Estrutura do tema Avaliação de Desempenho (IA-32)

1. A avaliação de sistemas de computação
2. Técnicas de otimização de código (IM)
3. Técnicas de otimização de *hardware*
4. Técnicas de otimização de código (DM)
5. Outras técnicas de otimização *(cont.)*
6. Medição de tempos

Análise de técnicas de otimização *(s/w)*

- técnicas de otimização de código (indep. máquina)
  - *já visto...*
- técnicas de otimização de código (dep. máquina)
  - dependentes do processador *(já visto...)*
- **outras técnicas de otimização**
  - na compilação: otimizações efectuadas pelo `Gcc`
  - na identificação dos "gargalos" de desempenho
    - *code profiling*
    - uso dum *profiler* para apoio à otimização
    - lei de Amdahl ... *já visto ...*
  - dependentes da hierarquia da memória
    - a localidade espacial e temporal dum program … *já visto ...*
    - influência da *cache* no desempenho … *próximo semestre...*


```
Options That Control Optimization
These options control various sorts of optimizations:
-O
-O1
    Optimize. Optimizing compilation takes somewhat more time, and a lot
    more memory for a large function. (...)
    With -O, the compiler tries to reduce code size and execution time,
    without performing any optimizations that take a great deal of
    compilation time.
-O2
    Optimize even more. GCC performs nearly all supported optimizations
    that do not involve a space-speed tradeoff. (...) this option
    increases both compilation time and the performance of the generated
    code.
    -O2 turns on all optional optimizations except for loop unrolling,
    function inlining, and register renaming.
-O3
    Optimize yet more. -O3 turns on all optimizations specified by -O2 and
    also turns on the -finline-functions and -frename-registers options.
-O0
    Do not optimize.
-Os
    Optimize for size. -Os enables all -O2 optimizations that do not
    typically increase code size. It also performs further optimizations
    designed to reduce code size.
```



```
Otimizações para código com arrays e loops:
-funroll-loops
    Unroll loops whose number of iterations can be determined at
    compile time or upon entry to the loop. -funroll-loops implies
    both -fstrength-reduce and -frerun-cse-after-loop. This option
    makes code larger, and may or may not make it run faster.
-funroll-all-loops
    Unroll all loops, even if their number of iterations is
    uncertain when the loop is entered. This usually makes programs
    run more slowly. -funroll-all-loops implies the same options as
    -funroll-loops,
-fprefetch-loop-arrays
    If supported by the target machine, generate instructions to
    prefetch memory to improve the performance of loops that access
    large arrays.
-fmove-all-movables
    Forces all invariant computations in loops to be moved outside
    the loop.
-freduce-all-givs
    Forces all general-induction variables in loops to be strength-
    reduced.
```

Otimizações para inserção de funções em-linha:

-finline-functions

Integrate all simple functions into their callers. The compiler heuristically decides which functions are simple enough to be worth integrating in this way. If all calls to a given function are integrated, and the function is declared static, then the function is normally not output as assembler code in its own right.

-finline-limit=*n*

By default, gcc limits the size of functions that can be inlined. This flag allows the control of this limit for functions that are explicitly marked as inline (ie marked with the inline keyword ...) *n* is the size of functions that can be inlined in number of pseudo instructions (not counting parameter handling). The default value of *n* is 600. Increasing this value can result in more inlined code at the cost of compilation time and memory consumption. Decreasing usually makes the compilation faster and less code will be inlined (which presumably means slower programs).

Ação

`gcc -O2 -pg prog. -o prog`

`./prog`

- executa como habitual/, mas tb gera o ficheiro `gmon.out`

`gprof prog`

- GNU *profiler*: a partir de `gmon.out` gera informação que caracteriza o perfil do programa

Factos

- calcula (aproximadamente) o tempo gasto em cada função
- método para cálculo do tempo (*mais detalhe adiante*)
  - periodicamente (~ cada 10ms) interrompe o programa
  - determina que função está a ser executada nesse momento
  - incrementa o seu temporizador de um intervalo (por ex., 10ms)
- para cada função mantém ainda um contador (nº de vezes que foi invocada)

Uso do `GProf` em 3 passos:

- **compilar com indicação explícita (-pg)**
  - ex.: análise do `combine1_sum_int` (vector com 10^7 elementos)

    gcc -O2 -pg combine1_sum_int.c -o comb1
- **executar o programa**

    ./comb1
  - vai gerar automaticamente o ficheiro `gmon.out`
- **invocar o GProf para analisar os dados em `gmon.out`**

    gprof comb1.exe [> comb1.txt]
  - análise parcial do ficheiro `comb1.txt` a seguir…

