High-Performance Computing

Getting good performance from your application

Tuning techniques for serial programs on cache-based computer systems

Application Tuning

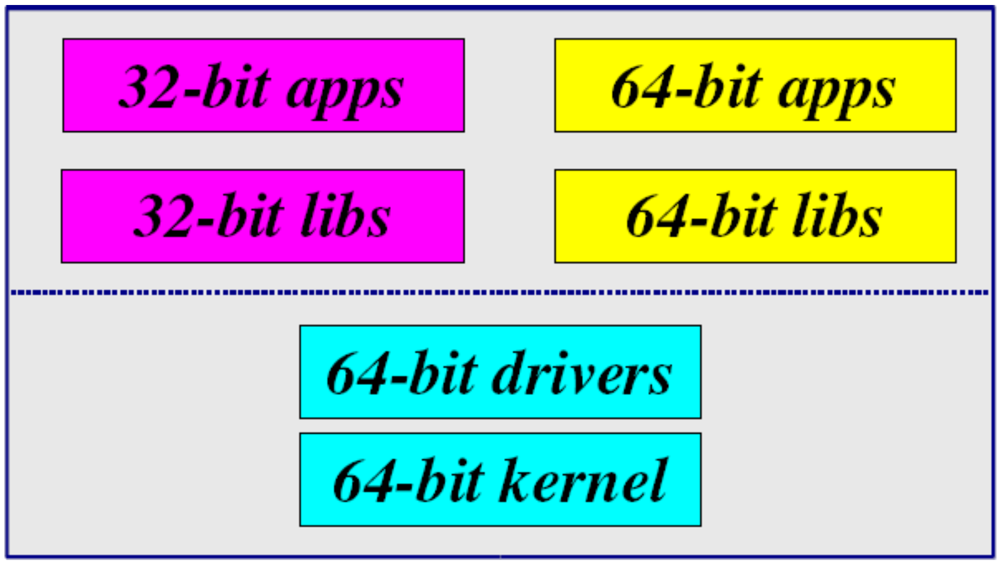
Selected Topics

Application Tuning

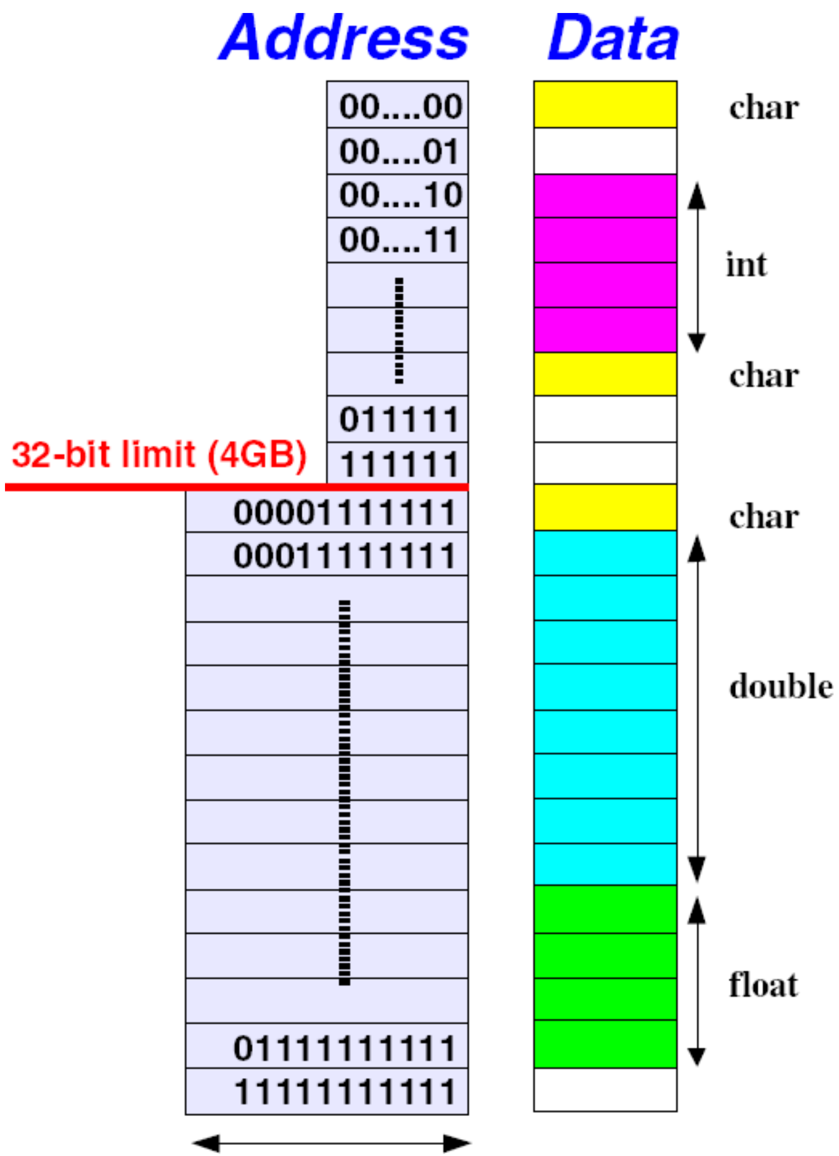
- Selected Topics:
  - 32- vs 64-bit
  - binary data portability
  - floating point numbers and IEEE 754
    - compiler options
  - a case study
- Summary

