“Write Once, Parallelize Anywhere”

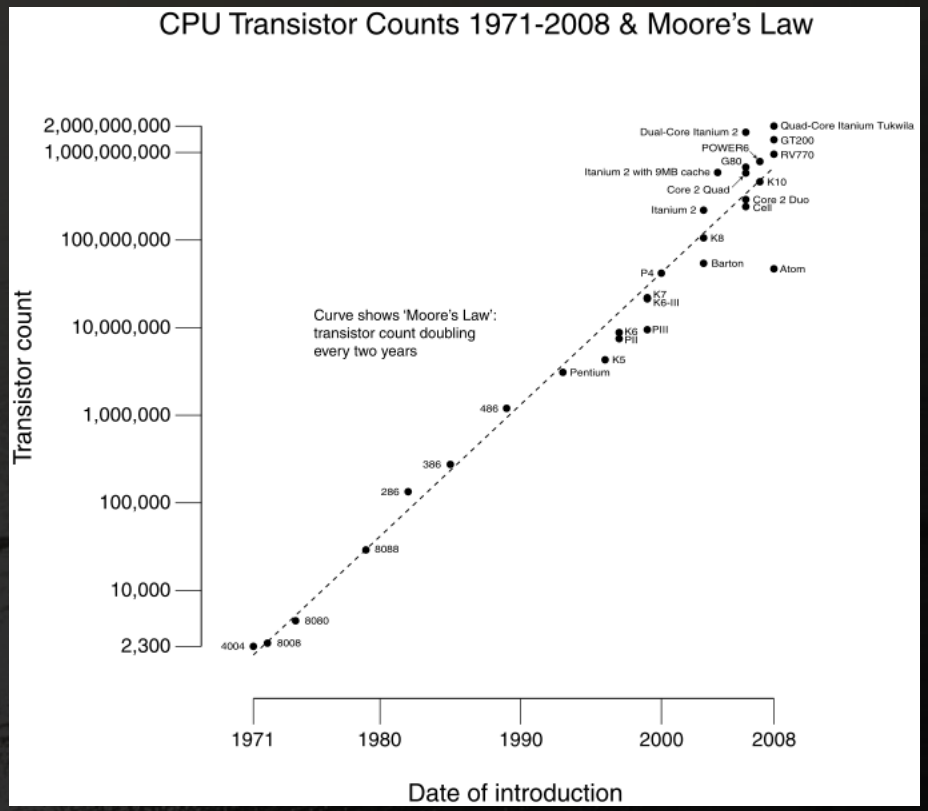
The Flow Programming Language:

An implicitly-parallelizing, programmer-safe language

Luke Hutchison

Moore's Law

- The number of transistors that can be placed inexpensively on an integrated circuit has doubled approximately every two years.



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- Computing is work; transistors do work; more transistors working in parallel should yield faster computers
  - => **Moore's Law has (so far) also applied to *CPU speed***

- BUT now we're hitting multiple walls:
  - **Transistor size**
    - tunneling; lithography feature size vs. wavelength
    - no more 2D density increases
  - **Thermal envelope**
    - function of frequency and feature size => we have hit a clockspeed wall
  - **Data width**
    - 128-bit CPUs? Need parallel control flow instead

But it's worse than that

It's not just the end of Moore's Law...

...it's the beginning of an era of **buggier software.**

Humans will **never** be good at
writing multi-threaded code –
our brains simply don't work like that.

(Abstractions like Futures only help a little bit.)

Parallel Programming Toolset

- Traditional locks: mutex, semaphore etc.
- Libraries: java.lang.concurrent
- Message passing: MPI; Actor model (Erlang)
- Futures, channels, STM
- **MapReduce**
- **Array programming**
  - Java7 ParallelArray
  - Intel Concurrent Collections (CnC)
  - Intel Array BuildingBlocks (ArBB)
  - Data Parallel Haskell (DPH)
  - ZPL

But—all require **programmer skill**, **extra effort** and **shoehorning of design.**

How to shoot yourself in the foot

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FORTRAN : You shoot yourself in each toe, iteratively, until you run out of toes, then you read in the next foot and repeat.

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My addition: **Explicit parallelization in any language** : You shoot in the yourself <*segfault*>

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=> The Multicore Dilemma

The root of the problem

- *Purely* functional programming languages can be safely implicitly parallelized
  - No side-effects, no state
  - => threads cannot interact
  - e.g. several parallel versions of Haskell

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but

purely functional programming languages
are extremely hard for mere mortals
to use to solve real-world problems.

