CSCI 2021: Program Performance Micro-Optimizations

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Logistics

Reading Bryant/O'Hallaron

- Ch 5: Optimization
- Ch 9: Virtual Memory (next)

Assignments

- Lab/HW 12: Code Optimizations
- Lab/HW 13: `mmap()` and Virtual Memory
  - Lab 13 will lead lecture a bit, TAs will introduce the `mmap()` function which is very useful for certain types of I/O
- P4 on the Horizon

Goals

- ~~Permanent Storage~~
- ~~Optimization Overview~~
- Micro-optimizations

Announcements

UMN Kernel Object Symposium

- Wed 19-Apr 6pm in Keller 3-230
- Student presentations on Linux and OS-related topics
- Like what you've done in 2021? Check out UKO
- Food provided if you RSVP:

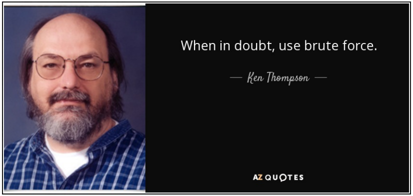
https://z.umn.edu/uko-symposium

Caution: Should I Optimize?

- Optimizing program execution saves CPU time, costs Human time
  - CPU Time: cheap
  - Human Time: expensive
- Determine if there is a NEED to optimize
- **Benchmark** your code - if it is fast enough, move on
- When optimizing, use data/tools to direct Human Effort (benchmarks/profiler)
- **Never sacrifice correctness** for speed

First make it work,
then make it right,
then make it fast.

- ***Kent Beck***

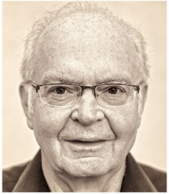


What to Optimize First

In order of impact

1. Algorithms and Data Structure Selection
2. Elimination of unneeded work/hidden costs
3. Memory Utilization
4. **Micro-optimizations**

"Premature optimization is the root of all evil" - Donald Knuth



Programmers waste enormous amounts of time thinking about, or worrying about, the speed of noncritical parts of their programs, and these attempts at efficiency actually have a strong negative impact when debugging and maintenance are considered. We should forget about small efficiencies, say about 97% of the time: *premature optimization is the root of all evil.* **Yet we should not pass up our opportunities in that critical 3%.**

– Donald Knuth

Exercise: Optimize This

- Prema Turopt is tasked by her boss to optimize performance of function `get_min()`
- The current version of the function code looks like the code to the right.
- Prema immediately jumps to the code for `bubble_sort()` and alters the code to enable better processor pipelining.
- This leads to a 2.5% improvement in speed.

```
int get_min(storage_t *st){
  int *arr =
   malloc(sizeof(int)*get_size(st));

  for(int i=0; i<get_size(st); i++){
    arr[i] = get_element(st,i);
  }

  bubble_sort(arr, get_size(st));

  int ans = arr[0];
  free(arr);
  return ans;
}

```

Suggest several alternatives that Prema should have explored

Answers: Optimize This

1. Don't use bubblesort: $O(N^2)$. Use an $O(N \log N)$ sort like Quicksort, Heapsort, Mergesort
2. Why sort at all? Determine the minimum element with the "get" loop.
3. What is the cost of `get_element()` and `get_size()`? Is there a more efficient iterator or array-extraction mechanism?
4. What data structure is used in `storage_t`? If it is already sorted such as a binary search tree or binary heap, there may be a more efficient way to determine the minimum element.

```
int get_min(storage_t *st){
  int *arr =
   malloc(sizeof(int)*get_size(st));

  for(int i=0; i<get_size(st); i++){
    arr[i] = get_element(st,i);
  }

  bubble_sort(arr, get_size(st));

  int ans = arr[0];
  free(arr);
  return ans;
}
```

5. If `get_min()` is called frequently, **cache** the min by adding a field to `storage_t` and modifying other code around it; frequently used strategy such as in Java's `String` class for `hashCode()` to get *O(1)* lookup.