Análise da primeira parte de `comb1.txt`:

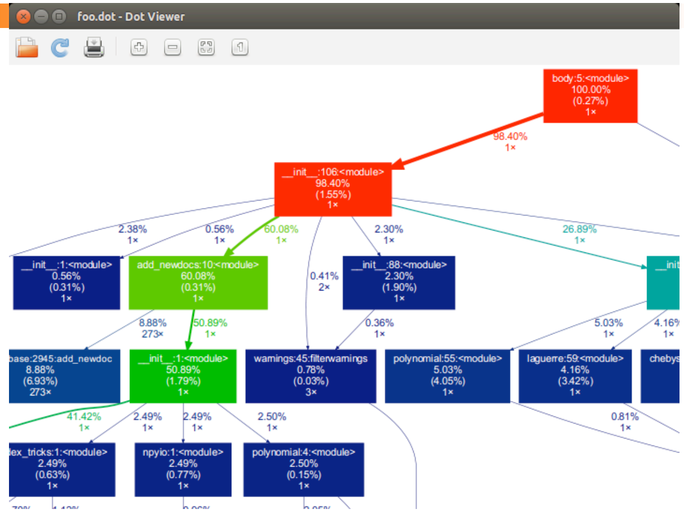
Flat profile:

Each sample counts as 0.01 seconds.

% time	cumulative seconds	self seconds	calls	self s/call	total s/call	name
39.33	2.58	2.58				_mcount
38.57	5.11	2.53	20000000	0.00	0.00	get_vec_element
12.65	5.94	0.83				mcount
6.40	6.36	0.42	2	0.21	1.57	combine1
3.05	6.56	0.20	20000002	0.00	0.00	vec_length
0.00	6.56	0.00	2	0.00	0.00	access_counter
0.00	6.56	0.00	1	0.00	0.00	get_counter
0.00	6.56	0.00	1	0.00	0.00	new_vec
0.00	6.56	0.00	1	0.00	0.00	start_counter

Análise em árvore da execução do prog. (em `comb1.txt`):

```
index  % time    self  children    called          name
                 0.42   2.73         2/2              main [2]
[1]     100.0    0.42   2.73         2             combine1 [1]
                 2.53   0.00 20000000/20000000        get_vec_element [3]
                 0.20   0.00 20000002/20000002        vec_length [4]
-----------------------------------------------
                                                   <spontaneous>
[2]     100.0    0.00   3.15                       main [2]
                 0.42   2.73         2/2              combine1 [1]
                 0.00   0.00         1/1              new_vec [11]
                 0.00   0.00         1/1              start_counter [12]
                 0.00   0.00         1/1              get_counter [10]
-----------------------------------------------
                 2.53   0.00 20000000/20000000        combine1 [1]
[3]      80.3    2.53   0.00  20000000             get_vec_element [3]
-----------------------------------------------
                 0.20   0.00 20000002/20000002        combine1 [1]
[4]       6.3    0.20   0.00  20000002             vec_length [4]
-----------------------------------------------
                 0.00   0.00         1/2              start_counter [12]
                 0.00   0.00         1/2              get_counter [10]
[9]       0.0    0.00   0.00         2             access_counter [9]
...
```

Vantagens

- ajuda a identificar os gargalos de desempenho
- particularmente útil em sistemas complexos com muitos componentes

Limitações

- apenas analisa o desempenho para o conjunto de dados de teste
- a metodologia de medição de tempos é rudimentar
  - apenas usável em programas com tempos de exec > 3 seg

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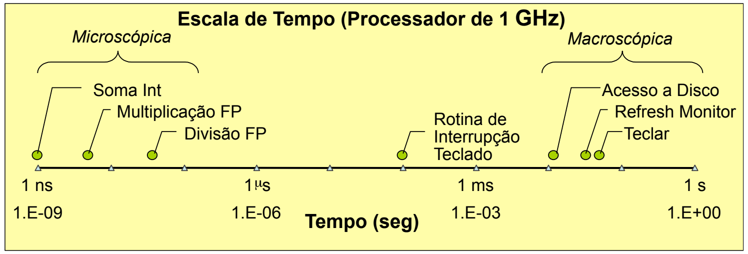
Os slides do tema 6. foram adaptados duma aula do Prof. Bryant

O correr do tempo na perspectiva de um computador

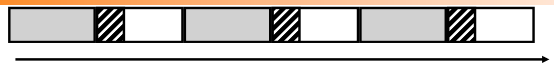


- Escalas fundamentais de tempo:
  - Processador: ~10^{-9} seg.
  - Eventos externos: ~10^{-2} seg.
    - *Keyboard input*
    - *Disk seek*
    - *Screen refresh*
- Implicações
  - pode executar várias instr enquanta espera que ocorram eventos externos
  - pode alternar execução entre código de vários proc sem ser notado

