# Single Node Optimisation Optimising with the Compiler





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#### Introduction



- Unless we write assembly code, we are always using a compiler.
- Modern compilers are (quite) good at optimisation
  - memory optimisations are an exception
- Usually much better to get the compiler to do the optimisation.
  - avoids machine-specific coding
  - compilers break codes much less often than humans
- Even modifying code can be thought of as "helping the compiler".



# **Compiler flags**



- Typical compiler has hundreds of flags/options.
  - most are never used
  - many are not related to optimisation
- Most compilers have flags for different levels of general optimisation.
  -O1, -O2, -O3,....
- When first porting code, switch optimisation off.
  - only when you are satisfied that the code works, turn optimisation on, and test again.
  - but don't forget to use them!
  - also don't forget to turn off debugging, bounds checking and profiling flags...



# Compiler flags (cont.)



- Note that highest levels of optimisation may
  - break your code.
  - give different answers, by bending standards.
  - make your code go slower.
- Always read documentation carefully.
- Isolate routines and flags which cause the problem.
  - binary chop
  - one routine per file may help



# Compiler flags (cont.)



- Many compilers are designed for an instruction set architecture, not one machine.
  - flags to target ISA versions, processor versions, cache configurations
  - defaults may not be optimal, especially if cross-compiling
- Some optimisation flags may not be part of -On
  - check documentation
  - use sparingly (may only be beneficial in some cases)



# Compiler hints



- A mechanism for giving additional information to the compiler, e.g.
  - values of variables (e.g. loop trip counts)
  - independence of loop iterations
  - independence of index array elements
  - aliasing properties
- Appear as comments (Fortran), or pre-processor pragmas (C)
  - don't affect portability



## Incremental compilation



- Compilers can only work with the limited information available to them.
- Most compilers compile code in an incremental fashion
  - Each source file is compiled independently of each other.
    - Most compilers ignore all source files other than those specified on the command line (or implicitly referenced via search paths, e.g. include files)
  - Routines from other source files treated as "black-boxes"
    - Make worst case assumptions based on routine prototype.
- You can help by providing more information
  - Information in routine prototypes
    - INTENT, PURE, const, etc.
  - Compiler hints
  - Command line flags



# Code modification



- When flags and hints don't solve the problem, we will have to resort to code modification.
- Be aware that this may
  - introduce bugs.
  - make the code harder to read/maintain.
  - only be effective on certain architectures and compiler versions.
- Try to think about
  - what optimisation the compiler is failing to do
  - what additional information can be provided to compiler
  - how can rewriting help





- How can we work out what the compiler has done?
  - eyeball assembly code
  - use diagnostics flags
- Increasingly difficult to work out what actually occurred in the processor.
  - superscalar, out-of-order, speculative execution
- Can estimate expected performance
  - count flops, load/stores, estimate cache misses
  - compare actual performance with expectations



## Locals and globals



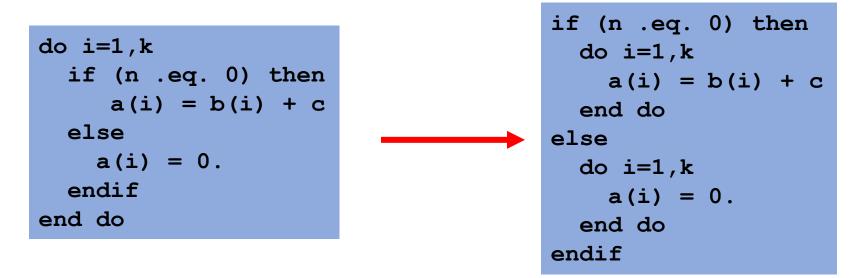
- Compiler analysis is more effective with local variables
- Has to make worst case assumptions about global variables
- Globals could be modified by any called procedure (or by another thread).
- Use local variables where possible
- Automatic variables are stack allocated: allocation is essentially free.
- In C, use file scope globals in preference to externals



#### Conditionals



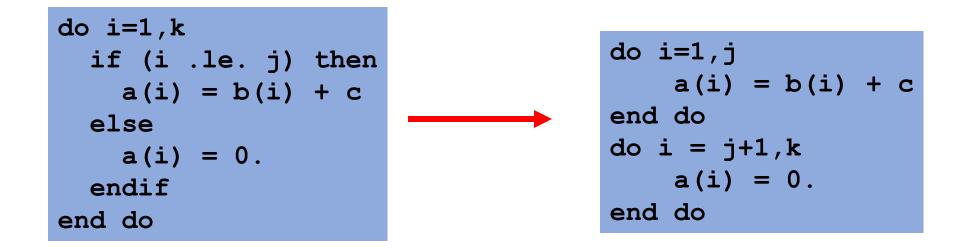
- Even with sophisticated branch prediction hardware, branches are bad for performance.
- Try to avoid branches in innermost loops.
  - if you can't eliminate them, at least try to get them out of the critical loops.





