CS 61A/CS 98-52

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Preliminaries

Today, we're going to learn how to add & multiply. **Exciting!**

Let's add two positive n-bit integers ($n = 8$ here):

```
Carry:               1 111111
Augend:               10110111
Addend:             + 10011101
                    ----------
Sum:                 101010100
```

This is called *ripple-carry addition*. Some questions:

1. How big can the sum be (at most)? What is the worst case?
2. How long does summation take in the worst case? **Why?**

...we'll come back to this!

History

First computer design (*difference engine*) in **1822** (!!) and later, the *analytical engine*, by Charles Babbage (1791-1871)

First description of "MIMD" parallelism in **1842** (!!!) in *Sketch of The Analytical Engine Invented by Charles Babbage*, by Luigi F. Menabrea

First theory of computation by Alan Turing in **1936**

First electronic *analog computer* created in **1942** for bombing in WWII

First electronic *digital computer* created in **1943**
⇒ *Electronic Numerical Integrator and Computer* (ENIAC)

First description of parallel programs in **1958** (Stanley Gill)

First multiprocessor system (*Multics*) in **1969**

Lots of parallel computing research starting in **1970**s... then faded away

Multi-core systems reinvigorated parallel computing around **2001**

History

Long story short...

- Parallel computing goes back longer than you think
- Lots of useful research from the 1900s finding life again since processors stopped getting faster

Terminology

Some basic terminology:

- **Process**: *A running program*
  Processes cannot access each others' memory by default
- **Thread**: *A unit of program flow*
  (N threads = n independent executions of code)
  Threads maintain their own *execution contexts* in a given process
- **Thread context**: *All the information a thread needs to run code*
  This includes the location of the code that it is currently being executing, as well as its current stack frame (local variables, etc.)
- **Concurrency**: *Overlapping operations* (X begins before Y ends)
- **Parallelism**: *Simultaneously-occurring operations* (multiple operations happening *at the same time*)

Terminology

Parallel operations are always concurrent by definition

Concurrent operations need not be in parallel (open door, open window, close door, close window)

Parallelism gives you a speed boost (multiple operations at the same time), but requires N processors for $N\times$ speedup

Concurrency allows you to avoid stopping one thing before starting another, and can occur on a single processor

Concepts

Distributed computation (running on multiple machines) is more difficult:

- Needs fault-tolerance (more machines = higher failure probability)
- Lack of shared memory
- More limited communication bandwidth (network slower than RAM)
- *Time* becomes problematic to handle

Rich literature, e.g. actor-based *models of computation* (MoC) such as discrete-event, synchronous-reactive, synchronous dataflow, etc. for analyzing/designing systems with guaranteed performance or reliability

Threading

Threading example:

```python
import threading
t = threading.Thread(target=print, args=('a',))
t.start()
print('b')  # may print 'b' before or after 'a'
t.join()  # wait for t to finish
```

Threading

Race condition: *When a thread attempts to access something being modified by another thread.* **Race conditions are generally bad.**

Example:

```
import threading
lst = [0]
def f():
    lst[0] += 1   # write 1 might occur after read 2
t = threading.Thread(target=f)
t.start()
f()
t.join()
assert lst[0] in [1, 2]  # could be any of these!
```

Concurrency Control

Mutex (Lock in Python): Object that can prevent concurrent access (***mut****ual-****ex****clusion*). Example:

```
import threading
lock = threading.Lock()
lst = [0]
def f():
    lock.acquire()  # waits for mutex to be available
    lst[0] += 1  # only one thread may run this code
    lock.release()  # makes mutex available to others
t = threading.Thread(target=f)
t.start()
f()
t.join()
assert lst[0] in [2]  # will always succeed
```

Concurrency Control

Sadly, in CPython, multithreaded operations **cannot** occur in parallel, because there is a "global interpreter lock" (GIL).
Therefore, Python code cannot be sped up in CPython.[1]

To obtain parallelism in CPython, you can use *multiprocessing*: running another copy of the program and communicating with it.

Jython, IronPython, etc. *can* run Python in parallel, and most other languages support parallelism as well.

[1]However, Python code can release GIL when calling non-Python code.

Inter-Thread and Inter-Process Communication (IPC)

Threads/processes need to communicate. Common techniques:

- Shared memory: mutating shared objects (if all on 1 machine)
  - Pros: Reduces copying of data (faster/less memory)
  - Cons: Must block execution until lock is acquired (slow)
- Message-passing: sending data through thread-safe queues
  - Pros: Queue can buffer & work asynchronously (faster)
  - Cons: Increases need to copy data (slower/more memory)
- Pipes: synchronous version of message-passing ("rendezvous")

Inter-Thread and Inter-Process Communication (IPC)

Message-passing example for parallelizing $f(x) = x^2$:

```
from multiprocessing import Process, Queue
def f(q_in, q_out):
    while True:
        x = q_in.get()
        if x is None: break
        q_out.put(x ** 2)     # real work
if __name__ == '__main__':   # only on main thread
    qs = (Queue(), Queue())
    procs = [Process(target=f, args=qs) for _ in range(4)]
    for proc in procs: proc.start()
    for i in range(10): qs[0].put(i)         # send inputs
    for i in range(10): print(qs[1].get())  # receive outputs
    for proc in procs: qs[0].put(None)      # notify finished
    for proc in procs: proc.join()
```

Addition

Common parallelism technique: **divide-and-conquer**

1. Divide problem into separate subproblems
2. Solve subproblems in parallel
3. Merge sub-results into main result

XOR (and AND, and OR) are easy to parallelize:

1. Split each n-bit number into p pieces
2. XOR each n/p-bit pair of numbers independently
3. Put back the bits together

Can we do something similar with **addition**?