32-bit vs 64-bit issues

- 64-bit operating systems
- Implication: The address space of a single application can be larger than 4 GB



32-bit vs 64-bit issues



- Addresses ≠ Data
- An 'n'-byte data type fills always n bytes in memory (byte addressable)
- I.e. the next element is n bytes further in memory
- This increment is not related to the size of the addresses (32-bit or 64-bit)

32-bit vs 64-bit issues

C data type	ILP32 (bits)	LP64 (bits)
char	8	same
short	16	same
int	32	same
long	32	64
long long	64	same
pointer	32	64
enum	32	same
float	32	same
double	64	same
long double	128	same

UNIX and Linux support LP64; Windows 64-bit uses LLP64, where long stays 32 bits

(p)ldd and LD_LIBRARY_PATH

How to check which shared-libraries are loaded?

- Static check: use the ldd command
  - `$ ldd executable`
- Dynamic check: use pldd on the PID
  - `$ pldd pid`
  - Solaris only
  - there are scripts available for Linux as well
  - we have installed pldd on the DTU HPC cluster

(p)ldd and LD_LIBRARY_PATH

- How to change the search path for dynamic libraries?
  - Use LD_LIBRARY_PATH – but use it with care!
- Best practice:
  - Compile the path into your application:
    - GCC: -Wl,-rpath <path_to_lib>
    - ld.so will then use this path
  - Avoid LD_LIBRARY_PATH in your shell environment – use a wrapper script for the application
  - Check out this blog note (www.hpc.dtu.dk/?page_id=1180), too!

Binary data storage

- Storing your data in binary format
- Advantages:
  - compact
  - fast
  - no loss of precision
- Drawbacks:
  - not “human readable”
  - data analysis more complicated
  - and ...

Binary data storage

- Example: integer 0x12345678 (hexadecimal)

```
value = 0x12345678;          // 305419896
printf("%d\n", value);
fwrite(&value, sizeof(value), 1, fptr);
```

- Write it ...
  - ... on i386:

```
305419896
Architecture: i386
Value written to endian_i386.dat.
```

  - ... on SPARC:

```
305419896
Architecture: sparc
Value written to endian_sparc.dat.
```

Binary data storage

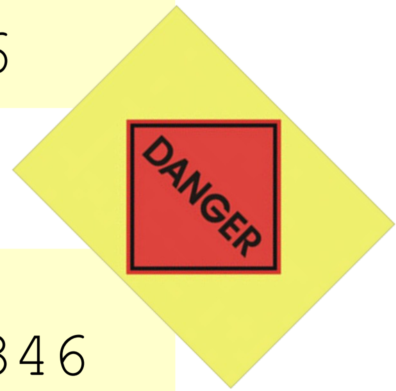
- Read it:

```
fread(&value, sizeof(value), 1, fptr);
printf("%d\n", value);
```

- on i386 data from i386:

```
Architecture: i386
Read from endian_i386.dat: 305419896
```

- on i386 data from SPARC:



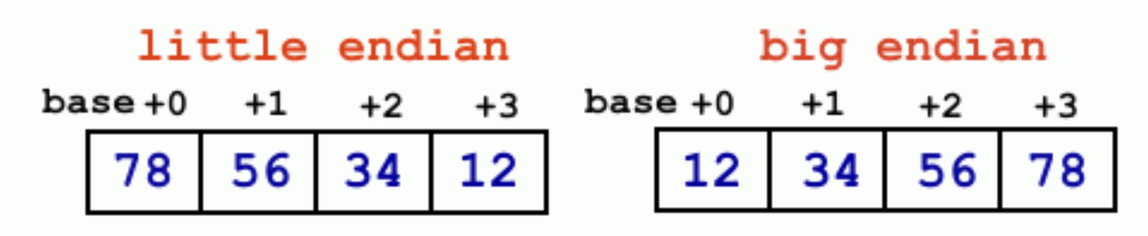

```
Architecture: i386
Read from endian_sparc.dat: 2018915346
```

Little Endian vs Big Endian

- The order in which the bits are interpreted has not been standardized!
- Two 'popular' formats in use
  - Big Endian – SPARC, PowerPC, ...
  - Little Endian – Intel x86, AMD64, ...
- This is an issue when using the same binary data file on both platforms ...

