection**),
3. analyzes the data (**Analysis**),
4. displays results (**Presentation**).

**Why do we want a monitor?**

- A programmer wants to find frequently used segments of a program to optimize them.
- A system administrator wants to measure resource utilization to find performance **bottlenecks**.
- A system administrator wants to tune the system and measure the impact of system parameters modifications on the system performance.
- An analyst wants to characterize the **workload**. Results may be used for capacity planning and for creating test workloads.
- An analyst wants to find **model** parameters, to validate models or to develop inputs for models.
Monitor Terminology

Event  A change in the system state (context switch, seek on a disk, packet arrival, . . . ).

Trace  Log of events usually including the time of the events, their type and other important parameters.

Overhead  Measurement generally induce slight perturbations and consume system resources (CPU, storage, . . . ).

Domain  The set of activities observable by the monitor (CPU time, number of bytes sent on a network card, . . . ).

Input Rate  The maximum frequency of events that a monitor can correctly observe. One generally distinguish between burst rate and sustained rate.

Resolution  Coarseness of the information observed.

Input Width  The number of bits of information recorded on an event.

Portability  Amount of system modifications required to implement the monitor.
The different types of metrics that an analyst may wish to measure can be classified into the following categories:

**Event-count metrics** Simply count the number of times a specific event occurs (e.g., number of page faults, number of disk I/O made by a program).

**Secondary-event metrics** These types of metrics record the values of some secondary parameters whenever a given event occurs (e.g., the average message size).

**Profiles** A profile is an aggregate metric used to characterize the overall behavior of an application program or of an entire system.
Observation is commonly performed with three mechanisms:

**Implicit spying** it is sometimes possible to spy the system without really interfering with it (listening on a local Ethernet bus or in wireless environments). Thus, there is almost no impact on the performance of the system being monitored. Implicit-spying is generally used with filters because many observed data are not interesting.

**Explicit Instrumenting** By incorporating trace points, probe points, hooks or counters, additional information to implicit-spying can be obtained. Some systems offer an API to incorporate such hooks or exports the values of internal counters.

**Probing** Making “feeler” requests on the system to sense its current performance.

Some activities can be observed by only one of the three mechanisms.
Activation Mechanisms

**Event-driven** Record the information whenever a given event occurs. Generally done with counters. The overhead is thus proportional to the frequency of events.

**Tracing** Similar to event-driven strategies, except that parts of the system state are also recorded. This is thus even more time-consuming and also requires much more storage.

**Sampling** Recording of information occurs periodically. The overhead and the resolution of the sampling can thus be adjusted. This strategy produces a statistical summary of the overall behavior of the system. Events that occur infrequently may be completely missed. Results may also be different from one run to the other.

**Indirect** An indirect measurement must be used if the metric that is to be determined is not directly accessible (e.g., for portability reasons or for practical reasons). In this case, one must find another metric that can be measured directly, from which one can deduce or derive the desired performance metric. Generally, a **model** of the system is underlying the deduced metric and the quality of this model is fundamental.
The collection mechanism highly depends on whether we are working on a on-line monitor (system state is displayed during monitoring) or on a batch monitor (system state is stored for later analysis). Most data need to be recorded in buffers, hence buffer management issues:

- buffer size is a function of input rate, input width and emptying rate,
- larger number of buffers allows to cope with variations in filling and emptying rates,
- buffer overflow management and tracking,
- data compression, on-line analysis,

Abnormal events should also be monitored and even handled at higher priority (low probability $\rightarrow$ low overhead, possibility to take preventive action before the system becomes unavailable).
The problem of communication between $m$ collectors and $n$ observers often arises.

We generally resort to hierarchy of collectors/observers for a better scalability. This intensifies all previous buffer management issues.

When collecting data from several observers, clock synchronization often becomes an important issue. The tolerance or maximum allowed clock skew is often related to the round-trip delay. The larger the system, the more problematic clock skews.
This layer is closely tied to the applications for which the monitor is used (performance monitoring, configuration monitoring, fault monitoring, . . .).

- **Presentation frequency** (for on-line monitors).
- **Hierarchical representation/aggregation** (space/time/states/values).
- **Alarm mode** (thresholds, abnormal events).
The system resources consumed by the measurement tool itself as it collects data will strongly affect how much perturbation the tool will cause in the system.

Tracing produces the highest level of perturbation (both CPU and disk are used), in particular on time measurements, spatial and temporal memory access (cache flush, different paging, ...), or on system response time (and thus on workload characterization).

The largest the overhead, the more likely the system behavior will be modified.

Measuring a system alters it

Remain alert to how these perturbations may bias your measurements and, ultimately, the conclusions you are able to draw from your experiments.
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Try to find the main characteristics, advantages and drawbacks of the following monitors.
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Measuring time by hand?

