Introducing Parallel Computing in Undergraduate Curriculum

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Curriculum Update

• Goal: Include parallel computing in many undergraduate courses, not a special new one
• Reason: Students learn different aspects of parallel computing throughout the four years.
• Steps:
  – Identify which courses to change
  – Determine the orders of the changes
  – Eliminate duplicates and unnecessary contents
  – Change the course requirements (ABET)
  – Implement and integrate changes
Identify the Courses to Change

**Algorithms**
- Data Structures (3)

**Hardware**
- Circuits and Devices (2)

**Software**
- C Programming (2)
- Script Programming (3)
- Compilers (4)
- Operating Systems (4)

- Microcontroller (3)
- Computer Architecture (4)
- Undergraduate Research Projects (2-4)
- Software Engineering (4)
- Object-Oriented Programming (3)
- Software Engineering (4)

**Digital Logic**
- Digital Logic (2)

**Introduction to Computing**
- Introduction to Computing (1)
- Undergraduate Research Projects (2-4)

* The numbers mean the years when students take the courses. Most courses are offered twice a year.*
Determine the Order of Changes

- Introduction to Computing (1)
  - C Programming (2)
    - Data Structures (3)
      - Compilers (4)
      - Operating Systems (4)
        (already include multi-tasking)
    - Object-Oriented Programming (3)
  - Circuits and Devices (2)
    - Digital Logic (2)
      - Microcontroller (3)
        - Computer Architecture (4)

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First Change: Elective Course

Introduction to Computing (1)
  ↓
  C Programming (2)
  ↓
  Data Structures (3)
  ↓
  Compilers (4)
  ↓
  Operating Systems (4)

Circuits and Devices (2)
  ↓
  Digital Logic (2)
  ↓
  Microcontroller (3)
  ↓
  Computer Architecture (4)

Object-Oriented Programming (3)
Second Changes from the Ends

Introduction to Computing (1) → C Programming (2) → Data Structures (3) → Compilers (4) → Operating Systems (4)

Circuits and Devices (2) → Digital Logic (2) → Microcontroller (3) → Computer Architecture (4)

Object-Oriented Programming (3)
Changes in Intermediate Levels

- Introduction to Computing (1)
  - C Programming (2)
    - Data Structures (3)
      - Compilers (4)
        - Operating Systems (4)
  - Circuits and Devices (2)
    - Digital Logic (2)
      - Microcontroller (3)
        - Computer Architecture (4)
  - Object-Oriented Programming (3)
Latest Change

Introduction to Computing (1)

C Programming (2)

Data Structures (3)

Compilers (4)

Operating Systems (4)

Circuits and Devices (2)

Digital Logic (2)

Microcontroller (3)

Computer Architecture (4)

Object-Oriented Programming (3)
Not Changed (Yet)

Introduction to Computing (1)
- C Programming (2)
  - Data Structures (3)
    - Compilers (4)
  - Operating Systems (4)
- Circuits and Devices (2)
  - Digital Logic (2)
  - Microcontroller (3)
  - Computer Architecture (4)
  - Object-Oriented Programming (3)
First Change (OOP)

• It is elective and not a prerequisite of any required course.
• Java has built-in support for threads with synchronized methods. C++ can use library (Qt) for threads. GUI uses threads.
• The original course content include duplicate materials that can be eliminated: how to use and how to implement container classes ⇒ already taught in data structures.
Connect Parallelism with Life

• Use laundry room as examples.
• Many washers + dryers ⇒ hardware resources.
• Many loads of clothes ⇒ data-level parallelism.
• Washing before drying ⇒ dependence and pipeline.
Pipeline in Everyday Life

- factory assembly line
- buffet line
Synchronization

• ATM withdrawal to motivate the need of synchronization.

• Library study room with a lock and only one key to explain mutual exclusion.
Concept Inventory

• Purpose: develop a set of questions to evaluate students' understanding of parallel computing across their four years of studies.

• It is a guideline for updating courses and designing assessments for multiple courses.

• Requirements: The questions must be understandable without using terminology introduced later (e.g. synchronization, mutual exclusion, lock, locality, cache miss ...)

• Approach: use everyday examples to motivate and to describe the problems
The complete concept inventory is in the paper.
Sample Assignments

• Programming assignments
  – Matrix multiplication
  – Image pixel-wise color inversion
  – Network echo server

• Non-programming assignments
  – Amdahl's Law
  – Distinguish SISD/SIMD/MISD/MIMD
  – Conditions and sample code for deadlocks
Most Recent Changes

- Second programming class (C)
- 2012 IEEE/TCPP Early Adopter Grant
- two $\Rightarrow$ three credit units since Fall 2012
- For most students, this is the first experience of writing programs with threads
- Programming assignments:
  - Image pixel-wise color inversion
  - Subset sums (count the number of solutions)
- Non-programming assignments: Amdahl's Law and distinguish SISD/SIMD/MISD/MIMD
Evaluation (SIMD, pthreads)

Image color inversion

for (p = 0; p < numPixels; p++)
{
    for (c = 0; c < 3; c++) // RGB 3 colors
    {
        pixels[p].color[c] = 255 - pixels[p].color[c];
    }
}

// parallelization: divide numPixels into
// non-overlapping regions for the threads
The time for color inversion
The time for reading and writing files is excluded
Evaluation (SIMD, pthreads)

• Subset sum
• Given a positive integer $n$ and a set of positive integers $S = \{s_1, s_2, \ldots, s_k\}$
• Find all subsets $A = \{a_1, a_2, \ldots, a_m\}$ ($A \subseteq S$, $m \leq k$) such that $a_1 + a_2 + \ldots + a_m = n$
• Count the number of subsets
• Parallelization:
  – Divide the $2^n-1$ subsets into regions
  – Each thread checks all subsets in that region
  – If a solution is found, a shared variable `numberSolution` increments
Observations

• Most students understand the concepts and can write correct parallel programs using pthreads.
• Some are not aware of the performance impacts of redundant statements in inner loops.
• Some students know the need of mutual exclusion but each thread has a unique lock.
• Some students put private data (not shared) inside the critical sections.
• Some use expensive operations (for example multiplication or division instead of shifts).
Lessons Learned

• Students are excited learning new concepts related to parallel computing.

• Curriculum update can take several years.

• The changes should be introduced gradually, with the consideration of dependence among courses. The changes should start from a course which has topics that can be eliminated.

• Students should know efficient algorithms are more important than parallelization only.
Lessons Learned

• Assignments should be designed to reduce dependence. For example, many students do not know locality yet \( \Rightarrow \) The speedup of matrix multiplication is limited by cache performance.

• Some assignments should have high computation and low communication or IO (e.g. subset sum).

• Performance competition can encourage students to pay attention to details.
Conclusion

• We present our experience updating the curriculum including parallel computing in multiple courses throughout the four years.
• We explain the sequence of changes and the rationales of the sequences.
• We describe the concept inventory for cross-cohort evaluations.
• The early-adopter changes provide promising results; most students understand the concepts and can write simple parallel programs.