Exercise: Eliminating Unnecessary Work

```
void lower1(char *s) {

  for (long i=0; i < strlen(s); i++){
    if (s[i] >= 'A' && s[i] <= 'Z'){
      s[i] -= ('A' - 'a');
    }
  }
}
```

```
void lower2(char *s) {
  long len = strlen(s);
  for (long i=0; i < len; i++){
    if (s[i] >= 'A' && s[i] <= 'Z'){
      s[i] -= ('A' - 'a');
    }
  }
}
```

- Bryant/O'Hallaron Figure 5.7
- Two versions of a lower-casing function
- Lowercase by subtracting off constant for uppercase characters: alters ASCII code
- Examine them to determine differences
- Project speed differences and **why one will be faster**

Answers: Eliminating Unnecessary Work

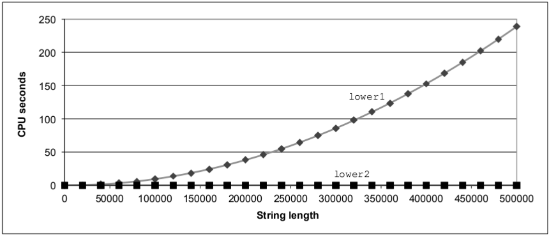
- `strlen()` is $O(N)$: searches for `\0` character in `for()` loop
- Don't loop with it if possible

```
void lower1(char *s) {

  for (long i=0; i < strlen(s); i++){
    if (s[i] >= 'A' && s[i] <= 'Z'){
      s[i] -= ('A' - 'a');
    }
  }
}
```

```
void lower2(char *s) {
  long len = strlen(s);
  for (long i=0; i < len; i++){
    if (s[i] >= 'A' && s[i] <= 'Z'){
      s[i] -= ('A' - 'a');
    }
  }
}
```

```
long strlen(char *s) {
  long len = 0;
  while(s[len] != '\0'){
    len++;
  }
  return len;
}
```



Exercise: Do Memory References Matter?

```
void sum_range1(int start,
                int stop,
                int *ans)
{
  *ans = 0;
  for(int i=start; i<stop; i++){
    *ans += i;
  }

}
```

```
void sum_range2(int start,
                int stop,
                int *ans)
{
  int sum = 0;
  for(int i=start; i<stop; i++){
    sum += i;
  }
  *ans = sum;
}
```

- What is the primary difference between the two routines above?
- What effect if any will this have on runtime?

Answers: Do Memory References Matter?

- `sum_range1()` makes repeated memory references
- `sum_range2()` uses a local variable with only a couple memory references

```
void sum_range1(int start,
                int stop,
                int *ans)
{
  *ans = 0;
  for(int i=start; i<stop; i++){
    *ans += i;  // main mem ref
  }

}
```

```
void sum_range2(int start,
                int stop,
                int *ans)
{
  int sum = 0;   // likely register
  for(int i=start; i<stop; i++){
    sum += i;    // add to register
  }
  *ans = sum;    // one main-mem ref
}
```

Primary difference is repeated access to Main Memory VS Register, this should indicate `sum_range2()` performs better BUT...

Memory References Matter, Compiler May Change Them

```
lila> gcc -Og sum_range.c   # Limit opt
lila> ./a.out 0 1000000000
sum_range1: 1.9126e+00 secs
sum_range2: 2.6942e-01 secs
```

- Minimal optimizations
- Memory reference definitely matters

```
lila> gcc -O1 sum_range.c  # Opt plz!
lila> ./a.out 0 1000000000
sum_range1: 2.8972e-01 secs
sum_range2: 2.7569e-01 secs
```

- Observe code differences between -Og and -O1
- Why is performance improved so much?

```
### Compiled with -Og: limited opt
sum_range1:
  movl     $0, (%rdx)    # init MEMORY
  jmp      .LOOTOP
.BODY:
  addl     %edi, (%rdx) # MEMORY add
  addl     $1, %edi     # in loop
.LOOPTOP:
  cmpl     %esi, %edi
  jl       .BODY
  ret

### Compiled with -O1: some opt
sum_range1:
  cmpl     %esi, %edi
  jge      .END
  movl     $0, %eax     # init REGISTER
.LOOP:
  addl     %edi, %eax   # REGISTER add
  addl     $1, %edi     # in loop
  cmpl     %edi, %esi
  jne      .LOOP
  movl     %eax, (%rdx) # MEMORY write
.END:
  ret
```

Dash-O! Compiler Optimizes for You

- `gcc` can perform many **micro-optimizations**, almost NEVER macro optimizations
- Series of `-OX` options authorize use of various micro-opts
- We will use `-Og` at times to disable many optimizations
  - `-Og`: Optimize debugging: "…offering a reasonable level of optimization while maintaining fast compilation and a good debugging experience."
- Individual optimizations can be enabled and disabled

- `-O` or `-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. As compared to `-O`, this option increases both compilation time and the performance of the generated code.
- `-O3`: Optimize yet more. `-O3` turns on all optimizations specified by -O2 and also…
- `-Ofast`: Disregard strict standards compliance. (!)