Little Endian vs Big Endian

- Example: integer 0x12345678 (hexadecimal)



- Check with 'od' command:

```
$ od -x endian_sparc.dat
0000000 1234 5678
0000004

$ od -x endian_i386.dat
0000000 7856 3412
0000004
```

Floating point numbers & IEEE 754

Lesser known side effects of IEEE 754:

- Will this code run or fail?

```
#include <stdio.h>
#include <math.h>

int
main(int argc, char *argv[]) {

    double x;

    for(int i = 0; i < 10; i++) {
        x = sqrt(5.0 - i);
        printf("%lf\n", x);
    }
}
```

Floating point numbers & IEEE 754

Lesser known side effects of IEEE 754:

- What do you prefer?

```
$ gcc -otrapex trapex.c -lm
$ ./trapex
2.236068
2.000000
1.732051
1.414214
1.000000
0.000000
-nan
-nan
-nan
-nan
$
```

IEEE 754 compliant!

```
$ suncc -ftrap=common -o trapex
$ ./trapex
2.236068
2.000000
1.732051
1.414214
1.000000
0.000000
Floating point exception
$
```

not(!) IEEE 754 compliant!

Floating point numbers & IEEE 754

Lesser known side effects of IEEE 754:

- The IEEE 754 standard doesn't “allow” traps on floating point exceptions, like invalid arguments, division by zero, over- and underflows
- Some compilers provide options to change that.
  - Studio: -ftrap=<exception_list>, e.g. common
  - Intel: -fp-trap=<exception_list>, e.g. common
- However: GCC has no such option, needs to be implemented by the programmer via library calls (see ‘man fenv’ – and next slide)

Floating point numbers & IEEE 754

Enabling floating point traps with GCC

```
#include <stdio.h>
#include <math.h>

#define __USE_GNU
#include "fenv.h"
void enable_ftraps(void) {
    feenableexcept (FE_DIVBYZERO);
    feenableexcept (FE_INVALID);
    feenableexcept (FE_OVERFLOW); }

int main(int argc, char *argv[]) {
    double x;
    enable_ftraps();
    for(int i = 0; i < 10; i++) {
        x = sqrt(5.0 - i);
        printf("%lf\n", x);
    }
}
```

Floating point numbers & IEEE 754

Now it works with GCC ...

```
$ gcc -o trapex2 trapex2.c -lm
$ ./trapex2
2.236068
2.000000
1.732051
1.414214
1.000000
0.000000
Floating point exception
$
```

not(!)
IEEE 754 compliant!

Floating point numbers & IEEE 754

- Compilers do not re-arrange your arithmetic expressions – unless you ask for it!
- This is part of the optimization flags (and varies from compiler to compiler!)
- Example on the next slides shows this for a division inside a for-loop
  - this is done with an old Studio compiler, but illustrates nicely what happens
  - the optimization option is ‘-fsimple=[0|1|2]’, from none (0) to aggressive arithmetic optimizations (2).

Floating point numbers & IEEE 754

Effects of -fsimple:

- compiled with -fast -xrestrict -fsimple=0:

```
void
divvec(int n, double div, double *a, double *b) {

    int i;

Source loop below has tag L1
L-1 scheduled with steady-state cycle count = 17
L-1 has 1 loads, 1 stores, 2 prefetches, 0 FPadds,
        0 FPmuls, and 1 FPdivs per iteration
    for(i = 0; i < n; i++)
        b[i] = a[i]/div;
}
```

UltraSPARC

Floating point numbers & IEEE 754

Effects of -fsimple:

- compiled with -fast -xrestrict -fsimple=2:

```
void
divvec(int n, double div, double *a, double *b) {

    int i;

Source loop below has tag L1
L-1 scheduled with steady-state cycle count = 1
L-1 unrolled 8 times
L-1 has 1 loads, 1 stores, 4 prefetches, 0 FPadds,
        1 FPmuls, and 0 FPdivs per iteration
    for(i = 0; i < n; i++)
        b[i] = a[i]/div;
}
```

UltraSPARC

A closer look ...