On the other hand,

getting explicit parallelization *right* –
and writing multithreaded code quickly –
may actually be *harder.*

Mere mortals

"*Recommendation:* Invest in research and development of programming methods that will enable efficient use of parallel systems not only by parallel systems experts *but also by typical programmers.*"

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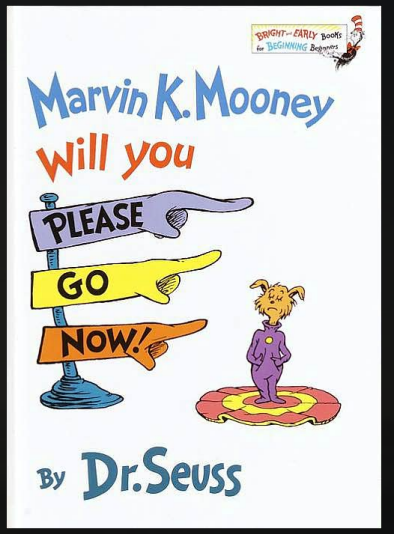


- But for imperative programming languages, it is impossible to tell the exact **data dependency graph** of a program by static analysis (by looking at the source).
  - (The data dependency graph tells you the order you need to compute values.)
  - Therefore you don't know what can be computed in parallel without:
    - (1) trusting the programmer (explicit parallelism) – VERY BAD
    - (2) guessing (static code analysis) – possibly/probably very bad
    - (3) trying and failing/bailing if you were wrong (STM)

Functional vs. imperative

- **Functional:**
  - *gather, pull, reduce*
- **Imperative:** same as functional, but adds
  - *scatter, push, produce*

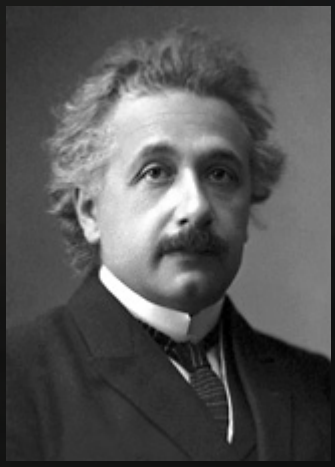
Training wheels

- How to *minimally* constrain imperative programming to allow for automatic implicit parallelization with guaranteed thread safety...

…*without* forcing the programmer to use training wheels?

The real root of the problem

- ...is **the ability to read the *current value of a variable*.** (Surprising. Foundational.)
  - => Einstein's theory of the relativity of simultaneity: there is no such thing as “now” given physical separation.
  - c.f. Values vs. variables.



- Remove the concept of “now”, and you *minimally restrict* a language such that it's impossible to create race conditions or deadlocks.
  - But you also don't have to program in purely functional style: Can support a *subset* of imperative, push-style programming.

Introducing Flow

- *Flow* is a new programming paradigm that enforces this restriction to solve the multicore dilemma while providing strong and specific guarantees about program correctness and runtime safety.

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- Flow is a compiler framework that can be targeted by a wide range of different languages
  - [will probably plug into LLVM]
- ...and (eventually), a reference language

- It doesn't actually exist yet, come help make it exist
  - http://flowlang.net/

Goals of Flow

- **Solve the multicore dilemma**
  - Ubiquitous implicit parallelization, zero programmer effort
  - “Write once, parallelize anywhere”
    - Cluster : hadoop / MapReduce, MPI or similar
    - JVM via Java Threads
    - C via pthreads
    - CPU ↔ GPU via CUDA
      - Optimal load balancing via big-Oh analysis of computation and communication cost
- **Prevent programmers from shooting themselves in the foot**
  - Make race conditions, deadlocks, segfaults/NPEs, memory leaks **impossible**

Back to the drawing board

Flow enables implicit parallelization by

syntactically enforcing
every program to be
a lattice or partial ordering,

such that

the program source code itself is
the data dependency graph.

This makes parallelization trivial.

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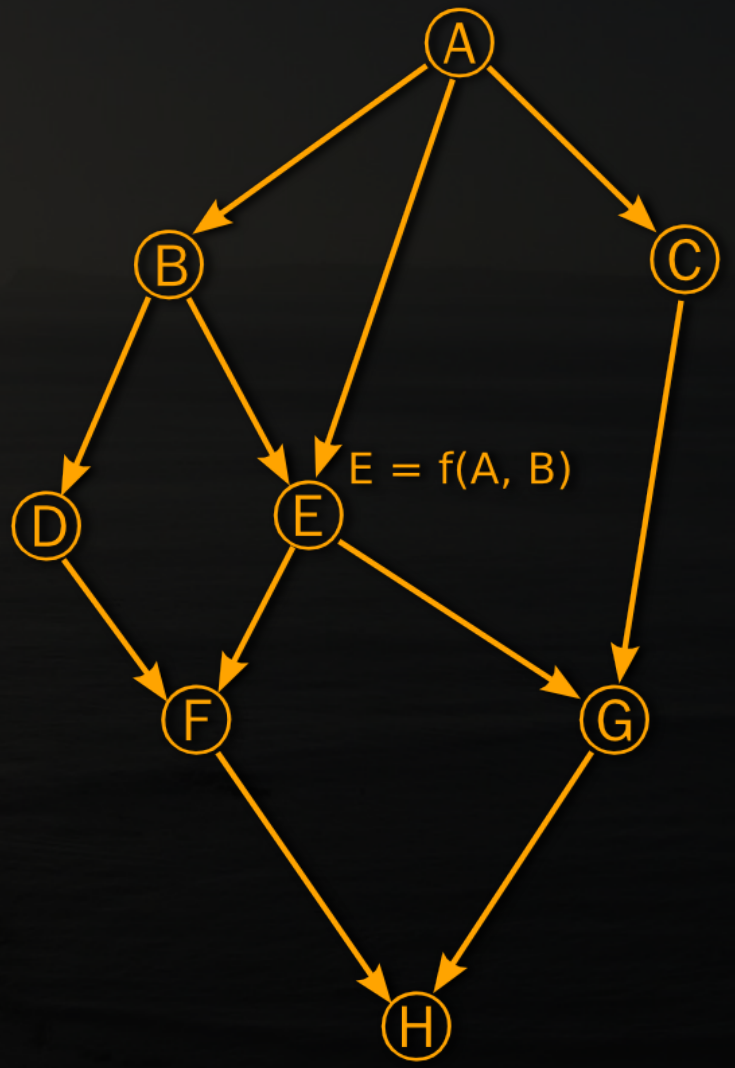
Also note that this does not eliminate “push” programming

