Code Optimization

First Steps: naives inefficiencies

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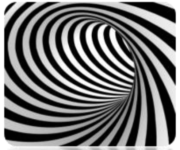
Outline

Avoid the avoidable inefficiencies

Cache & Memory



Loops

Branches

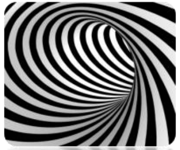
Pipelines

Unleash the Compiler

Outline

Avoid the avoidable inefficiencies

Cache & Memory



Loops

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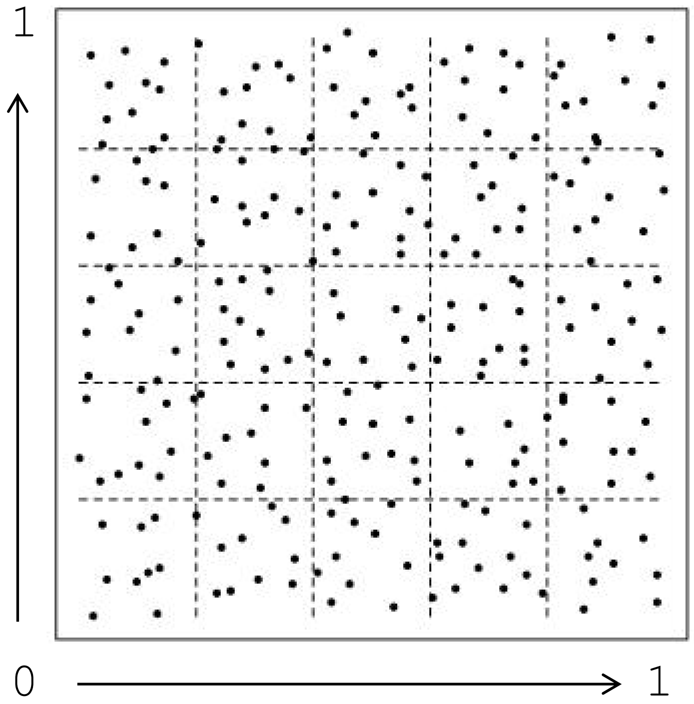
Pipelines

Unleash the Compiler

For the purpose of setting-up an example, let's suppose that

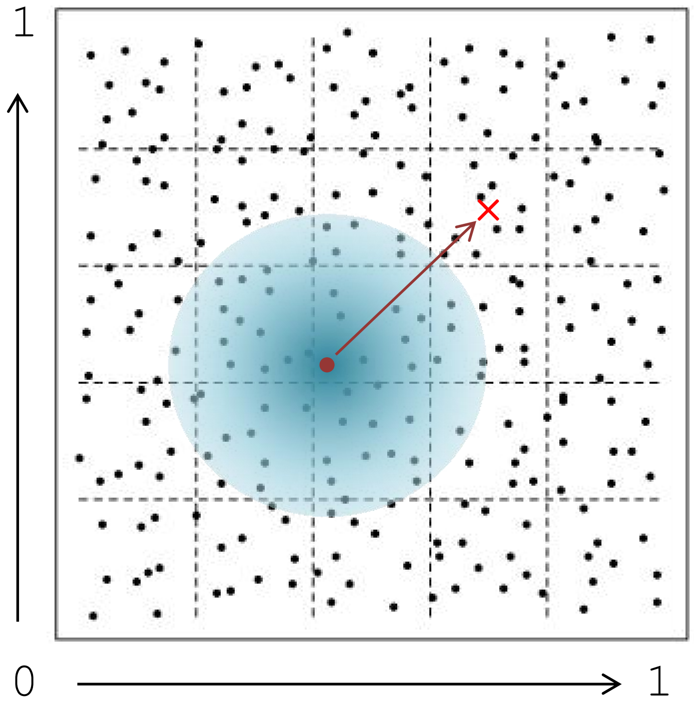
1) we have a distribution of random data points on a 2D plane which we subdivide in sub-regions using a grid.



For the purpose of setting-up an example, let’s suppose that

1) we have a distribution of random data points on a 2D plane which we subdivide in sub-regions using a grid.

