SAPIENZA
UNIVERSITÀ DI ROMA

Input-Sensitive Profiling

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Outline

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   - Drawbacks classical approach
2. Read Memory Size
   - Our approach
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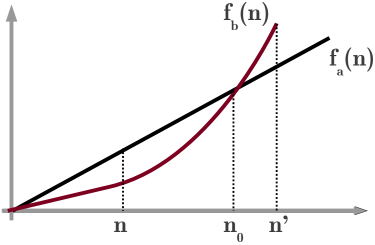
Conventional profilers

Conventional profilers gather **cumulative info** over a whole execution



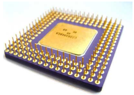
$\Longrightarrow$ No information about how single portions of the code **scale** as a function of **input size**

Drawbacks classical approach

- Often hard to extract portions of code from an application and analyze them separately

- Hard to collect real data about typical usage scenarios to be reproduced in experiments

- Miss cache effects due to interaction with the overall application



Critical algorithmic code should be analyzed within the **actual** context of applications it is deployed in

Our approach

"Input-Sensitive" profiling: aggregating routine times by input sizes

For each routine f, collect a tuple:

$$< n_i, c_i, max_i, min_i, sum_i, q_i >$$

for each distinct value of the input size, where:

- n_i = estimate of an input size
- $c_i = \#$ of times the routine is called on input size n_i
- max_i/min_i = maximum and minimum costs required by any execution of f on input size n_i
- sum_i/q_i = sum of the costs required by the executions of f on input size n_i and the sum of the costs' squares

How to measure input size automatically?

Input size ≈ Read Memory Size

The **read memory size** (RMS) of the execution of a routine f is the number of distinct memory cells first accessed by f, or by a descendant of f in the call tree, with a read operation.

Read Memory Size (Example)

```
void swap(int * a, int * b) {
    int temp = *a;
    *a = *b;
    *b = temp;
}
```

The function `swap` has RMS 2 because it reads (first access) objects `*a` and `*b`, and writes (first access) variable `temp`

Read Memory Size (Example 2)

```
call f
   read x
   write y
   call g
       read x
       read y
       read z
       write w
       return
   read w
   return
```

Fn	Accessed cells (first-read green)	RMS

Read Memory Size (Example 2)

```
→ call f
      read x
      write y
      call g
          read x
          read y
          read z
          write w
          return
      read w
      return
```

Fn	Accessed cells (first-read green)	RMS
f		

Read Memory Size (Example 2)

```
call f
    read x
    write y
    call g
        read x
        read y
        read z
        write w
        return
    read w
    return
```

Fn	Accessed cells (first-read green)	RMS
f	x	

Read Memory Size (Example 2)

```
call f
   read x
   write y
   call g
      read x
      read y
      read z
      write w
      return
   read w
   return
```

Fn	Accessed cells (first-read green)	RMS
f	$\boxed{x}$ y	

Read Memory Size (Example 2)

```
call f
   read x
   write y
   call g
       read x
       read y
       read z
       write w
       return
   read w
   return
```

Fn	Accessed cells (first-read green)	RMS
f	x y	
g		

Read Memory Size (Example 2)

```
call f
    read x
    write y
    call g
        read x
        read y
        read z
        write w
        return
    read w
    return
```

Fn	Accessed cells (first-read green)	RMS
f	x y	
g	x	

Read Memory Size (Example 2)

```
call f
   read x
   write y
   call g
       read x
       read y
       read z
       write w
       return
   read w
   return
```

Fn	Accessed cells (first-read green)	RMS
f	x y	
g	x y	

Read Memory Size (Example 2)

```
call f
    read x
    write y
    call g
        read x
        read y
        read z
        write w
        return
    read w
    return
```

Fn	Accessed cells (first-read green)	RMS
f	$\boxed{x}$ y $\boxed{z}$	
g	$\boxed{x}$ $\boxed{y}$ $\boxed{z}$	

Read Memory Size (Example 2)

```
call f
   read x
   write y
   call g
       read x
       read y
       read z
→      write w
       return
   read w
   return
```