- on x86_64 Linux, we have no compiler that does give us the information we want ... i.e. the number of fpmul and fpdiv
- What now???
- We need some other tools, to get this information.
  - objdump – a Linux tool “to look into” executables
  - objdump has a lot of options – we need just one
    - objdump -S file.o : show disassembly and source intermixed
  - ... but how to interprete the assembly code???

A closer look ...

The really quick guide to x86 assembly

- instructions of interest: double precision floating point multiplication and division
- multiplication: *mul*d
  - mulsd, mulpd, vmulsd, vmulpd
- division: *div*d
  - divsd, divpd, vdivsd, vdivpd
- ‘s’ is for single data, ‘p’ for packed data (vector)
- the leading letter indicates vector type

A closer look ...

compiled with ‘suncc -g -fast -fsimple=0’:

```
$ objdump -S divvec.o | egrep "mul.d|div.d"
  9d:   c5 e3 5e e0             vdivsd %xmm0,%xmm3,%xmm4
  b8:   c5 d3 5e f0             vdivsd %xmm0,%xmm5,%xmm6
  c8:   c5 43 5e c0             vdivsd %xmm0,%xmm7,%xmm8
  d8:   c5 33 5e d0             vdivsd %xmm0,%xmm9,%xmm10
  e8:   c5 23 5e e0             vdivsd
%xmm0,%xmm11,%xmm12
  f8:   c5 13 5e f0             vdivsd
%xmm0,%xmm13,%xmm14
 108:   c5 83 5e c8             vdivsd %xmm0,%xmm15,%xmm1
 118:   c5 eb 5e d8             vdivsd %xmm0,%xmm2,%xmm3
 149:   c5 f3 5e d0             vdivsd %xmm0,%xmm1,%xmm2
 1cf:   c5 35 5e d6             vdivpd %ymm6,%ymm9,%ymm10
 1ed:   c5 25 5e e6             vdivpd
%ymm6,%ymm11,%ymm12
 21a:   c5 45 5e c6             vdivpd %ymm6,%ymm7,%ymm8
 259:   c5 db 5e e8             vdivsd %xmm0,%xmm4,%xmm5
```

- single data and packed: multi-versioning of loop

A closer look ...

compiled with ‘suncc -g -fast -fsimple=2’:

```
$ objdump -S divvec.o | egrep  "mul.d|div.d"
  82:   c5 d3 5e f0           vdivsd %xmm0,%xmm5,%xmm6
  a8:   c5 4b 59 04 06        vmulsd (%rsi,%rax,1),%xmm6,%xmm8
  ba:   c5 4b 59 4c 06 08     vmulsd 0x8(%rsi,%rax,1),%xmm6,%xmm9
  ca:   c5 4b 59 54 06 10     vmulsd 0x10(%rsi,%rax,1),%xmm6,%xmm10
  d6:   c5 4b 59 5c 06 18     vmulsd 0x18(%rsi,%rax,1),%xmm6,%xmm11
  e2:   c5 4b 59 64 06 20     vmulsd 0x20(%rsi,%rax,1),%xmm6,%xmm12
  ee:   c5 4b 59 6c 06 28     vmulsd 0x28(%rsi,%rax,1),%xmm6,%xmm13
  fa:   c5 4b 59 74 06 30     vmulsd 0x30(%rsi,%rax,1),%xmm6,%xmm14
 106:   c5 4b 59 7c 06 38     vmulsd 0x38(%rsi,%rax,1),%xmm6,%xmm15
 130:   c5 cb 59 3c 06        vmulsd (%rsi,%rax,1),%xmm6,%xmm7
 19b:   c4 41 45 5e c8        vdivpd %ymm8,%ymm7,%ymm9
 1cf:   c4 41 1d 59 e9        vmulpd %ymm9,%ymm12,%ymm13
 1ee:   c4 41 0d 59 f9        vmulpd %ymm9,%ymm14,%ymm15
 21a:   c4 41 2d 59 d9        vmulpd %ymm9,%ymm10,%ymm11
 25e:   c5 e3 5e c0           vdivsd %xmm0,%xmm3,%xmm0
 270:   c5 fb 59 24 06        vmulsd (%rsi,%rax,1),%xmm0,%xmm4
```

- ❑ mostly multiplications – it works!