- G can be an unordered collection

It also does not mean you can't “change the value of a variable”

- But you have to specify a specific timestamp, e.g.
  x@(t) = x@(t-1) + 1
  (then each value of x is a specific node in the DAG)

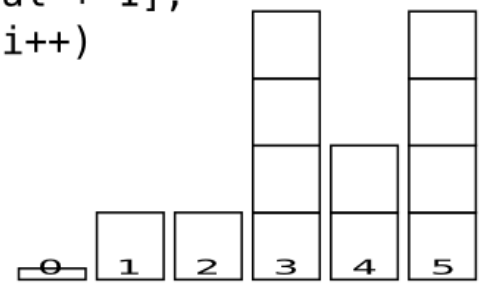
=> Minimally-restricted imperative programming with maximum implicit parallelization



An example

- Histogram generation

```
public int[] histogram(int[] input, int maxVal) {
    public int[] output = new int[maxVal + 1];
    for (int i = 0; i < input.length; i++)
        output[input[i]]++;
    return output;
}
```



{5,3,1,4,3,4,2,3,5,3,5,5} -> {0, 1, 1, 4, 2, 4}

- Multithreaded version? Two options:
  (1) locks (=> contention!)
  (2) keep separate copies in TLS; combine at end of operation
- Both options are manual
  => not easily composable, load-balanceable or scalable