Compiler Optimizations

gcc -O or gcc -O1 turns on the following optimization flags:

```
-fauto-inc-dec -fbranch-count-reg -fcombine-stack-adjustments
--fcompare-elim fcprop-registers -fdce -fdefer-pop -fdelayed-branch
--fdse -fforward-propagate fguess-branch-probability -fif-conversion2
--fif-conversion finline-functions-called-once -fipa-pure-const
--fipa-profile -fipa-reference fmerge-constants -fmove-loop-invariants
--freorder-blocks -fshrink-wrap fshrink-wrap-separate
--fsplit-wide-types -fssa-backprop -fssa-phiopt -ftree-bit-ccp
-ftree-ccp -ftree-ch -ftree-coalesce-vars -ftree-copy-prop -ftree-dce
-ftree-dominator-opts -ftree-dse -ftree-forwprop -ftree-fre
--ftree-phiprop -ftree-sink ftree-slsr -ftree-sra -ftree-pta
--ftree-ter -funit-at-a-time
```

- Some combination of these enables `sum_range2()` to fly as fast as `sum_range1()`
- We will look at some "by-hand" versions of these optimizations but **let the compiler optimize for you whenever possible**

Exercise: Loop Unrolling

Have seen copying loop iterations manually *may* lead to speed gains

1. **Why?** Which of the following unrolled versions of `sum_rangeX()` seems fastest?
2. Why the **second loop** in `sum_rangeB()` and `sum_rangeC()`?

```
void sum_rangeA(long stop, long *ans){
  long sum=0, i;
  for(i=0; i<stop; i++){
    sum += i+0;
  }
  *ans = sum;
}

void sum_rangeB(long stop, long *ans){
  long sum = 0, i;
  for(i=0; i<stop-3; i+=3){
    sum += (i+0);
    sum += (i+1);
    sum += (i+2);
  }
  for(; i<stop; i++){
    sum += i;
  }
  *ans = sum;
}

void sum_rangeC(long stop, long *ans){
  long sum0=0, sum1=0, sum2=0, i;
  for(i=0; i<stop-3; i+=3){
    sum0 += (i+0);
    sum1 += (i+1);
    sum2 += (i+2);
  }
  for(; i<stop; i++){
    sum0 += i;
  }
  *ans = sum0 + sum1 + sum2;
}
```

Answers: Loop Unrolling

1. Version C seems most likely to get performance
   - Unrolling of loop and use of `sum1, sum2, sum3`
   - Pipelined processors benefit from more straight-line code, less branch prediction
   - Pipelined / Superscalar features benefit from adding to separate registers: no hazards or data conflicts
2. Second loop is required as unrolled versions go by 3's
   - Arrays with length not divisible by 3 will have some "leftover" elements
   - "Cleanup" loops a few times with increment 1 to add on leftover elements

Loop Unrolling in Practice

Expectations

Version	Notes	Performance
`sum_rangeA()`	Not unrolled	Baseline
`sum_rangeB()`	Unroll x3, same destinations for sum	Less good
`sum_rangeC()`	Unroll x3, different destinations sum add	Expected Best

Actual Performance

```
apollo> gcc -Og unroll.c
apollo> ./a.out 1000000000
sum_rangeA: 1.0698e+00 secs
sum_rangeB: 6.2750e-01 secs
sum_rangeC: 6.2746e-01 secs

phaedrus> ./a.out 1000000000
sum_rangeA: 2.8913e-01 secs
sum_rangeB: 5.3285e-01 secs
sum_rangeC: 2.6774e-01 secs
```

Unrolling is Unpredictable

- Performance Gains vary from one compiler+processor to another
- All unrolling requires **cleanup loops** like those in the B/C versions: add on remaining elements