A closer look ...

compiled with ‘suncc -g -fast -fsimple=2’

- ... and using the ‘restrict’ keyword:

```
$ objdump -S divvec.o | egrep  "mul.d|div.d"
  7d:   c4 41 35 5e da          vdivpd %ymm10,%ymm9,%ymm11
  af:   c4 41 0d 59 fb          vmulpd %ymm11,%ymm14,%ymm15
  ce:   c4 c1 75 59 d3          vmulpd %ymm11,%ymm1,%ymm2
  fa:   c4 41 1d 59 eb          vmulpd %ymm11,%ymm12,%ymm13
 140:   c5 db 5e e8             vdivsd %xmm0,%xmm4,%xmm5
 150:   c4 a1 53 59 34 0e       vmulsd (%rsi,%r9,1),%xmm5,%xmm6
```

- mostly multiplications – it works!
- the multi-versioning is gone – only the vectorized code (and a clean-up loop) left!

A closer look ... now with GCC

- -O3 does not enable math optimizations, like replacing a division with a constant by a multiplication with the inverse
- to enable this, we need -ffast-math option
- to get some optimization information (at compile time), we can use -fopt-info

A closer look ... now with GCC

compiled with ‘gcc -g -O3 -fopt-info’

```
 $ gcc  -g -O3  -fopt-info -c divvec.c
divvec.c:11:5: optimized: loop vectorized using 16 byte
vectors
divvec.c:11:5: optimized:  loop versioned for vectorization
because of possible aliasing
```

```
 $ objdump -S divvec.o | egrep  "mul.d|div.d"
  35:   66 0f 5e c8             divpd  %xmm0,%xmm1
  55:   f2 0f 5e c2             divsd  %xmm2,%xmm0
  70:   f2 0f 5e c2             divsd  %xmm2,%xmm0
```

- GCC does multi-versioning, too!
- no multiplications – only divisions!

A closer look ... now with GCC

compiled with 'gcc -g -O3 -ffast-math -fopt-info'

```
 $ gcc  -g -O3 -ffast-math -fopt-info -c divvec.c
divvec.c:11:5: optimized: loop vectorized using 16 byte
vectors
divvec.c:11:5: optimized:  loop versioned for vectorization
because of possible aliasing
```

```
 $ objdump -S divvec.o | egrep  "mul.d|div.d"
  1e:   f2 0f 5e c1             divsd  %xmm1,%xmm0
  45:   66 0f 59 ca             mulpd  %xmm2,%xmm1
  60:   f2 0f 59 04 c6          mulsd  (%rsi,%rax,8),%xmm0
  80:   f2 0f 59 c8             mulsd  %xmm0,%xmm1
```

- GCC does multi-versioning, too!
- mostly multiplications – it works!

Application Tuning

Application Tuning

A closer look ... now with GCC

compiled with ‘gcc -g -O3 -ffast-math -fopt-info’

- ... and using the ‘restrict’ keyword

```
 $ gcc  -g -O3 -ffast-math -fopt-info -c divvec.c
divvec.c:11:5: optimized: loop vectorized using 16 byte
vectors
```

```
 $ objdump -S divvec.o | egrep  "mul.d|div.d"
  10:   f2 0f 5e c1             divsd  %xmm1,%xmm0
  35:   66 0f 59 ca             mulpd  %xmm2,%xmm1
  52:   f2 0f 59 04 c6          mulsd  (%rsi,%rax,8),%xmm0
```

- multi-versioning is gone!
- less instructions than with the suncc compiler!?!

A closer look ... now with GCC

GCC does not unroll loops with -O3!

- we need to add -funroll-loops, too!

```
gcc -g -O3 -ffast-math -funroll-loops -fopt-info -c divvec.c
divvec.c:11:5: optimized: loop vectorized using 16 byte
vectors
divvec.c:11:16: optimized: loop unrolled 7 times
```

```
 $ objdump -S divvec.o | egrep  "mul.d|div.d" | grep -c mulpd
  15
```

- now we have more mulpd instructions (14 more from loop unrolling)
- Lesson learned: check what ‘-O3’ does!
  - Reminder: ‘gcc -g -Q --help=optimizers ...’

A closer look ... summary

- Even with no compiler commentary, we can still get useful information, using
  - extra compiler options like -fopt-info (gcc)
  - tools like objdump – plus some basic knowledge about assembly code
- Caveat: this kind of analysis is feasible on small code kernels, only!
- Best practice: extract a small kernel from larger application, do the tests/tuning (- and reinsert).

Summary

- You have now heard about
  - tuning techniques
  - tools: compilers, analysis tools
  - libraries (see extra slide deck – self study)
  - other performance parameters
  - debuggers: try Totalview
- Now you have to apply that and get experience!
- But never forget:

Correct code has the highest priority – not speed!