Measurement Challenge

- How Much Time Does Program **X** Require?
  - CPU time
    - How many total seconds are used when executing **X**?
    - Measure used for most applications
    - Small dependence on other system activities
  - Actual ("Wall") Time
  - How many seconds elapse between the start and the completion of X?
  - Depends on system load, I/O times, etc.
- Confounding Factors
  - How does time get measured?
  - Many processes share computing resources
    - Transient effects when switching from one process to another
    - Suddenly, the effects of alternating among processes become noticeable

"Time" on a Computer System



real (wall clock) time

= **user time** *(time executing instructions in the user process)*

= **system time** *(time executing instructions in kernel on behalf of user process)*

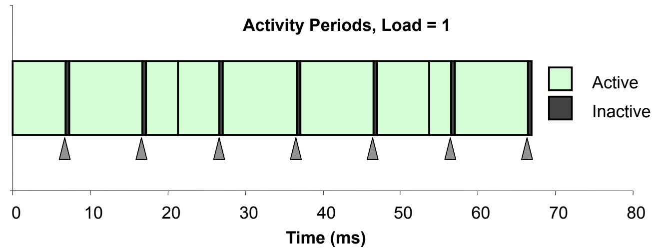
= **some other user's time** *(time executing instructions in different user's process)*

\+ \+ = **real (wall clock) time**

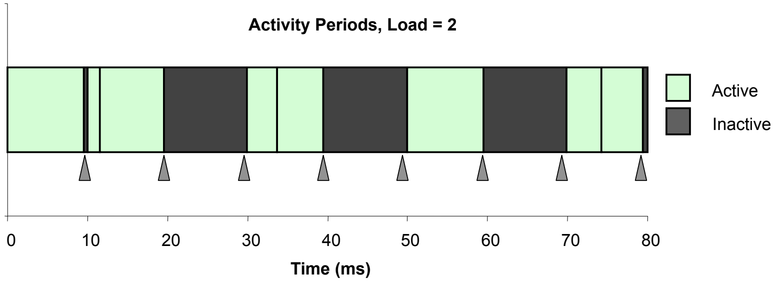
We will use the word "time" to refer to user time.

cumulative user time

Activity Periods: Light Load

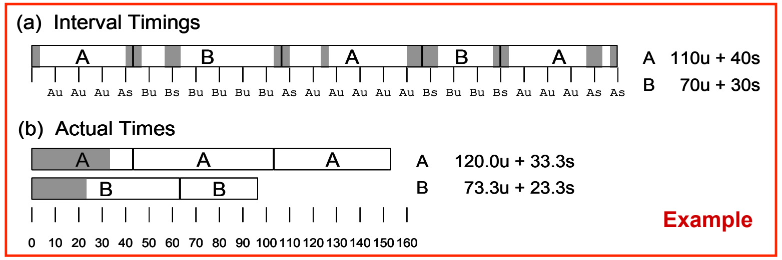


- Most of the time spent executing one process
- Periodic interrupts every 10ms
  - Interval timer
  - Keep system from executing one process to exclusion of others
- Other interrupts
  - Due to I/O activity
- Inactivity periods
  - System time spent processing interrupts
  - ~250,000 clock cycles



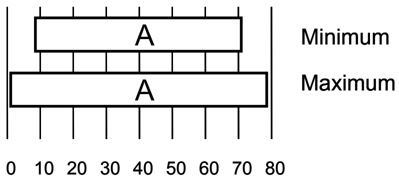
- Sharing processor with one other active process
- From perspective of this process, system appears to be "inactive" for ~50% of the time
  - Other process is executing

- OS Measures Runtimes Using Interval Timer
  - Maintain 2 counts per process
    - User time
    - System time
  - Each time: (i) get timer interrupt, (ii) increment counter for executing process
    - User time if running in user mode
    - System time if running in kernel mode



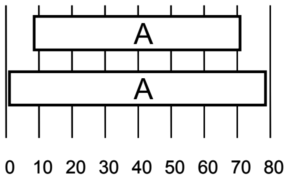

```
time make osevent
gcc -O2 -Wall -g  -march=i486 -c clock.c
gcc -O2 -Wall -g  -march=i486 -c options.c
gcc -O2 -Wall -g  -march=i486 -c load.c
gcc -O2 -Wall -g  -march=i486 -o osevent
osevent.c . . .
0.820u 0.300s 0:01.32 84.8%     0+0k 0+0io 4049pf
+0w
```