GCC Options to Unroll

- gcc has options to unroll loops during optimization
- Unrolling has unpredictable performance implications so unrolling is **not enabled** for `-O1, -O2, -O3`
- Can manually enable it with compiler options like `-funroll-loops` to check for performance bumps

```
apollo> gcc -Og unroll.c
## limited compiler opts
apollo> ./a.out 1000000000
sum_rangeA: 1.0698e+00 secs
sum_rangeB: 6.2750e-01 secs
sum_rangeC: 6.2746e-01 secs
```

```
apollo> gcc -O3 unroll.c
## Many opts, no unrolling
apollo> ./a.out 1000000000
sum_rangeA: 9.4124e-01 secs
sum_rangeB: 4.1833e-01 secs
sum_rangeC: 4.1832e-01 secs
```

```
apollo> gcc -Og -funroll-loops unroll.c
## loops unrolled by compiler
apollo> ./a.out 1000000000
sum_rangeA: 7.0386e-01 secs
sum_rangeB: 6.2802e-01 secs
sum_rangeC: 6.2797e-01 secs

apollo> gcc -Og -funroll-loops -fvariable-expansion-in-unroller unroll.c
apollo> ./a.out 1000000000   ## loops unrolled + multiple intermediates used
sum_rangeA: 5.2711e-01 secs
sum_rangeB: 6.2759e-01 secs
sum_rangeC: 6.2750e-01 secs
```

Exercise: Quick Review

1. What's the first thing to consider when optimization seems necessary?
2. What kinds of optimizations would have the biggest impact on performance?
3. What is the smartest way to "implement" micro-optimizations, to get their benefit with minimal effort?

Answers: Quick review

1. What's the first thing to consider when optimization seems necessary?
   A: Is optimization ***really*** *necessary? Or is there something else that would be more worth the effort (e.g. fixing bugs, adding features, improving documentation, etc.)*
2. What kinds of optimizations would have the biggest impact on performance?
   A: From most to least important
   - *Algorithms and Data Structure Selection*
   - *Elimination of unneeded work/hidden costs*
   - *Memory Utilization*
   - *Micro-optimizations (today's lecture)*
3. What is the smartest way to "implement" micro-optimizations, to get their benefit with minimal effort?
   A: Use the compiler to mechanically perform code transforms to achieve micro-optimizations. Using -O2 will produce faster-running code because the compiler is transforming generated assembly instructions from C sources.

Conditional Code and Performance

Consider two examples of adding even numbers in a range

```
// CONDITION version
long sum_evensA(long start, long stop){
  long sum=0;
  for(int i=start; i<stop; i++){
    if((i & 0x01) == 0){
      sum += i;
    }
  }
  return sum;
}
// STRAIGHT-LINE version
long sum_evensB(long start, long stop){
  long sum=0;
  for(int i=start; i<stop; i++){
    int is_odd = i & 0x01;
    int even_mask = is_odd - 1;
    // 0x00000000 for odd
    // 0xFFFFFFFF for even
    sum += even_mask & i;
  }
  return sum;
}
```

Timings for these two are shown below at two levels of optimization.

```
lila> gcc -Og condloop.c
lila> a.out 0 400000000
sum_evensA: 1.1969e+00 secs
sum_evensB: 2.8953e-01 secs
# 4x speedup

lila> gcc -O3 condloop.c
lila> a.out 0 400000000
sum_evensA: 2.3662e-01 secs
sum_evensB: 9.6242e-02 secs
# 2x speedup
```

Message is simple: **eliminate conditionals** whenever possible to improve performance

Exercise: Row Sums with Function v Macro

- How is a macro different from a function call?
- Which of the below codes will run faster and why?

```
int mgets(matrix_t mat,
          int i, int j)
{
  return
    mat.data[i*mat.cols + j];
}
int vsets(vector_t vec,
          int i, int x)
{
  return vec.data[i] = x;
}
void row_sumsA(matrix_t mat,
               vector_t sums)
{
  for(int i=0; i<mat.rows; i++){
    int sum = 0;
    for(int j=0; j<mat.cols; j++){
      sum += mgets(mat,i,j);
    }
    vsets(sums, i, sum);
  }
}
```

```
#define MGET(mat,i,j) \
  ((mat).data[((i)*((mat).cols)) + (j)])
#define VSET(vec,i,x) \
  ((vec).data[(i)] = (x))
void row_sumsB(matrix_t mat,
               vector_t sums)
{
  for(int i=0; i<mat.rows; i++){
    int sum = 0;
    for(int j=0; j<mat.cols; j++){
      sum += MGET(mat,i,j);
    }
    VSET(sums, i, sum);
  }
}
```