Addition

Let's go back to **addition**.

We have two n-bit numbers to add.

What if we take the same approach for + as for XOR?

1. Split each n-bit number into p pieces
2. Add each n/p-bit pair of numbers independently
3. Put back the bits together
4. ...
5. Profit? No? **What's wrong?**

We need to propagate carries! How long does it take? $\Theta(n)$ *time*

(How) can we do better?

Addition

Key idea #1: A carry can be either 0 or 1... and **we add different pieces in parallel**... and then select the correct one based on carry!
⇒ This is called a **carry-select adder**.

Key idea #2: We can do this **recursively**.
⇒ This is called a **conditional-sum adder**.

How fast is a conditional-sum adder?

- Running time is proportional to *maximum propagation depth*
- We solve two problems of *half the size simultaneously*
- We combine solutions with constant extra work
- Therefore, parallel running time is $\Theta(\log n)$

However, we do **more work**: $T(n) = 2T(n/2) + c = \Theta(n \log n)$

Addition

Other algorithms also exist with different trade-offs:

- Carry-skip adder
- Carry-lookahead adder (CLA)
- Kogge–Stone adder ("parallel-prefix" CLA; widely used)
- Brent-Kung adder
- Han–Carlson adder
- Lynch–Swartzlander spanning tree adder (fastest?)

...I don't know them. But $\Theta(\log n)$ is already asymptotically optimal. :-)

Some algorithms are better suited for hardware due to lower "fan-out": e.g. 1 bit is too "weak" to drive 16 bits all by itself.

Multiplication

How do we multiply?

```
Multiplicand:          10110111
Multiplier:          * 10011101
               -----------------
                       10110111
               +      00000000
               +     10110111
               +    10110111
               +   10110111
               +  00000000
               + 00000000
               + 10110111
               -----------------
Product:       111000000111011
```

Multiplication

For two n-bit numbers, how long does it take in parallel?

- Multiplication by 1 is a copy, taking $\Theta(1)$ depth
- There are n additions
- Divide-and-conquer therefore takes $\Theta(\log n)$ additions
- Each addition takes $\Theta(\log n)$ depth
- Total depth is therefore $\Theta\left((\log n)^2\right)$

...can we do better? :-) How?

Multiplication

Carry-save addition: reduce every $a + b + c$ into $r + s$ in parallel:

- Compute all carry bits r independently
  $\Rightarrow$ This is just OR, so $\Theta(1)$ depth
- Compute all sums-excluding-carries s independently
  $\Rightarrow$ This is just XOR, so $\Theta(1)$ depth
- Recurse on new $r_1 + s_1 + r_2 + s_2 + \ldots$ until final $r + s$ is obtained.
  $\Rightarrow$ This takes $\Theta(\log n)$ levels of recursion
- Compute final sum in additional $\Theta(\log n)$ depth

Total depth is therefore $\Theta(\log n)$![2]

[2] Simplified; detailed analysis is a little tedious. See here.

Parallel Prefix

There isn't too much special about *addition* from basic arithmetic.

Often the same tricks apply to any binary operator $\bigoplus$ that is associative!

Parallel addition can be generalized this way, called "parallel prefix":

- Say we want to compute cumulative sum of 1, 2, 3, ...
- First, group into binary tree: (((1 2) (3 4)) ((5 6) (7 8))) ...
- Then, evaluate sums for all nodes recursively toward root
- Finally, propagate sums back down from root to right-hand children

This is a very flexible operation, useful as a basic parallel building block. (More notes can be found on MIT's website.)

MapReduce

A common pattern for parallel data processing is:

```python
from functools import reduce

outputs = map(lambda x: ..., inputs)
result = reduce(lambda r, x: ..., outputs, initial)
```

- `map` you have already seen: it *transforms* elements
- `reduce` is anything like $+$, $\times$ to *summarize* elements
- Transformations assumed to ignore order (to allow parallelism)

MapReduce

Google recognized this and built a fast framework called MapReduce for automatically parallelizing & distributing such code across a cluster

- *MapReduce: Simplified Data Processing on Large Clusters*
  by Jeffrey Dean and Sanjay Ghemawat (2004)
- System and method for efficient large-scale data processing
  U.S. Patent 7,650,331

Fault-tolerance is handled automatically (why is this possible?)

Apache Hadoop later developed as an open-source implementation

"MapReduce" became a general *programming model* for distributed data processing

Spark (Matei Zaharia, UCB AMPLab, now at Databricks) developed as a faster implementation that processes data in RAM

MapReduce

Parallel `map` is easy in Python!

```python
>>> import math
>>> from multiprocessing.pool import Pool
>>> pool = Pool()
>>> pool.map(math.sqrt, [1, 2, 3, 4])
[1.0, 1.4142135623730951, 1.7320508075688772, 2.0]
```

This a *higher-level* threading construct that makes your life simpler.

MapReduce

Not everything fits into a MapReduce model

- Inputs may be generated on the fly
- Mappers might depend on many inputs
- Mappers may need lots of communication
- Computation may not be nicely “layered” at all
- ...

Parallel & distributed computation still an open research problem.