An example

- More complex example

```
// Generate a histogram of avg number of spaces vs. string len

@SuppressWarnings("unchecked")  // Stupid Java generics
public int[][] avgNumSpacesGivenStrLen(String[] input, int maxLen) {

    // Alloc memory (even GC'd languages require this sort of stuff)
    ArrayList[] strsOfLen = new ArrayList[maxLen + 1];
    for (int i = 0, n = maxLen + 1; i < n; i++)
        stsOfLen[i] = new ArrayList();

    // Scatter inputs by string length
    for (int i = 0; i < input.length; i++)
        strsOfLen[input[i].length()].add(input[i]);

    // Calc avg number of spaces among all inputs with same string length
    public int[] output = new int[maxLen + 1];
    for (int len = 0; len <= maxLen; len++) {
        ArrayList<String> strs = (ArrayList<String>) strsOfLen[len];
        int totSpaces = 0;
        for (String str : strs)
            totSpaces += countSpaces(str);
        output[len] = strs.size() == 0 ? 0.0f : totSpaces / (float) strs.size();
    }
    return output;
}
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- strsOfLen[*j*] can be an *unordered collection* (Set), does not affect result
- Allows writes to be interleaved or reordered => auto TLS split

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- The less we constrain subproblems, the more parallelizable the code
- To relax constraints, must understand properties of functions / collections

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Map

Reduce

- Turns out any function can be split into Map and Reduce stages
- But MapReduce doesn't incl flow control, + MR can't be auto-generated yet

Back to the drawing board