Fn	Accessed cells (first-read green)	RMS
f	x y z w	
g	x y z w	

Read Memory Size (Example 2)

```
call f
    read x
    write y
    call g
        read x
        read y
        read z
        write w
→       return
    read w
    return
```

Fn	Accessed cells (first-read green)				RMS
f	$\boxed{x}$	y	$\boxed{z}$	w	
g	$\boxed{x}$	$\boxed{y}$	$\boxed{z}$	w	3

Read Memory Size (Example 2)

```
call f
    read x
    write y
    call g
        read x
        read y
        read z
        write w
        return
→   read w
    return
```

Fn	Accessed cells (first-read green)	RMS
f	$\boxed{x}$ y $\boxed{z}$ w	
g	$\boxed{x}$ $\boxed{y}$ $\boxed{z}$ w	3

Read Memory Size (Example 2)

```
call f
    read x
    write y
    call g
        read x
        read y
        read z
        write w
        return
    read w
→   return
```

Fn	Accessed cells (first-read green)				RMS
f	$\boxed{x}$	y	$\boxed{z}$	w	2
g	$\boxed{x}$	$\boxed{y}$	$\boxed{z}$	w	3

Case study: wf

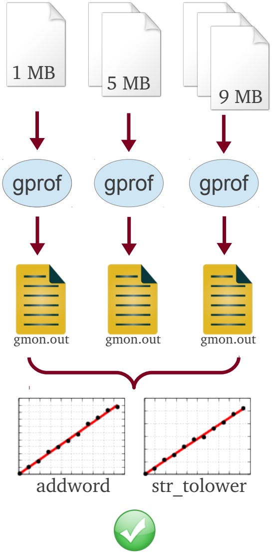
We discuss `wf-0.41`, a simple word frequency counter included in the current development head of Linux Fedora (Fedora 17–Beefy Miracle).

We profile `wf` with:

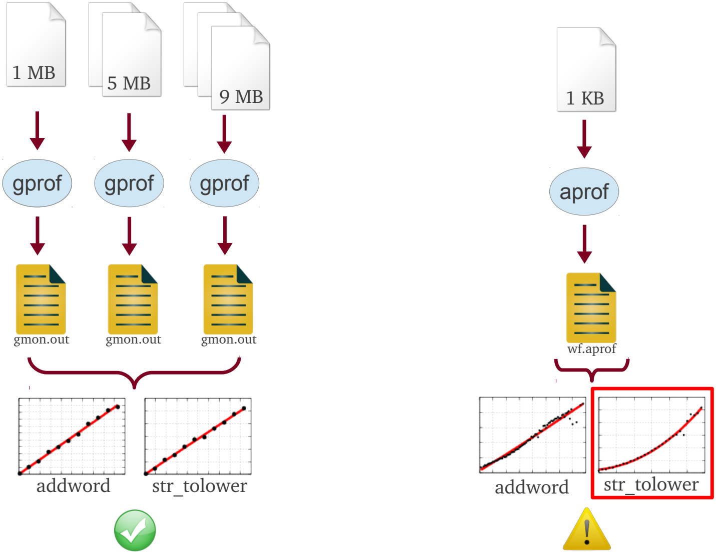
gprof
: a traditional and well-known call graph execution profiler – http://www.gnu.org/software/binutils/

aprof
: our implementation of an input-sensitive profiler – http://code.google.com/p/aprof/

gprof vs aprof



gprof vs aprof



Is there any bottleneck in str_tolower?

```
void str_tolower(char* str) {
    int i;
    for (i = 0; i < strlen(str); i++)
        str[i] = wf_tolower(str[i]);
}
```

Is there any bottleneck in str_tolower?

```
void str_tolower(char* str) {
    int i;
    for (i = 0; i < strlen(str); i++)
        str[i] = wf_tolower(str[i]);
}
```

Is there any bottleneck in str_tolower?

```
void str_tolower(char* str) {
    int i;
    for (i = 0; i < strlen(str); i++)
        str[i] = wf_tolower(str[i]);
}
```

Why did gprof **fail** to reveal the quadratic trend of `str_tolower`?