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• A little harder for the compiler.....





#### Data types



- Performance can be affected by choice of data types
  - often a difference between 32-bit and 64-bit arithmetic (integer and floating point).
  - complicated by trade-offs with memory usage and cache hit rates
- Avoid unnecessary type conversions
  - e.g. int to long, float to double
  - N.B. some type conversions are implicit
  - However sometimes better than the alternative e.g.
    - Use DP reduction variable rather than increase array precision.







- Compilers are generally good at Common Subexpression Elimination.
- A couple of cases where they might have trouble:

Different order of operands

$$d = a + c$$
  
 $e = a + b + c$ 

Function calls

$$d = a + func(c)$$
  
 $e = b + func(c)$ 



# CSE including function calls.



- To extract a CSE containing a function call the compiler has to be sure of various things:
  - The function always returns the same value for the same input.
  - The function does not cause any side effects that would be effected by changing the number of times the function is called:
    - Modifying its inputs.
    - Changing global data.
- Need to be very careful with function prototypes to allow compiler to know this.



#### **Register use**



- Most compilers make a reasonable job of register allocation.
  - But only limited number available.

- Can have problems in some cases:
  - loops with large numbers of temporary variables
  - such loops may be produced by inlining or unrolling
  - array elements with complex index expressions
  - can help compiler by introducing explicit scalar temporaries, most compilers will use a register for an explicit scalar in preference to an implicit CSE.