Flow syntactically enforces that a program's structure be a partial ordering or DAG (specifically a *lattice*).

Each node is the result of a function application of some sort

=> the process of computing each node can be thought of as a MapReduce operation

Back to the drawing board

Because Flow enforces program structure to be a partial ordering, some amazing properties emerge:

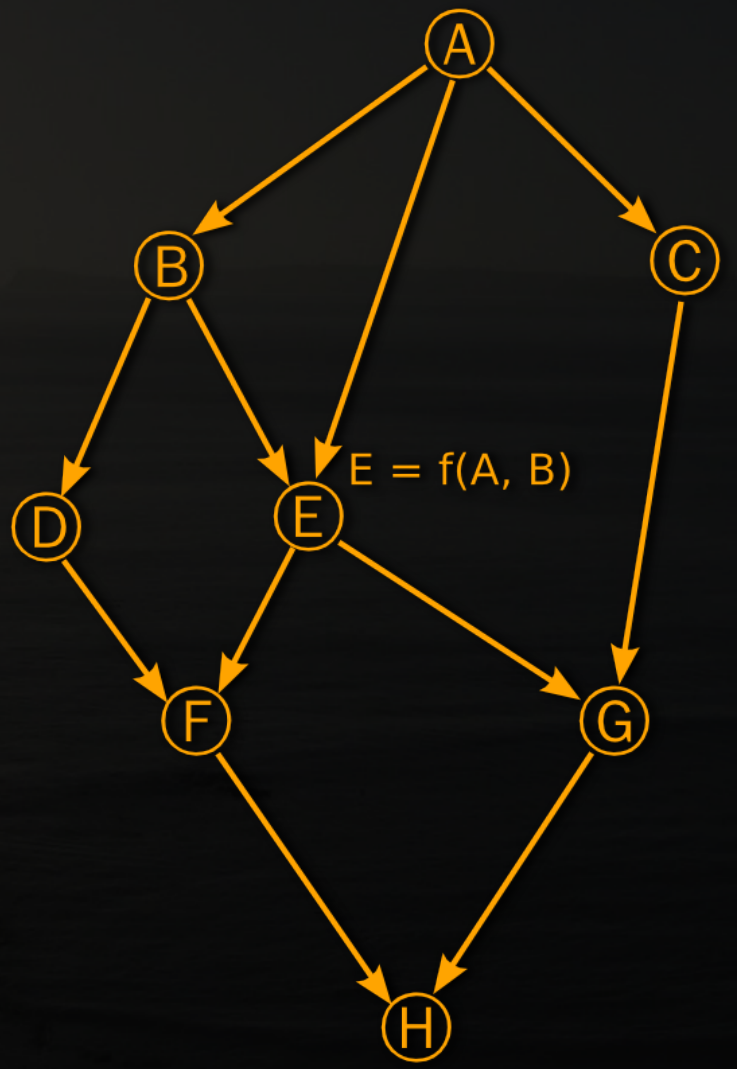
(1) Precise memory allocation:

- E only allocated (or computed) after both A and B have been computed
- E freed as soon as F and G are computed

No malloc/free, but *no GC either!*

- [Google will not use Java for core infrastructure because of GC]

No wasted memory



Back to the drawing board

(2) Precise execution order; direct knowledge of parallelizability.

- The program structure *is* the data dependency graph, which directly constrains the execution order, so there are no **race conditions**

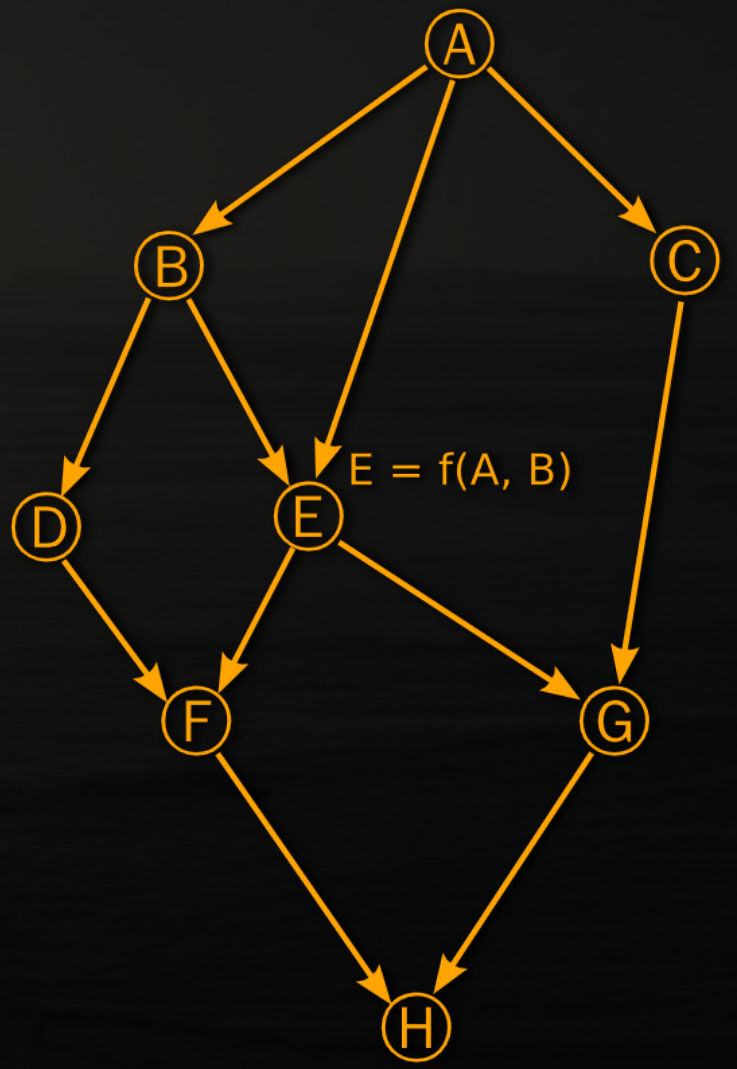
(3) There are no cycles in a DAG by definition, so **deadlocks** are impossible too.

(4) You can write the statements in your program *in any order* within each scope, and it will still run identically – you no longer need to do a *topological sort* in your head to artificially serialize your code (ABDEFCGH)

Back to the drawing board

(5) Next-gen source-code editor: forget text editors, edit the program directly as a DAG!

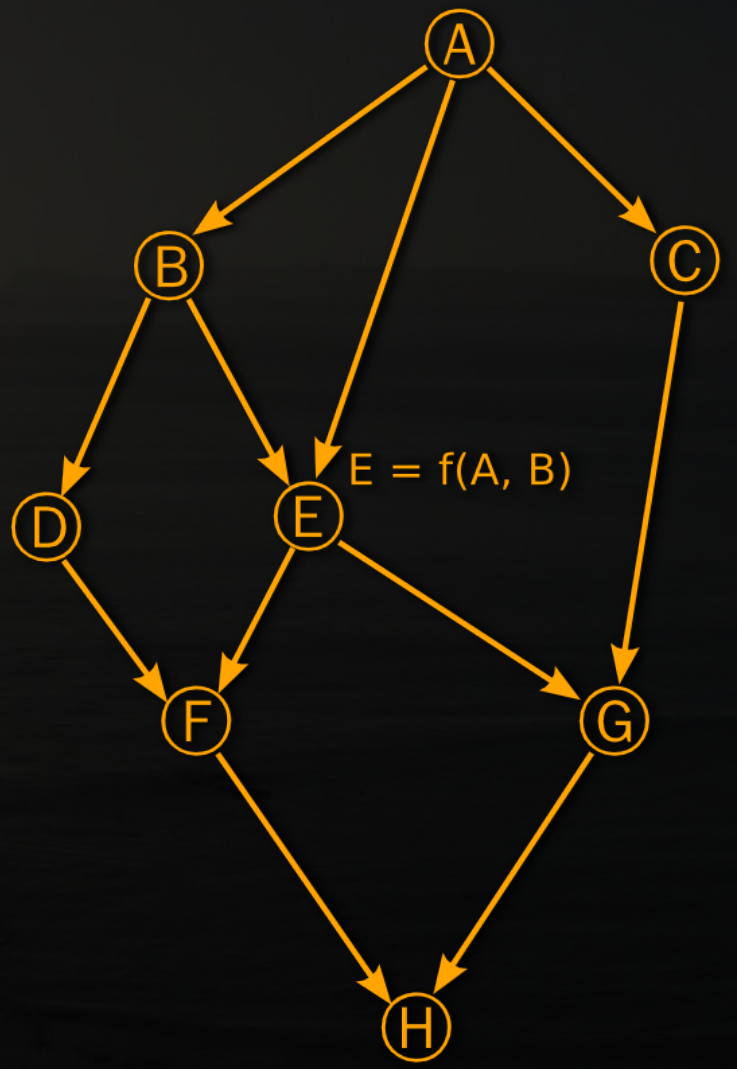
- Why do a topo sort on the source at all? It's completely artificial.
- Tap into the shape recognition power of the human visual system



Back to the drawing board

(6) Next-gen debugging

- Watch nodes light up on the DAG as they are computed