Short vs long words

Input: Anna Karenina	
52.2%	`addword`
31.3%	`str_tolower`

Input: Protein sequences	
61.8%	`str_tolower`
32.6%	`addword`

- Need to have different workloads for different routines!
- How do we know in advance which routine is a bottleneck?

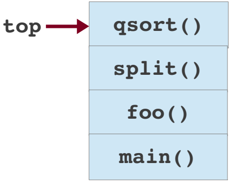
Fixing the code

Loop invariant code motion:

```
void str_tolower(char* str) {
    int i;
    int len = strlen(str);
    for (i = 0; i < len; i++)
        str[i] = wf_tolower(str[i]);
}
```

Improvements:	6%	Anna Karenina
	30%	Protein sequences

Computing RMS (data structures)



Shadow run-time stack S

For each $i \in [0, top]$, the i-th stack entry $S[i]$ stores:

- *rtn*: id of the routine
- *ts*: timestamp assigned to this activation
- *cost*: cumulative cost
- *rms*: *partial read memory size* of the activation

Each memory location w has a timestamp $ts[w]$ which contains the time of the **latest access** to w

Computing RMS (algorithm)

procedure `call`(r):

$top{+}{+}$

$S[top].rtn \leftarrow r$

$S[top].ts \leftarrow count$

$S[top].rms \leftarrow 0$

$S[top].cost \leftarrow \texttt{get\_cost()}$

procedure `return`():

$\texttt{collect}(S[top].rtn,\ S[top].rms,\ \texttt{get\_cost()} - S[top].cost)$

$S[top-1].rms \mathrel{+}= S[top].rms$

$top{-}{-}$

Computing RMS (algorithm)

procedure `read`(w):
    if $ts[w] < S[top].ts$ **then**
        $S[top].rms{+}{+}$
        if $ts[w] \neq 0$ **then**
            let i be the max index in S
            such that $S[i].ts \leq ts[w]$
            $S[i].rms{-}{-}$
        end if
    end if
    $ts[w] \leftarrow count$

procedure `write`(w):
    $ts[w] \leftarrow count$

Computing RMS (example)

```
call f
    read x
    write y
    write z
    call g
        read x
        read y
        read z
        return
    return
```

Step 1:

```
S[0].id = f
S[0].cost = 0
S[0].ts = 1
S[0].rms = 0
```

```
ts[x] = 0
ts[y] = 0
ts[z] = 0
```

Computing RMS (example)

```
call f
    read x
    write y
    write z
    call g
        read x
        read y
        read z
        return
    return
```

Step 2:

```
S[0].id = f
S[0].cost = 0
S[0].ts = 1
S[0].rms = 1

ts[x] = 1
ts[y] = 0
ts[z] = 0
```

Computing RMS (example)

```
call f
    read x
    write y
    write z
    call g
        read x
        read y
        read z
        return
    return
```

Step 3:

```
S[0].id = f
S[0].cost = 0
S[0].ts = 1
S[0].rms = 1

ts[x] = 1
ts[y] = 1
ts[z] = 1
```

Computing RMS (example)

```
call f
    read x
    write y
    write z
    call g
        read x
        read y
        read z
        return
    return
```

Step 4:

```
S[1].id = g
S[1].cost = 4
S[1].ts = 2
S[1].rms = 0
S[0].id = f
S[0].cost = 0
S[0].ts = 1
S[0].rms = 1

ts[x] = 1
ts[y] = 1
ts[z] = 1
```

Computing RMS (example)

```
call f
    read x
    write y
    write z
    call g
        read x
        read y
        read z
        return
    return
```

Step 5:

```
S[1].id = g
S[1].cost = 4
S[1].ts = 2
S[1].rms = 3

S[0].id = f
S[0].cost = 0
S[0].ts = 1
S[0].rms = -2

ts[x] = 2
ts[y] = 2
ts[z] = 2
```