- One possibility would be to do this by just “looking” at a clock, launching the program, “looking” at the clock again when the program terminates.

- This of course has some drawbacks:
  - Poor resolution
  - Requires the user’s attention

- Therefore operating systems provide ways to time programs automatically.

- UNIX provide the `time` command.
The UNIX time Command

- You can put `time` in front of any UNIX command you invoke.
- When the invoked command completes, `time` prints out timing (and other) information.

```
surf:~$ /usr/bin/X11/time ls -la -R ~/ > /dev/null
4.17user 4.34system 2:55.83elapsed 4%CPU
(0avgtext+0avgdata 0maxresident)k
0inputs+0outputs (0major+1344minor)pagefaults 0swaps
```

- 4.17 seconds of user time
- 4.34 seconds of system time
- 2 minutes and 55.85 seconds of wall-clock time
- 4% of CPU was used
- 0+0k memory used (text + data)
- 0 input, 0 output (file system I/O)
- 1344 minor pagefaults and 0 swaps
User, System, Wall-Clock?

- **User Time**: time that the code spends executing user code (i.e., non system calls)

- **System Time**: time that the code spends executing system calls

- **Wall-Clock Time**: time from start to end

Wall-Clock $\geq$ User + System. Why?

- because the process can be suspended by the O/S due to contention for the CPU by other processes
- because the process can be blocked waiting for I/O
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Wall-Clock ≥ User + System. Why?

Because the process can be suspended by the O/S due to contention for the CPU by other processes because the process can be blocked waiting for I/O
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Wall-Clock $\geq$ User + System. Why?

- because the process can be suspended by the O/S due to contention for the CPU by other processes
- because the process can be blocked waiting for I/O
Using time

- It’s interesting to know what the user time and the system time are
  - for instance, if the system time is really high, it may be that the code does to many calls to malloc(), for instance
  - But one would really need more information to fix the code (not always clear which system calls may be responsible for the high system time)
- Wall-clock - system - user $\approx$ I/O + suspended
  - If the system is dedicated, suspended $\approx 0$
  - Therefore one can estimate the cost of I/O
  - If I/O is really high, one may want to look at reducing I/O or doing I/O better
- Therefore, time can give us insight into bottlenecks and gives us wall-clock time
- Measurements should be done on dedicated systems
- time relies on times(2), getrusage(2) and clock(3).
Measuring the performance of a code must be done on a “quiescent”, “unloaded” machine (the machine only runs the standard O/S processes)

The machine must be dedicated
  - No other user can start a process
  - The user measuring the performance only runs the minimum amount of processes (basically, a shell)

Nevertheless, one should always present measurement results as averages over several experiments (because the (small) load imposed by the O/S is not deterministic)
The `time` command has poor resolution
  - “Only” milliseconds
  - Sometimes we want a higher precision, especially if our performance improvements are in the 1-2% range

`time` times the whole code
  - Sometimes we’re only interested in timing some part of the code, for instance the one that we are trying to optimize
  - Sometimes we want to compare the execution time of different sections of the code
Timing with `gettimeofday`

- `gettimeofday` from the standard C library
- Measures the number of microseconds since midnight, Jan 1st 1970, expressed in seconds and microseconds

```c
struct timeval start;
...
gettimeofday(&tv,NULL);
printf("%ld,%ld\n",start.tv_sec, start.tv_usec);
```

- Can be used to time sections of code
  - Call `gettimeofday` at beginning of section
  - Call `gettimeofday` at end of section
  - Compute the time elapsed in microseconds:
    ```c
    (end.tv_sec*1000000.0 + end.tv_usec -
     start.tv_sec*1000000.0 - start.tv_usec) / 1000000.0
    ```
Other Ways to Time Code

- **ntp_gettime()** (Internet RFC 1589)
  - Sort of like `gettimeofday`, but reports estimated error on time measurement
  - Not available for all systems
  - Part of the GNU C Library

- **Java**: `System.currentTimeMillis()`
  - Known to have resolution problems, with resolution higher than 1 millisecond!
  - Solution: use a native interface to a better timer

- **Java**: `System.nanoTime()`
  - Added in J2SE 5.0
  - Probably not accurate at the nanosecond level

- Tons of “high precision timing in Java” on the Web
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A profiler is a tool that monitors the execution of a program and that reports the amount of time spent in different functions.

Useful to identify the expensive functions.

Profiling cycle:
- Compile the code with the profiler
- Run the code
- Identify the most expensive function
- Optimize that function (i.e. call it less often if possible or make it faster)
- Repeat until you can't think of any ways to further optimize the most expensive function.
Using gprof

- Compile your code using gcc with the -pg option
- Run your code until completion
- Then run gprof with your program’s name as single command-line argument
- Example: `gcc -pg prog.c -o prog; ./prog gprof prog > profile_file`
- The output file contains all profiling information (amount and fraction of time spent in which function)
Callgrind is a tool that uses runtime code instrumentation framework of Valgrind for call-graph generation.