- Watch data literally flowing through the pipeline.
- Easy to add checkpointing for stop/restart because you know all data deps
  - Stopped at a breakpoint => run *backwards* one step and re-compute values at a previous node
  - Holy grail of debugging



Back to the drawing board

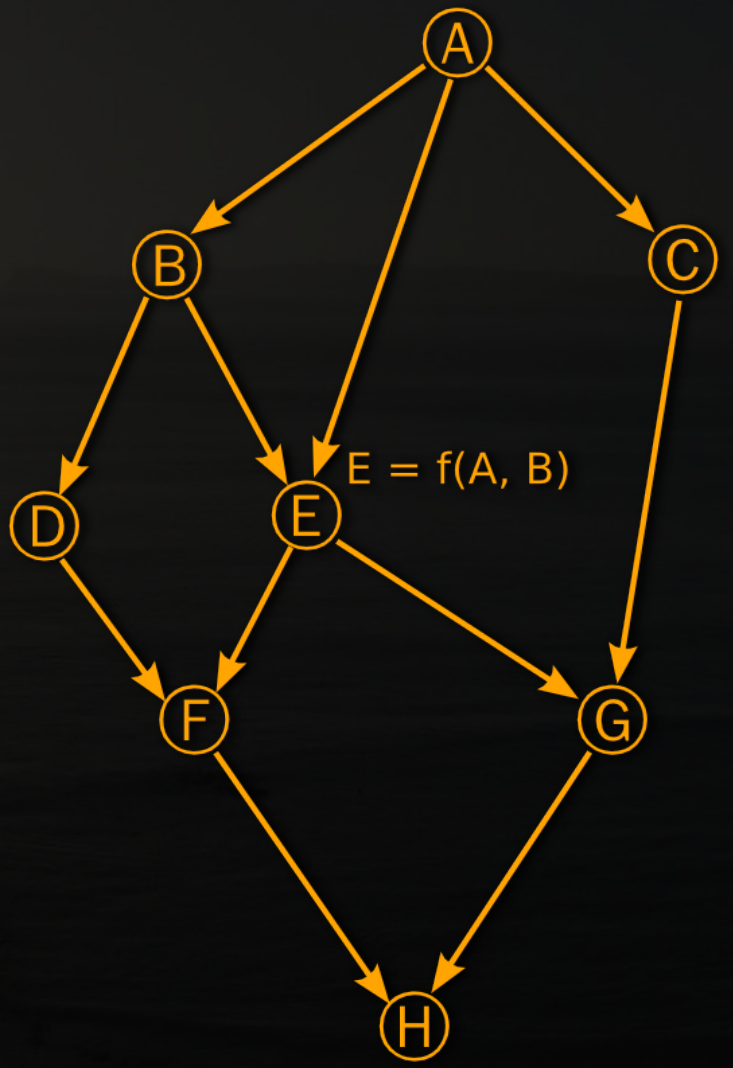
(7) There is no execution stack in Flow!

- Weird and rare among programming languages, Prolog is a notable exception
- Stack is conceptually replaced by conditional recursive expansion of sub-lattices within a lattice
- (Compiler will of course generate code that uses CPU stack)

Back to the drawing board

(8) Because each node is effectively a collection (Map/Set/List), we can calculate the big-Oh size of each collection, i.e. the big-Oh time required to compute it

- Every operation can now provide multiple equivalent algorithms or different parallelization strategies with different scaling characteristics, and Flow will switch between them at compiletime or runtime depending on input sizes
  - e.g. switch to single-threaded code for small inputs
- Find CPU bottlenecks and memory hogs before you even run your code (compile-time profiling!)



Category Theory

- **Further optimize implicit parallelization by data reordering and grouping**
  - Uses ***category theory*** for inference over function properties: associativity, commutativity, idempotence, …
  - Each property offers a degree of freedom to parallelize more efficiently
  - e.g. successive applications of functions that are associative and commutative can be reordered/grouped at will:
    (1+(3+(9+(2+(4+7))))) = (1+3+9)+(2+4+7)
    serial → parallel