Computing RMS (example)

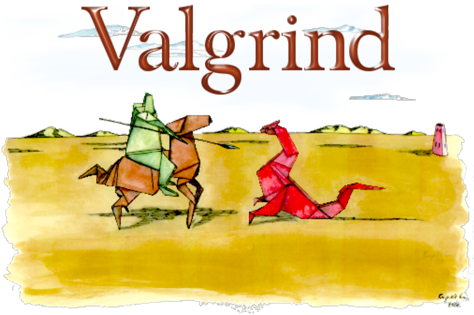
```
call f
    read x
    write y
    write z
    call g
        read x
        read y
        read z
        return
    return
```

Step 6:

```
S[0].id = f
S[0].cost = 0
S[0].ts = 1
S[0].rms = -2 + 3 = 1

ts[x] = 2
ts[y] = 2
ts[z] = 2
```

Implementation

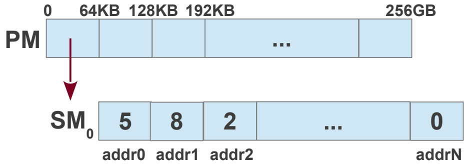


A dynamic instrumentation infrastructure that translates the binary code into an architecture-neutral intermediate representation (`VEX`)

Events	Instrumentation	Data structures
memory accesses	easy	shadow memory
threads	easy	thread state
function calls/returns	hard	shadow stack

Implementation: shadow memory

To maintain the timestamps ts of memory cells needed for computing the RMS values, we shadow each memory location accessed by the program with a 32-bit counter and we use a two-levels lookup table:



Implementation: memory tracing resolution

To reduce the space needed by the lookup table, `aprof` allows it to configure the resolution k of distinct observable memory objects:

- $k = 1$: finest resolution
- $k = 2$: 2-bytes words $\rightarrow$ half of timestamps
- $k = 4$: default, 4-bytes words $\rightarrow$ 1/4 of timestamps!
- ...

$\Longrightarrow$ this can impact the # of distinct `RMS` observed!

SPEC CPU2006 – Time (slowdown)

	memcheck	callgrind-base	callgrind-cache	aprof
CINT	15.7×	46.5×	98.8×	31.8×
CFP	21.3×	20.4×	92.7×	27.9×

`memcheck` does not trace function calls/returns
`callgrind-base` does not trace memory accesses

$\Longrightarrow$ `aprof` delivers comparable perfomance wrt other Valgrind tools
$\Longrightarrow$ single run with `aprof` $\approx$ N runs with `gprof`!

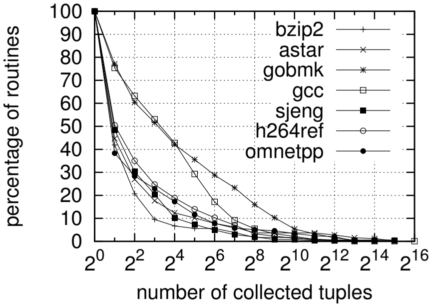
SPEC CPU2006 – Space (overhead)

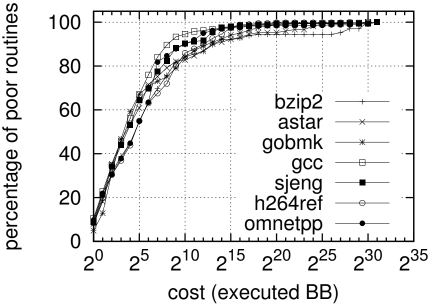
	`memcheck`	`callgrind-base`	`callgrind-cache`	`aprof`
CINT	1.8×	1.3×	1.3×	2.2×
CFP	1.5×	1.3×	1.3×	1.9×

`callgrind-base` does not use a shadow memory
`memcheck` applies different compression schemes

Experimental evaluation

How many performance tuples can be automatically collected for each routine from a ***single run*** of a program on a typical workload?





Demo

Thanks!
Questions?