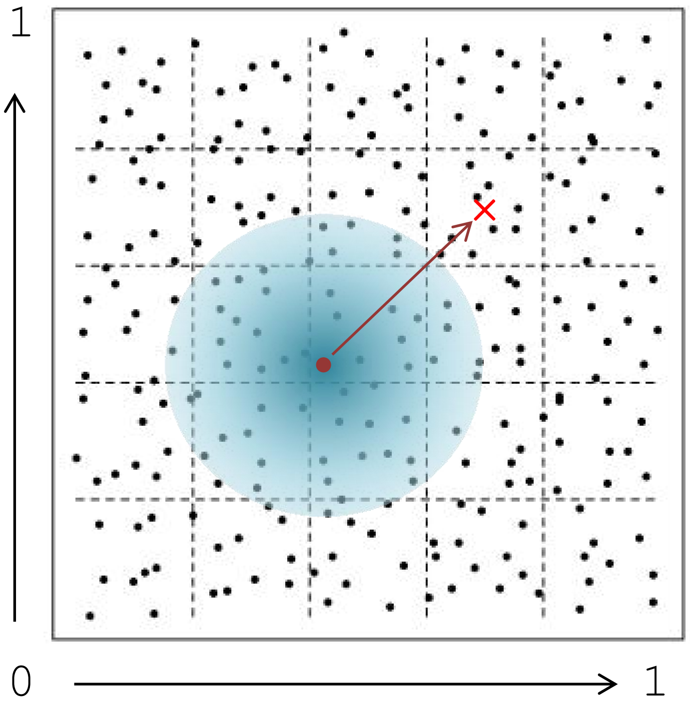
2) for each point *p*, we want to
(i) select all the grid cells whose center is closer to *p* than a given radius *r*;
(ii) perform some operations accordingly to our search result.



For the purpose of setting-up an example, let's suppose that

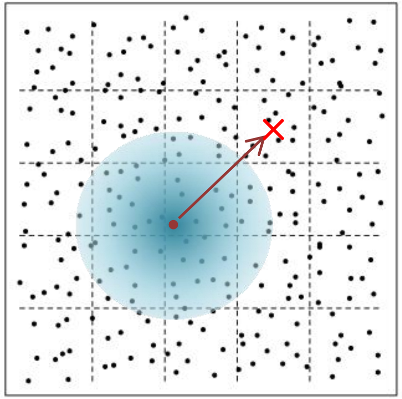
1) we have a distribution of random data points on a 2D plane which we subdivide in sub-regions using a grid.

2) for each point *p*, we want to select all the grid cells whose center is closer to *p* than a given radius *r*, and to perform some operations accordingly to our search result.



We may consider to use a nested loop like this one →

Is there anything you would change?



```
for(p = 0; p < Np; p++)

    for(i = 0; i < Ng; i++)
      for(j = 0; j < Ng; j++)
        for(k = 0; k < Ng; k++)
          {
            dist = sqrt(
                    pow(x[p] - (double)i/Ng - half_size, 2) +
                    pow(y[p] - (double)j/Ng - half_size, 2) +
                    pow(z[p] - (double)k/Ng - half_size, 2));

                if(dist < R)
                  do something;
          }
```

SCO/avoid_the_avoidable/loop.0.c

(1) Avoid expensive function calls

Some function calls are particularly expensive. Those include, among others, **`sqrt()`**, …

Try to avoid them *if possible*.

```
for(p = 0; p < Np; p++)

    for(i = 0; i < Ng; i++)
      for(j = 0; j < Ng; j++)
        for(k = 0; k < Ng; k++)
          {
            dist2 = pow(x[p] - (double)i/Ng - half_size, 2) +
                    pow(y[p] - (double)j/Ng - half_size, 2) +
                    pow(z[p] - (double)k/Ng - half_size, 2));

                    if(dist2 < R2)
                       do something;
          }
```

SCO/avoid_the_avoidable/loop.1.c

(1) Avoid expensive function calls

Some function calls are particularly expensive. Those include, among others, **`sqrt()`**, **`pow()`**, **`floating point division`**, ..
Try to avoid them *if possible*.

```
for(p = 0; p < Np; p++)

    for(i = 0; i < Ng; i++)
      for(j = 0; j < Ng; j++)
        for(k = 0; k < Ng; k++)
          {
            dx = x[p] - (double)i * Ng_inv - half_size;
            dy = y[p] - (double)j * Ng_inv - half_size;
            dz = z[p] - (double)k * Ng_inv - half_size;

            dist2 = dx*dx + dy*dy + dz*dz;
            if(dist2 < R2)
               do something with sqrt(dist2);
          }
```

SCO/avoid_the_avoidable/loop.3.c

(2) *Hoisting* of expressions

```
(double)<i,j,k> * Ng_inv + half_size
```

was performed N^3+N^2+N times, always returning the same values.