Iteration and Turing-completeness

- The Structured Program Theorem: *every computable function can be implemented by combining subprograms in only three ways:*

  (1) Executing one subprogram, and then another subprogram (sequence)

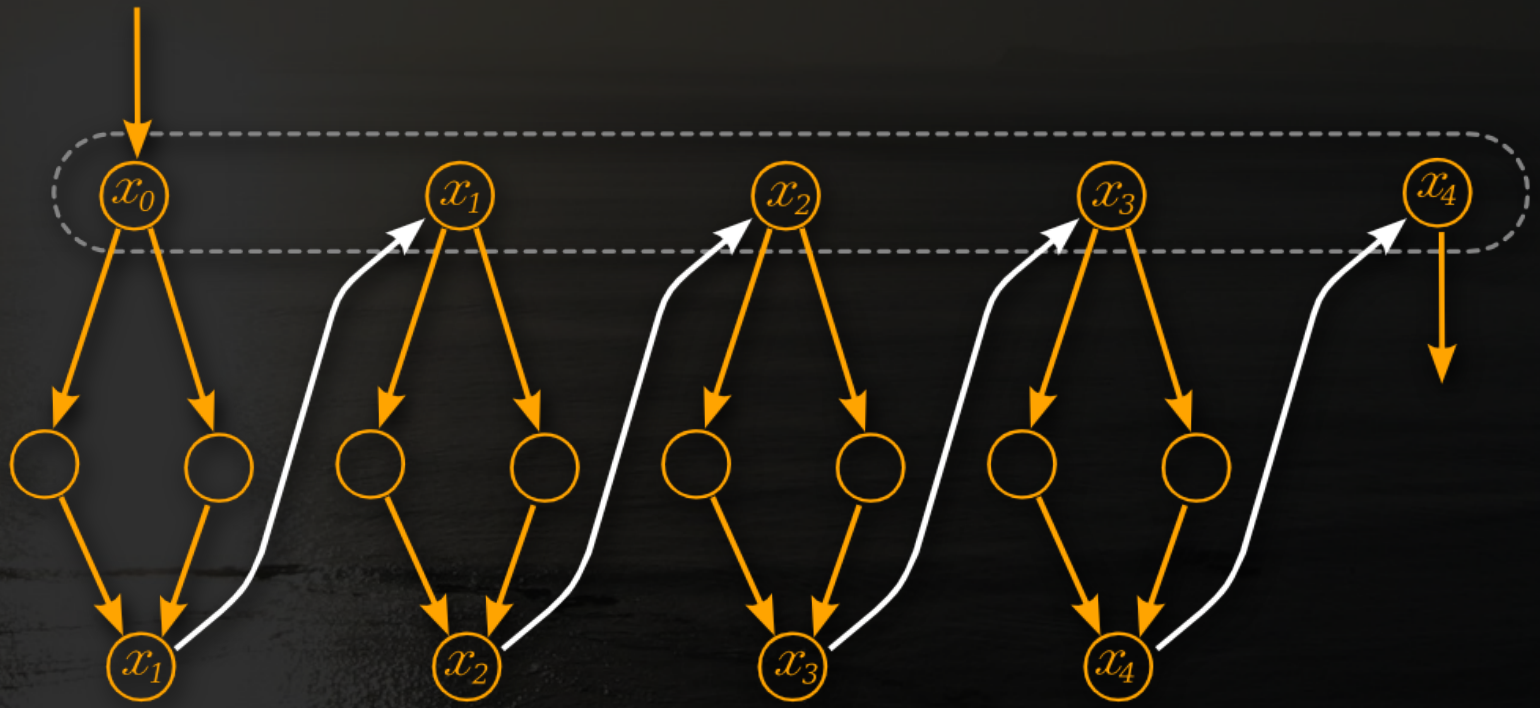
  - Composition of lattices in Flow

  (2) Executing one of two subprograms according to the value of a boolean variable (selection)

  - Trivial boolean function application in Flow

Iteration and Turing-completeness

(3) Executing a subprogram until a boolean variable is true (repetition)



Conclusion

- Flow imposes only the minimally invasive constraint on an imperative programming language to allow implicit parallelization with zero programmer effort
- *Many* different language syntaxes could be built on top of this paradigm (sharing the compiler backend)
- Mere mortal programmers can continue to work (mostly) as normal, the compiler will figure out the hard stuff
  - This (in theory) solves the multicore dilemma – it was a human issue to start with.

flowlang.net

twitter.com/LH

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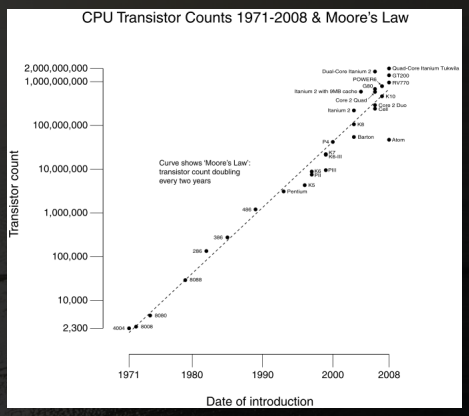

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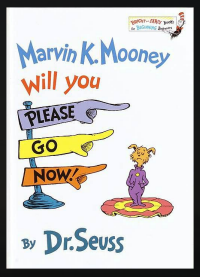

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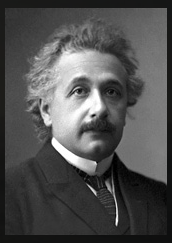

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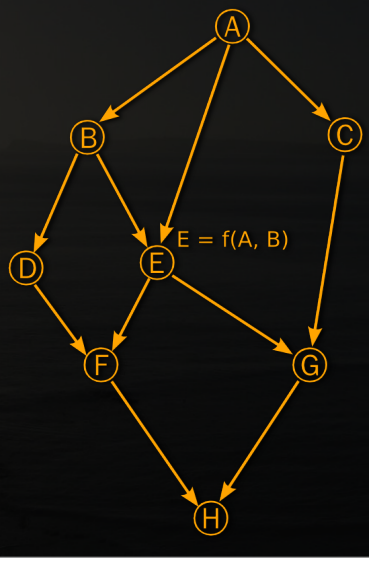

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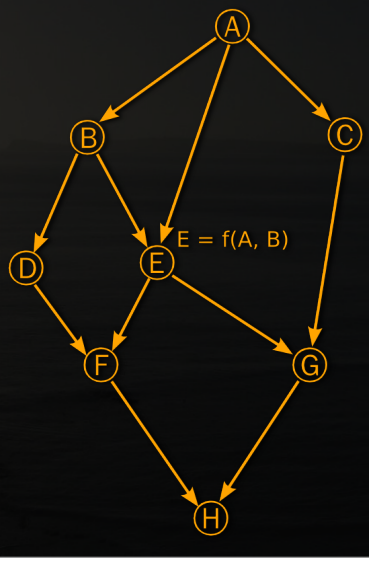

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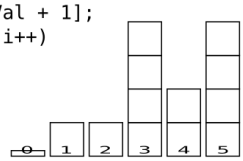
    return output;
}
```