Answers: Row Sums with Function v Macro

- `row_sumsA()` uses standard function calls to retrieve elements
- `row_sumsB()` uses **macros** to do the element retrieval
- A macro is a textural expansion done by the **preprocessor**: insert the literal text associated with the macro
- See macro results with

  ```
  gcc -E func_v_macro.c
  ```

  which stops after preprocessor step (early)
- Function calls cost some operations but not many
- Function calls **prevent optimization across boundaries**
- Cannot pipeline effectively when jumping around, using registers for arguments, restoring registers, etc
- Macros can alleviate this but they are a **pain** to write and notoriously buggy
- Better to let the compiler do this for us

Inlining Functions/Procedures

- **Function Inlining** inserts the body of a function where it would have been called
- Turned on fully partially at -O2 and fully at -O3
- Enables other optimizations blocked by function boundaries
- Can only be done if source code (C file) for function is available
- Like loop unrolling, function inlining has trade-offs
  - Enables pipelining
  - More predictable control
  - More register pressure
  - Increased code size

```
val> FILES="func_v_macro.c matvec_util.c"

val> gcc -Og $FILES
val> ./a.out 16000 8000
row_sums_FUNC:   2.8037e-01 secs
row_sums_MACRO:  9.2829e-02 secs

val> gcc -Og -finline-small-functions $FILE
val> ./a.out 16000 8000
row_sums_FUNC:   1.3620e-01 secs
row_sums_MACRO:  1.2969e-01 secs

val> gcc -O3 $FILES
val> ./a.out 16000 8000
row_sums_FUNC:   3.1132e-02 secs
row_sums_MACRO:  3.6975e-02 secs
```

- Inlining typically most effective for for small functions (getters/setters)

Profilers: gprof and Friends

- **Profiler**: a tool that monitors code execution to enable performance optimizations
- gprof is stock on Linux systems, interfaces with gcc
- Compile with profiling options: gcc -pg
- Run code to produce data file
- Examine with gprof
- **Note:** gcc version 6 and 7 contain a bug requiring use of -no-pie option, not a problem on apollo

```
# Compile
# -pg : instrument code for profiling
# -no-pie : bug fix for new-ish gcc's
> gcc -pg -no-pie -g -Og -o unroll unroll.c

> ls
unroll  unroll.c

> ./unroll 1000000000
sum_rangeA: 2.9401e-01 secs
sum_rangeB: 5.3164e-01 secs
sum_rangeC: 2.6574e-01 secs

# gmon.out now created with timing info
> ls
gmon.out  unroll  unroll.c

> file gmon.out
gmon.out: GNU prof performance data

> gprof -b unroll
... output on next slide ...
```

gprof output for unroll

```
> gprof -b unroll
Flat profile:
Each sample counts as 0.01 seconds.
  %   cumulative   self              self     total
 time   seconds   seconds    calls  ms/call  ms/call  name
 50.38      0.54     0.54        1   544.06   544.06  sum_rangeB
 26.12      0.83     0.28        1   282.11   282.11  sum_rangeA
 24.26      1.09     0.26        1   261.95   261.95  sum_rangeC

                        Call graph
index % time    self  children    called     name
[1]    100.0    0.00    1.09                 main [1]
                0.54    0.00       1/1           sum_rangeB [2]
                0.28    0.00       1/1           sum_rangeA [3]
                0.26    0.00       1/1           sum_rangeC [4]
-----------------------------------------------
                0.54    0.00       1/1           main [1]
[2]     50.0    0.54    0.00       1         sum_rangeB [2]
-----------------------------------------------
                0.28    0.00       1/1           main [1]
[3]     25.9    0.28    0.00       1         sum_rangeA [3]
-----------------------------------------------
                0.26    0.00       1/1           main [1]
[4]     24.1    0.26    0.00       1         sum_rangeC [4]
-----------------------------------------------
```