Hoisting would save $N(N^2+N^1+1)$ **mul**, **add** and **mem** accesses.

```
for(i = 0; i < Ng; i++) {
    dx2 = x[p] - (double)i * Ng_inv - half_size;
    dx2 = dx2*dx2;

        for(j = 0; j < Ng; j++) {
            dy2 = y[p] - (double)j * Ng_inv - half_size;
            dy2 = dy2*dy2;
            dist2_xy = dx2 + dy2;

            for(k = 0; k < Ng; k++) {
                dz = z[p] - (double)k * Ng_inv - half_size;
                dist2 = dist2_xy + dz*dz;
                if(dist2 < Rmax2)
                    do something with sqrt(dist2);  } } }
```

SCO/avoid_the_avoidable/loop.4.c

(2) *Hoisting* of expressions

You could do even better by pre-computing the relevant values:

```
double ijk[Ng];
for(i = 0; i < Ng; i++)
   ijk[i] = i * Ng_inv - half_size
```

```
for(i = 0; i < Ng; i++) {
   dx2 = x[p] - Ng_inv[i] - half_size;
   dx2 = dx2*dx2;

      for(j = 0; j < Ng; j++) {
         dy2 = y[p] - Ng_inv[j] - half_size;
         dist2_xy = dx2 + dy2*dy2;

         for(k = 0; k < Ng; k++) {
            dz = z[p] - Ng_inv[k] - half_size;
            dist2 = dist2_xy + dz*dz;
            if(dist2 < Rmax2)
               do something with sqrt(dist2);  } } }
```

SCO/avoid_the_avoidable/loop.6.c

(3) Clarify the variables' scope

All these variables are very local, there's no need for them to have a wider scope.

That will help you in writing the code, and *may* help the compiler in optimizing the stack and perhaps the registers usage.

```
for(int i = 0; i < Ng; i++) {
   double dx2 = x[p] - (double)i * Ng_inv - half_size;
   dx2 *= dx2;

      for(j = 0; j < Ng; j++) {
         double dy2 = y[p] - (double)j * Ng_inv - half_size;
         double dist2_xy = dx2 + dy2*dy2;

         for(k = 0; k < Ng; k++) {
            double dz = z[p] - (double)k * Ng_inv - half_size;
            double dist2 = dist2_xy + dz*dz;

            if(dist2 < Rmax2)
               do something with sqrt(dist2);  } } }
```

(4) Suggest what is important

These variables are often calculated and reused subsequently.

Keeping a register dedicated to them may be useful.

Note: *this is a suggestion, the compiler, after analyzing the code, may decide differently*

```
double register Ng_inv = 1.0 / Ng;
for(int i = 0; i < Ng; i++) {
   double dx2 = x[p] - (double)i * Ng_inv - half_size;
   dx2 *= dx2;

      for(j = 0; j < Ng; j++) {
         double dy2 = y[p] - (double)j * Ng_inv - half_size;
         dy2 *= dy2;
         double register dist2_xy = dx2 + dy2;

         for(k = 0; k < Ng; k++) {
            double register dz = z[p] - (double)k * Ng_inv - …;
            double register dist2 = dist2_xy + dz*dz;

            if(dist2 < Rmax2)
               do something with sqrt(dist2);  } } }
```

SCO/avoid_the_avoidable/loop.5.c

| (5) Don’t repeat unnecessary checks

Do you expect any great performance from this code ?

If not, why ?

```
char * find_char_in_string( char *string, char c )
{
    int i = 0;
    while ( i < strlen(string) )
       if( string[i] == c )
         break;
       else
         i++;

    if( i < strlen(string) )
       return &string[i];
    else
       return NULL;
}
```

(5) Don't repeat unnecessary checks

There are several details that dump the performance, i.e. the CPE, of this loop.

The one I want to draw your attention to is the repeated call to the `strlen()` function.

Do you expect the string to change while you are scanning it?
No, but the compiler does not know that and has no way to understand that by code analysis.
Moreover, the memory pointed by string could be modified somewhere else between iterations.

```
char * find_char_in_string( char *string, char c )
{
    int i = 0;
    while ( i < strlen(string) )
       if( string[i] == c )
         break;
       else
         i++;

    if( i < strlen(string) )
       return &string[i];
    else
       return NULL;
}
```

(5) Don't repeat unnecessary checks

This very simple change will save you a lot of CPE

CPE =
Cycles Per Element

```
char * find_char_in_string( char *string, char c )
 {
    int i = 0;
    int len = strlen(string);
    while ( i < len )
       if( string[i] == c )
         break;
       else
         i++;

    if( i < strlen(string) )
       return &string[i];
    else
       return NULL;
 }
```

(5) Don’t repeat unnecessary checks

For a number of reasons, this version is even more efficient than the previous one.

