Introduction to High Performance Computing

April 15, 2019

1 Syllabus

This calendar is subject to change. Anything posted in the future is certainly tentative. Also, anything posted in the recent past may not be correct if I haven't updated it yet.

1.1 Week 1

1. **Von Neumann Architecture (VNA)**	Tue April 23, 2019

- Motivation for using the ULM (Ulm's Lecture Machine) as reference model.
- Representation of unsigned integer numbers as decimal, binary and hexadecimal numerals.
- Components: RAM, Data bus, CPU.
- Von Neumann Cycle: How machine code gets executed.
- Short excerpt of the ULM instruction set (Machine code).

2. **VNA: Conditional Jumps and Integer Arithmetic**	Fri April 26, 2019

- Assembly language for the ULM.
- Connection to C:
  - pointers and (referenced) values.
  - variable types.
- Signed integer (two's complement).
- Arithmetic logical unit (ALU) and its status flags.
- Conditional jumps in machine/assembly code

1.2 Week 2

3. **VNA: Control Structures**	Tue April 30, 2019

- Macros for assembly code
- Example: Stack
- Control structures (if-then-else, for-loops, while-loops)

4. **VNA: Function Calls**	Fr May 3, 2019

- Functions and procedures:
  - Passing parameters (call by value, call by reference).
  - Returning from call.
  - Local and global variables.
- Memory layout of a process: Text segment, data segment, stack and heap.
- Layout of a program file.
- Concept of a linker.

1.3 Week 3

5. **Introduction to C (C99)**	Tue May 7, 2019

- How to describe the syntax of a programming language
- Tools for creating a executable program:
  - Preprocessor
  - Tokenizer
  - Parser
  - Assembler
  - Linker
- Differences and similarities between ULM and actual computers:
  - Virtual memory
  - Processes
  - Program loader

6. **C99: Control Statements and Functions**	Fr May 10, 2019

- Types and variables
- C control statements: if-then statements and loops.
- Special variable types: Pointers
- Functions

1.4 Week 4

7. **C99: Arrays, Memory Allocation and Benchmarks**	Tue May 14, 2019

- Dynamic memory allocation
- BLAS (Basic Linear Algebra Subprogram) Level 1 operations (as application for arrays).
- Timer for benchmarks
- Gnuplot

8. **C99: Representing matrices**	Fr May 17, 2019

- Full storage format for matrices (and vectors).
- Introducing some BLAS Level 2 Operations.
- Notes on testing and benchmarking BLAS operations:
  - General form of a benchmark (that also tests correctness).
  - Test cases with random numbers and NaNs
  - Estimating the error
  - Controlling test parameters through macros

1.5 Week 5

9. **CPU Caches**	Tue May 21, 2019

- Concept of CPU caches:
  - Cache line, cache miss, cache hit.
  - Cache associativity.
- Prefetching

10. **CPU Caches: Optimized matrix vector product**	Fr May 24, 2019

- Mathematical notation for blocked matrix operations.
- Simple optimization for row or column major storage.
- Advanced optimization using fused vector operations.

1.6 Week 6

11.	**Outlook: Generic and object oriented programming**	Tue May 28, 2019

- Namespaces in C99 and C++.
- Generic programming (of functions):
  - In C99 with macros.
  - In C++ with template functions.
- Object oriented programming (OOP)
  - In C99 with *struct* and function pointers.
  - In C++ with *struct* (or *class*) and builtin language features (RAII, methods, operators).
- Combining generic programming and OOP.
- Typical pitfalls (focus on examples from generic programming).

12.	**General Matrix-Matrix Product (GEMM)**	Fr May 31, 2019

- Definition of the GEMM operation.
- Potential for high performance.
- Relevance for other numerical linear algebra operations.
- Some obvious ways to implement the GEMM operation relatively efficient.
- Test and benchmark suite for the GEMM operation.

1.7 Week 7

13.	**GEMM: Simple Cache Optimization.**	Tue June 4, 2019

- Benchmark comparing our GEMM with the Intel MKL implementation.
- Blocked and buffered computation.

14.	**GEMM: Advanced Cache Optimization**	Fr June 7, 2019

- Exploiting the complete cache hierarchy:
  - Frame function and macro/micro kernel for GEMM.
  - Packing matrix blocks.
- Testing components of the overall algorithm.

1.8 Week 8

15. **GEMM: Advanced Cache Optimization** Tue June 11, 2019

- Using a profiler: identify code spots where performance gets lost.
- Instruction pipeline optimizations: Enable compilers to unroll loops.
- Enable compilers to inline functions.

16. **GEMM: Optimized Micro Kernel** Fr June 14, 2019

- Single Instruction Multiple Data (SIMD).
- GEMM micro kernel in assembly code exploiting SIMD processor features.

1.9 Week 9

17. **GEMM: Optimized Micro Kernel** Tue June 18, 2019

- Manual loop unrolling in the assembly micro kernels.
- Manual instruction pipeline optimizations.
- Manual cache prefetching.

18. **Building libraries (ulmBLAS)** Fr June 21, 2019

- Static and dynamic libraries.
- Creating and working with static libraries:
  - Split a project in different compile units (and provide header files).
  - Identify and resolve linker problems.
  - Awareness of issues with inline functions.
- Concept of *functional programming* in Makefiles.
- Special features of GNU make:
  - Text functions.
  - Recursions.

1.10 Week 10

19. **ulmBLAS: Providing a Fortran interface** Tue June 25, 2019

- Short introduction of Fortran.
- Calling Fortran functions from C.
- Calling C functions from Fortran.

20. **LU Factorization (LU)**	Fr June 28, 2019

- Mathematical background: LU factorization with and without pivoting.
- Using the factorization to solve linear matrix equations.
- LU factorization of non-square matrices.
- Exercise: Setup a test and benchmark suite.

1.11 Week 11

21. **LU: Unblocked**	Tue July 2, 2019

- Deriving unblocked variants (i.e. based on BLAS level 2 operations) of the LU factorization.

22. **LU: Blocked**	Fr July 5, 2019

- Deriving blocked variants (i.e. based on BLAS level 3 operations and a unblocked variant) of the LU factorization.

1.12 Week 12

23. **Triangular Solvers (TRS)**	Fr July 9, 2019

24. **TRS: Unblocked**	Tue July 12, 2019

1.13 Week 13

25. **TRS: Blocked**	Tue July 16, 2019

26. **TRS: Blocked**	Fr July 19, 2019

1.14 Week 14

27. **Final Benchmarks and Outlook on Multithreading**	Tue July 23, 2019

28. **Final Benchmarks and Outlook on Multithreading**	Fr July 26, 2019