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```
tmp = c[0];
for (i=0;i<n;i++) {
    b[i] += a[c[i]];
    c[i+1] = 2*i;
}
tmp = c[0];
for (i=0;i<n;i++) {
    b[i] += a[tmp];
    tmp = 2*i;
    c[i+1] = tmp;
}
```



# Spilling



- If compiler runs out of registers it will generate spill code.
  - store a value and then reload it later on
- Examine your source code and count how many loads/stores are required
- Compare with assembly code
- May need to distribute loops



# Loop unrolling



- Loop unrolling and software pipelining are two of the most important optimisations for scientific codes on modern RISC processors.
- Compilers generally good at this.
- If compiler fails, usually better to try and remove the impediment, rather than unroll by hand.
  - cleaner, more portable, better performance
- Compiler has to determine independence of iterations



# Loop unrolling



- Loops with small bodies generate small basic blocks of assembly code
  - lot of dependencies between instructions
  - high branch frequency
  - little scope for good instruction scheduling
- Loop unrolling is a technique for increasing the size of the loop body
  - gives more scope for better schedules
  - reduces branch frequency
  - make more independent instructions available for multiple issue.



# Loop unrolling

- Replace loop body by multiple copies of the body
- Modify loop control
  - take care of arbitrary loop bounds
- Number of copies is called unroll factor





- Remember that this is in fact done by the compiler at the IR or assembly code level.
- If the loop iterations are independent, then we end up with a larger basic block with relatively few dependencies, and more scope for scheduling.
  - also reduce no. of compare and branch instructions
- Choice of unroll factor is important (usually 2,4,8)
  - if factor is too large, can run out of registers
- Cannot unroll loops with complex flow control
  - hard to generate code to jump out of the unrolled version at the right place



# Outer loop unrolling



- If we have a loop nest, then it is possible to unroll one of the outer loops instead of the innermost one.
- Can improve locality.

do i=1,n
 do j=1,m
 a(i,j)=c\*d(j)
 end do
end do

2 loads for 1 flop

5 loads for 4 flops



#### Variable expansion

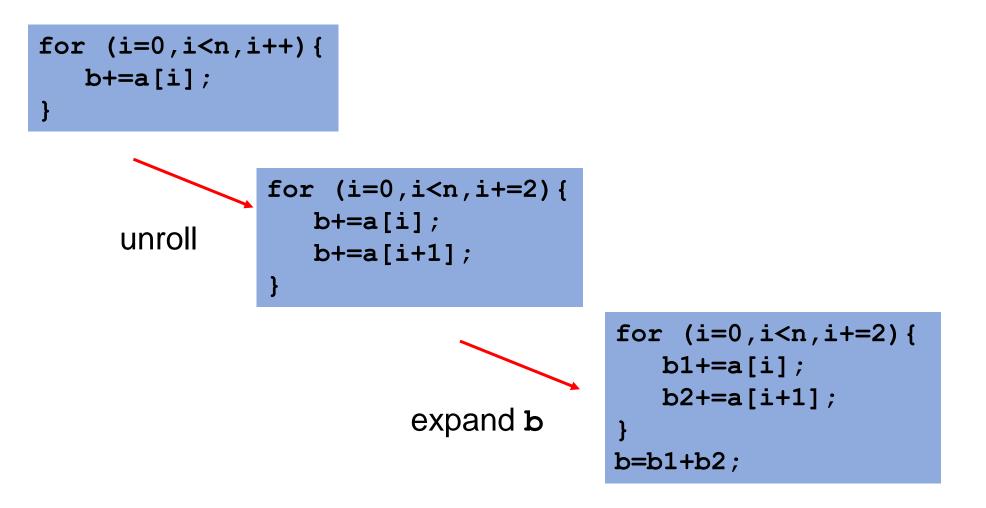


- Variable expansion can help break dependencies in unrolled loops
  - improves scheduling opportunities

• Close connection to reduction variables in parallel loops



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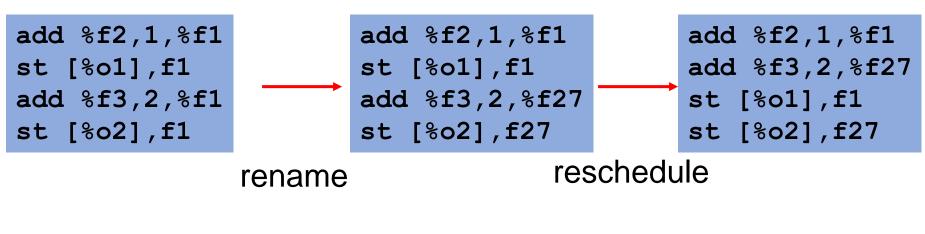




## **Register renaming**



- Registers may be reused within a basic block introducing unnecessary dependencies.
- Using two (or more) different registers can preserve program correctness, but allow more scheduling flexibility
  - Some CPUs perform register rename and reschedule in hardware, this can utilise additional registers not visible to compiler.





# Software pipelining



- Problem with scheduling small loop bodies is that there are dependencies between instructions in the basic block.
- Potentially possible to start executing instructions from the next iteration before current one is finished.
- Idea of software pipelining is to construct a basic block that contains instructions from different loop iterations.
  - fewer dependencies between instructions in block
  - needs additional code at start and end of loop



### Software pipelining

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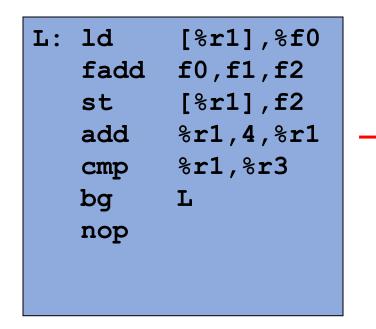
# for (i=0;i<n;i++) { a(i) += b; }</pre>

<pre>for (i=0;i<n;i++) pre="" {<=""></n;i++)></pre>			
t1 = a(i);	//L i		
t2 = b + t1;	//A i		
a(i) = t2;	//S i		
}			

//epilogue a(n-2) = t2; //S n-2 t2 = b + t1; //A n-1 a(n-1) = t2; //S n-1



#### Instruction level



st must wait for fadd
to complete: pipeline stall
for data hazard

	ld	[%r1],%f0
	fadd	f0,f1,f2
	ld	[%r1+4],%f0
L:	st	[%r1],f2
	fadd	f0,f1,f2
	ld	[%r1+8],%f0
	cmp	%r1,%r3-8
	bg	L
	add	%r1,4,%r1
	st	[% <b>r1],f2</b>
	add	%r1,4,%r1
	fadd	f0,f1,f2
	st	[%r1],f2



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# Impediments to unrolling

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- Function calls
  - except in presence of good interprocedural analysis and inlining
- Conditionals
  - especially control transfer out of the loop
  - lose most of the benefit anyway as they break up the basic block.
- Pointer/array aliasing
  - compiler can't be sure different values don't overlap in memory



#### Example



```
for (i=0;i<ip;i++) {
    a[indx[i]] += c[i] * a[ip];
}</pre>
```

- Compiler doesn't know that a[indx[i]] and a[ip] don't overlap
- Could try hints
  - tell compiler that indx is a permutation
  - tell compiler that it is OK to unroll
- Or could rewrite: tmp = a[ip];