- 0.82 seconds user time
  - 82 timer intervals
- 0.30 seconds system time
  - 30 timer intervals
- 1.32 seconds wall time
- 84.8% of total was used running these processes
  - (.82+0.3)/1.32 = .848



- **Computed time = 70ms**
- **Min Actual = 60 + ε**
- **Max Actual = 80 – ε**

- Worst Case Analysis
  - Timer Interval = δ
  - Single process segment measurement can be off by ±δ
  - No bound on error for multiple segments
    - Could consistently underestimate, or consistently overestimate



Minimum

Maximum

- **Computed time = 70ms**
- **Min Actual = 60 + ε**
- **Max Actual = 80 – ε**

- Average Case Analysis
  - Over/underestimates tend to balance out
  - As long as total run time is sufficiently large
    - Min run time ~1 second
    - 100 timer intervals
  - Consistently miss 4% overhead due to timer interrupts

- Most modern systems have built in registers that are incremented every clock cycle
  - Very fine grained
  - Maintained as part of process state
    - In Linux, counts elapsed global time
- Special assembly code instruction to access
- On (recent model) Intel machines:
  - 64 bit counter.
  - RDTSC instruction sets **`%edx`** to high order 32-bits, **`%eax`** to low order 32-bits

- Wrap Around Times for **550 MHz** machine
  - Low order 32 bits wrap around every
    $2^{32} / (550 * 10^6) = 7.8$ seconds
  - High order 64 bits wrap around every
    $2^{64} / (550 * 10^6) = 33539534679$ seconds
    - 1065 years
- For **2 GHz** machine
  - Low order 32-bits every 2.1 seconds
  - High order 64 bits every 293 years

- Idea
  - Get current value of cycle counter
    - store as pair of unsigned's `cyc_hi` and `cyc_lo`
  - Compute something
  - Get new value of cycle counter
  - Perform double precision subtraction to get elapsed cycles

```
/* Keep track of most recent reading of cycle counter */
static unsigned cyc_hi = 0;
static unsigned cyc_lo = 0;

void start_counter()
{
  /* Get current value of cycle counter */
  access_counter(&cyc_hi, &cyc_lo);
}
```

Accessing the Cycle Counter (1)

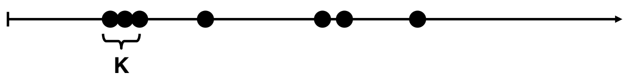
- GCC allows inline assembly code with mechanism for matching registers with program variables
- Code only works on x86 machine compiling with GCC

```
void access_counter(unsigned *hi, unsigned *lo)
{
  /* Get cycle counter */
  asm("rdtsc; movl %%edx,%0; movl %%eax,%1"
      : "=r" (*hi), "=r" (*lo)
      : /* No input */
      : "%edx", "%eax");
}
```

- Issue assembly with `rdtsc` and two `movl` instructions

Multitasking Effects

- Cycle Counter Measures Elapsed Time
  - Keeps accumulating during periods of inactivity
    - System activity
    - Running other processes
- Key Observation
  - Cycle counter never underestimates program run time
  - Possibly overestimates by large amount
- K-Best Measurement Scheme
  - Perform up to N (e.g., 20) measurements of function
  - See if fastest K (e.g., 3) within some relative factor ε (e.g., 0.1%)



Time of Day Clock

- Unix `gettimeofday()` function
- Return elapsed time since reference time (Jan 1, 1970)
- Implementation
  - Uses interval counting on some machines
    - Coarse grained
  - Uses cycle counter on others
    - Fine grained, but significant overhead and only 1 μsec resolution

```
#include <sys/time.h>
#include <unistd.h>

  struct timeval tstart, tfinish;
  double tsecs;
  gettimeofday(&tstart, NULL);
  P();
  gettimeofday(&tfinish, NULL);
  tsecs = (tfinish.tv_sec - tstart.tv_sec) +
      1e6 * (tfinish.tv_usec - tstart.tv_usec);
```


Measurement Summary

- Timing is highly case and system dependent
  - What is <u>overall duration</u> being measured?
    - **> 1 second**: interval counting is OK
    - **<< 1 second**: must use cycle counters
  - On what hardware / OS / OS-version?
    - Accessing counters
      - How `gettimeofday` is implemented
    - Timer interrupt overhead
    - Scheduling policy
- Devising a Measurement Method
  - <u>Long durations</u>: use Unix timing functions
  - <u>Short durations</u>
    - If possible, use `gettimeofday`
    - Otherwise must work with cycle counters
    - K-best scheme most successful