Valgrind is a kind of emulator or virtual machine.

- It uses JIT (just-in-time) compilation techniques to translate x86 instructions to simpler form called ucode on which various tools can be executed.
- The ucode processed by the tools is then translated back to the x86 instructions and executed on the host CPU.

This way even shared libraries and dynamically loaded plugins can be analyzed but this kind of approach results with huge slow down (about 50 times for callgrind tool) of analyzed application and big memory consumption.
Data produced by callgrind can be loaded into KCacheGrind tool for browsing the performance results.
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top - 11:05:41 up 3 days, 1:01, 1 user, load average: 0.22, 0.23, 0.38
Tasks: 177 total, 2 running, 166 sleeping, 0 stopped, 9 zombie
Cpu(s): 5.8%us, 1.7%sy, 0.0%nI, 89.9%id, 0.0%wa, 0.0%hi, 2.7%si, 0.0%st
Mem: 1035156k total, 983544k used, 51612k free, 30320k buffers
Swap: 1984016k total, 67020k used, 1916996k free, 365876k cached

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How does top get all these information?

It uses /proc!

kanza: $ ldd ‘which top’
    linux-gate.so.1 libproc-3.2.7.so.5
    libncurses.so libc.so.6
    libdl.so.2 /lib/ld-linux.so.2

/proc is a way for the kernel to provide information about the status of entries in its process table. On systems where /proc is available, there is no need to instrument the kernel or the application to get these information. Measures are always but it doesn’t mean that top does not induce perturbations. Other tools (e.g., gkrellm) rely on the same API.
TCPdump is based on libpcap and enables to dump the traffic on a network card. /proc is rather common but accessing such information requires specific access permissions. Such library does not work on high performance cards such as MyriNet, InfiniBand, ....
The Simple Network Management Protocol (SNMP) is an application layer protocol that facilitates the exchange of management information between network devices. It is part of the Transmission Control Protocol/Internet Protocol (TCP/IP) protocol suite. SNMP enables network administrators to manage network performance, find and solve network problems, and plan for network growth.

Many tools build upon SNMP to gather information on routers.

SNMP can even be used to build maps of the network. However, SNMP requires specific access permissions and is often closed for network security reasons.
An API to access monitoring information is often available but not always...

Even when these monitors are “built-in”, they are generally low-level and building a usable high-level monitoring tool requires a lot of work on:

- Sampling
- Collection
- Analysis and Presentation

When such an API is not available you can:

- either design a low-level monitor if possible,
- to try to evaluate the metric you are interested in another way.
Outline

1 Introduction, Definitions, Classifications
   - Performance Metric
   - Monitors & Measurements

2 Monitoring Examples
   - Measuring Time: Practical Considerations
   - Sequential Program Execution Monitoring: Profiling
   - “API-based” Monitoring Examples
   - Indirect Metrics
ATLAS (Automatically Tuned Linear Algebra Software) is an approach for the automatic generation and optimization of numerical software (BLAS and a subset of the linear algebra routines in the LAPACK library).

To produce such kernels, ATLAS needs to know the number of cache levels, their respective sizes, whether the processor has the ability to perform additions and multiplications at the same time, whether it can make use of vector registers or specific instruction sets (e.g., 3dnow, SSE1, or SSE2 extensions)...

There is no portable API providing such information, therefore ATLAS runs some probes to guess these values.
The Network Weather Service is the de facto standard of the emerging Grid community to monitor the system availability. It provides high-level metrics to help applications and schedulers. It also provides trends thanks to a set of statistical forecasters.

Available CPU share for a new process \( ((\text{system+user})/(\text{total})) \): due to the process priorities and other scheduling tricks, this value is hard to guess from the \(/\text{proc}\) values without actually probing. As probes are intrusive, NWS uses \(/\text{proc}\) values and uses a correcting factor based on regular probes.

Available bandwidth between two hosts: how much bandwidth would get an application using a single standard socket? Active probes are performed.

What about the capacity of network links between two hosts? Pathchar infers the characteristics of links along an Internet path by sending series of probes with varying values of TTL and of size and using statistical analysis.
Peer-to-peer systems:

▶ Having good evaluations of the current number of peers is a crucial problem and an active research domain.
▶ “Probabilistic games” give good results.

Main Issue

All the previous approach rely on a model of the system and on parameters estimation based on the expected model prediction. When the model is incorrect, the estimation is likely to be incorrect as well.
R. K. Jain.  

David J. Lilja.  