Can you tell why ?

```
char * find_char_in_string( char *string, char c )
 {
    char *pos = string;
    while( ( *pos != ‘\0’ ) && ( *pos != c ) )
       pos++;

    return ( *pos == ‘\0’ ? NULL : pos );
 }
```

(6) Avoid unnecessary memory references

This simple loop for a reduction of an array accumulates the partial results de-referencing the pointer `sum` at each iteration.

```
void reduce_vector( int n, double *array, double *sum )
 {
    for ( int i = 0; i < n; i++ )
         *sum += array[i];
    return;
 }
```

(6) Avoid unnecessary memory references

This simple loop for a reduction of an array accumulates the partial results de-referencing the pointer `sum` multiple times.

(asm obtained with -O1)

```
void reduce_vector( int n, double *array, double *sum )
 {
    for ( int i = 0; i < n; i++ )
          *sum += array[i];
    return;
 }
```

```
.L3:
  movsd xmm0, QWORD PTR [rdx]
  addsd xmm0, QWORD PTR [rax]
  movsd QWORD PTR [rdx], xmm0
  add   rax, 8
  cmp   rax, rcx
  jne   .L3
```

```
movsd   xmm0, value of *sum
addsd   xmm0, value of *array
movsd   address of sum, xmm0
add     rax, 8          ( array++ )
cmp     rax, n
```

(6) Avoid unnecessary memory references

Introducing a separated, local accumulator will save memory accesses

(asm obtained with -O1)

NOTE
Try to get the point..
example simple enough in introductory lectures has the cons that they may be too simple for the compiler
In very simple cases as this one, the compiler is able to do the job for you most of the time.

```
void reduce_vector( int n, double *array, double *sum )
 {
    double cum = 0;
    for ( int i = 0; i < n; i++ ) cum += array[i];
    *sum = cum;
    return;
 }
```

```
.L11:
  addsd xmm0, QWORD PTR [rax]
  add   rax, 8
  cmp   rax, rdx
  jne   .L11
```

```
addsd    xmm0, value of *array
add      rax, 8       (array++)
cmp      rax, rdx     (array with end-of-array)
```

The compiler is smart..

.. but it is also **constrained**.

A compiler is

a program that translates a program from a source-language into an *equivalent* program in a target-language

| CAVEAT !!

Do not suppose that your compiler is *always* able to re-arrange calculations – like avoiding expensive calls or using mathematically-equivalent more convenient expressions – all the time.
It may be able to do that for ***integer*** calculations but it will not do it for ***floating-point*** calculations.

The reason is simple, and it is related to the fact that on a digital system the math is *not* always as it is on the blackboard:

Integer math (+ and ×) in 2's complement
is commutative and associative.

Floating point math (+ and ×) is
commutative between 2 operands
is *never* associatve.

CAVEAT !!

In fact, if you study, as you should, the "what every computer scientist should know about floating-point" paper (find it in the `SCO/materials/` folder on `github`), you discover that if **a**, **b**, and **c** are FP numbers,

$$(a + b) + c \neq a + (b + c)$$

due to the very nature of floating-point representation in a digital system (with a finite number of digits).
The issue is related to the limited number of digits available to represent the number which, in turn, limits the precision.

CAVEAT !!

Let’s suppose that we have 3 digits of precision for the mantissa. For the sake of simplicity, we consider a base 10 (so every single digit ranges in [0..9]).

Then the following hold:

```
1.00 + 0.01  = 1.01
1.00 + 0.001 = 1.00
```

The last is true because, although we can represent 0.001 (it is 1.00 with a -3 exponent) the summation of 1.00 and 0.001 is beyond our precision: 1.001 would require *4* digits. As a consequence, we are not able to distinguish it from 1.00.

CAVEAT !!

Then again:

These sum up to 0.01

```
0.001 +
0.001 +
0.001 +
0.001 +
0.001 +
0.001 +
0.001 +
0.001 +
0.001 +
0.001 +
1.00  =
1.01
```

```
1.00 +
0.001 +
0.001 +
0.001 +
0.001 +
0.001 +
0.001 +
0.001 +
0.001 +
0.001 +
0.001 =
1.00
```

Each of these ops results in 1.00

So, **the compiler is NOT free to reshuffle the order of floating-point operations,**

..even if a mathematically-equivalent formulation, different than the one you coded, would be more performant.

We'll see the impact of that in the next slides.

that’s all, have fun