```
tmp = a[ip];
for (i=0;i<ip;i++){
    a[indx[i]] += c[i] * tmp;
}
```



# Inlining

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- Compilers very variable in their abilities
- Hand inlining possible
  - very ugly (slightly less so if done via pre-processor macros)
  - causes code replication
- Compiler has to know where the source of candidate routines is.
  - sometimes done by compiler flags
  - easier for routines in the same file
  - try compiling multiple files at the same time
- Very important for OO code
  - OO design encourages methods with very small bodies
  - inline keyword in C++ can be used as a hint



## Multiple Optimisation steps



- Sometimes multiple optimisation steps are required.
  - Multiple levels of in-lining.
  - In-lining followed by loop un-rolling followed by CSE.
- The compiler may not be able to perform all steps at the same time
  - You may be able to help the compiler by performing some of the steps by hand.
  - Look for the least damaging code change that allows the compiler to complete the rest of the necessary changes.
  - Ideally try each step in isolation before attempting to combine handoptimisations.



# **General Cray Compiler Flags**

- Optimisation Options
  - -02
  - -03
  - -O ipaN (ftn) or -hipaN (cc/CC)
- Create listing files with optimization info
  - -ra (ftn) or -hlist=a (cc/CC) optimization info
  - -rm (ftn) or -hlist=m (cc/CC) loopmark information
- Parallelization Options
  - -O omp (ftn) or -h omp (cc/CC) [default]
  - -O threadN (ftn) or
  - -h threadN (cc/CC) N=0-3 [default N=2]

➔ More info: man crayftn, man craycc, man crayCC

optimal flags [enabled by default] aggressive optimization

inlining, N=0-5 [default N=3]

creates a listing file with all

produces a source listing with

Recognize OpenMP directives

control the compilation and optimization of OpenMP directives,



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# **Recommended CCE Compilation Options**

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- Use default optimization levels
  - It's the equivalent of most other compilers -O3 or -fast
  - It is also our most thoroughly tested configuration
- Use -O3,fp3 (or -O3 -hfp3, or some variation) if the application runs cleanly with these options
  - -O3 only gives you slightly more than the default -O2
  - Cray also test this thoroughly
  - -hfp3 gives you a lot more floating point optimization (default is -hfp2)
- If an application is intolerant of floating point reordering, try a lower -hfp number
  - Try -hfp1 first, only -hfp0 if absolutely necessary (-hfp4 is the maximum)
  - Might be needed for tests that require strict IEEE conformance
  - Or applications that have 'validated' results from a different compiler
- Do not use too aggressive optimizations , e.g. -hfp4
  - Higher numbers are not always correlated with better performance



## OpenMP



- OpenMP is ON by default
  - This is the opposite default behavior that you get from GNU and AMD compilers
  - Optimizations controlled by -OthreadN (ftn) or -hthreadN (cc/CC), N=0-3 [default N=2]
  - To shut off use -O/-h thread0 or -xomp (ftn) or -hnoomp
- Autothreading is NOT on by default
  - -hautothread to turn on
  - Interacts with OpenMP directives
- If you do not want to use OpenMP and have OMP directives in the code, make sure to shut off OpenMP at compile time



## CCE – GNU – AMD compilers



- More or less all optimizations and features provided by CCE are available in AMD and GNU compilers
  - GNU compiler serves a wide range of users & needs
    - Default compiler with Linux, some people only test with GNU
    - GNU defaults are conservative (e.g. -O1)
      - -O3 includes vectorization and most inlining
    - Performance users set additional options
  - AMD compiler is typically more aggressive in the optimizations
    - AMD defaults are more aggressive (e.g -O2), to give better performance "out-of-the-box"
      - Includes vectorization; some loop transformations such as unrolling; inlining within source file
    - Options to scale back optimizations for better floating-point reproducibility, easier debugging, etc.
    - Additional options for optimizations less sure to benefit all applications
  - **CCE is even more aggressive** in the optimizations by default
    - Better inlining and vectorization
    - Aggressive floating-point optimizations
    - OpenMP enabled by default
- GNU users probably have to specify higher optimisation levels



## Cray, AMD and GNU compiler flags



Feature	Cray	AMD	GNU
Listing	-hlist=a	-ast-view	-fdump-tree-all
Free format (ftn)	-f free	-Mfreeform	-ffree-form
Vectorization	By default at -O1 and above	By default at –O1 or above	By default at -O3 or using -ftree-vectorize
Inter-Procedural Optimization	-hwp –hpl=tmp		-flto (note: link-time optimization)
Floating-point optimizations	-hfpN, N=04	-ffast-math -ffp- contract=fast	-f[no-]fast-math or -funsafe-math-optimizations
Suggested Optimization	(default)	(default)	-O2 -mavx -ftree-vectorize -ffast-math -funroll-loops
Aggressive Optimization	-O3 -hfp3	-Ofast	-Ofast -funroll-loops
OpenMP recognition	(default)	-fopenmp	-fopenmp
Variables size (ftn)	-s real64 -s integer64	-r8, -fdefault-real-8	-freal-4-real-8 -finteger-4-integer-8







- Remember compiler is always there.
- Try to help compiler, rather than do its job for it.
- Use flags and hints as much as possible
- Minimise code modifications