gprof Example: Dictionary Application

```
> ./dictionary < craft-67.txt
... Total time = 0.829561 seconds
> gprof -b dictionary
  %   cumulative   self              self     total
 time   seconds   seconds    calls  ms/call  ms/call  name
 50.07      0.18     0.18        1   180.25   180.25  sort_words
 19.47      0.25     0.07   463016     0.00     0.00  find_ele_rec
 13.91      0.30     0.05  2862749     0.00     0.00  Strlen
  8.34      0.33     0.03   463016     0.00     0.00  lower1
  2.78      0.34     0.01   463017     0.00     0.00  get_token
  2.78      0.35     0.01   463016     0.00     0.00  h_mod
  2.78      0.36     0.01    20451     0.00     0.00  save_string
  0.00      0.36     0.00   463017     0.00     0.00  get_word
  0.00      0.36     0.00   463016     0.00     0.00  insert_string
  0.00      0.36     0.00    20451     0.00     0.00  new_ele
  0.00      0.36     0.00        7     0.00     0.00  add_int_option
  0.00      0.36     0.00        1     0.00     0.00  add_string_option
  0.00      0.36     0.00        1     0.00     0.00  init_token
  0.00      0.36     0.00        1     0.00     0.00  new_table
  0.00      0.36     0.00        1     0.00     0.00  parse_options
  0.00      0.36     0.00        1     0.00     0.00  show_options
  0.00      0.36     0.00        1     0.00   360.50  word_freq
```

gprof Example Cont'd: Dictionary Application

```
> ./dictionary < craft-67.txt     ## After upgrading sort_words() to qsort()
... Total time = 0.624172 seconds
> gprof -b dictionary
  %   cumulative   self              self     total
 time   seconds   seconds    calls  ms/call  ms/call  name
 60.08      0.12     0.12   463016     0.00     0.00  find_ele_rec
 15.02      0.15     0.03  2862749     0.00     0.00  Strlen
 10.01      0.17     0.02   463016     0.00     0.00  lower1
  5.01      0.18     0.01   463017     0.00     0.00  get_token
  5.01      0.19     0.01   463016     0.00     0.00  h_mod
  5.01      0.20     0.01    20451     0.00     0.00  save_string
  0.00      0.20     0.00   463017     0.00     0.00  get_word
  0.00      0.20     0.00   463016     0.00     0.00  insert_string
  0.00      0.20     0.00    20451     0.00     0.00  new_ele
  0.00      0.20     0.00        8     0.00     0.00  match_length
  0.00      0.20     0.00        7     0.00     0.00  add_int_option
  0.00      0.20     0.00        1     0.00     0.00  add_string_option
  0.00      0.20     0.00        1     0.00     0.00  find_option
  0.00      0.20     0.00        1     0.00     0.00  init_token
  0.00      0.20     0.00        1     0.00     0.00  new_table
  0.00      0.20     0.00        1     0.00     0.00  parse_options
  0.00      0.20     0.00        1     0.00     0.00  show_options
  0.00      0.20     0.00        1     0.00     0.00  sort_words ** was 0.18 **
  0.00      0.20     0.00        1     0.00   200.28  word_freq
```

Optional Exercise: Allocation and Hidden Costs

Consider the following **Java** code

```
public class StringUtils{
  public static
  String repString(String str, int reps)
  {
    String result = "";
    for(int i=0; i<reps; i++){
      result = result + str;
    }
    return result;
  }
}
```

- Give a Big-O estimate for the runtime
- Give a Big-O estimate for the memory overhead

Answers: Allocation and Hidden Costs

- Strings are **immutable** in Java (Python, many others)
- Each iteration must
  - **allocate** new memory for a new string sized `result.length + str.length`
  - Copy `result` to the first part
  - Copy `str` to the second part
- Leads to $O(N^2)$ complexity
- Much worse memory usage: as much as $O(N^2)$ wasted memory for garbage collector to clean up

```
public class StringUtils{
  public static
  String repString(String str, int reps)
  {
    String result = "";
    for(int i=0; i<reps; i++){
      result = result + str;
    }
    return result;
  }

  // Efficient version
  public static
  String repString2(String str, int reps)
  {
    StringBuilder result =
      new StringBuilder();
    for(int i=0; i<reps; i++){
      result.append(str);
    }
    return result.toString();
  }

}
```