{5,3,1,4,3,4,2,3,5,3,5,5} -> {0, 1, 1, 4, 2, 4}

- Multithreaded version? Two options:
  (1) locks (=> contention!)
  (2) keep separate copies in TLS; combine at end of operation
- Both options are manual
  => not easily composable, load-balanceable or scalable

An example

- More complex example

```
// Generate a histogram of avg number of spaces vs. string len

@SuppressWarnings("unchecked")  // Stupid Java generics
public int[][] avgNumSpacesGivenStrLen(String[] input, int maxLen) {

    // Alloc memory (even GC'd languages require this sort of stuff)
    ArrayList[] strsOfLen = new ArrayList[maxLen + 1];
    for (int i = 0, n = maxLen + 1; i < n; i++)
        stsOfLen[i] = new ArrayList();

    // Scatter inputs by string length
    for (int i = 0; i < input.length; i++)
        strsOfLen[input[i].length()].add(input[i]);

    // Calc avg number of spaces among all inputs with same string length
    public int[] output = new int[maxLen + 1];
    for (int len = 0; len <= maxLen; len++) {
        ArrayList<String> strs = (ArrayList<String>) strsOfLen[len];
        int totSpaces = 0;
        for (String str : strs)
            totSpaces += countSpaces(str);
        output[len] = strs.size() == 0 ? 0.0f : totSpaces / (float) strs.size();
    }
    return output;
}
```

- strsOfLen[*j*] can be an *unordered collection* (Set), does not affect result
- Allows writes to be interleaved or reordered => auto TLS split

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```

- The less we constrain subproblems, the more parallelizable the code
- To relax constraints, must understand properties of functions / collections

An example

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Map

Reduce

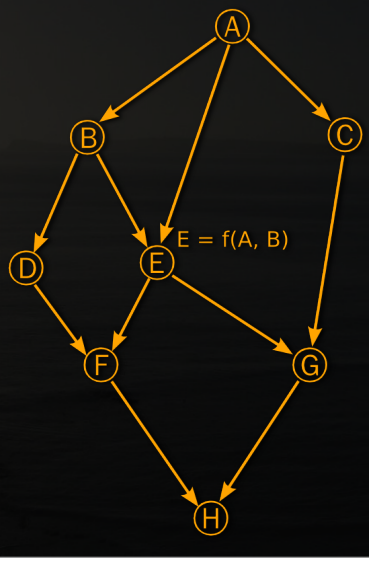
- Turns out any function can be split into Map and Reduce stages
- But MapReduce doesn't incl flow control, + MR can't be auto-generated yet

Back to the drawing board

Flow syntactically enforces that a program's structure be a partial ordering or DAG (specifically a *lattice*).

Each node is the result of a function application of some sort

=> the process of computing each node can be thought of as a MapReduce operation



Back to the drawing board

Because Flow enforces program structure to be a partial ordering, some amazing properties emerge:

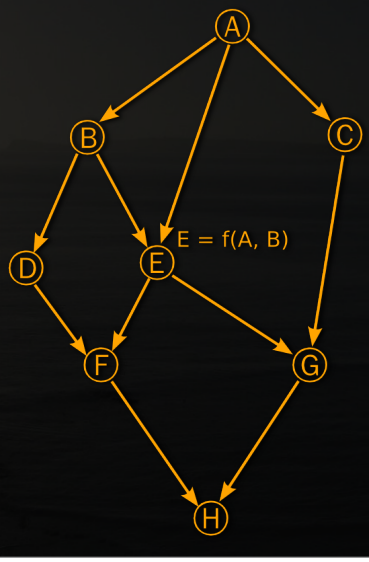
(1) Precise memory allocation:

- E only allocated (or computed) after both A and B have been computed
- E freed as soon as F and G are computed

No malloc/free, but *no GC either!*

- [Google will not use Java for core infrastructure because of GC]

No wasted memory



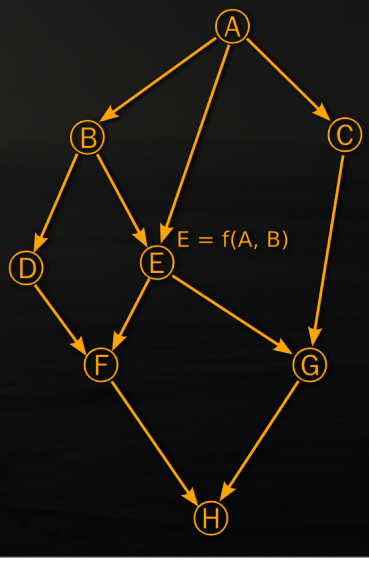
Back to the drawing board

(2) Precise execution order; direct knowledge of parallelizability.

- The program structure *is* the data dependency graph, which directly constrains the execution order, so there are no **race conditions**

(3) There are no cycles in a DAG by definition, so **deadlocks** are impossible too.

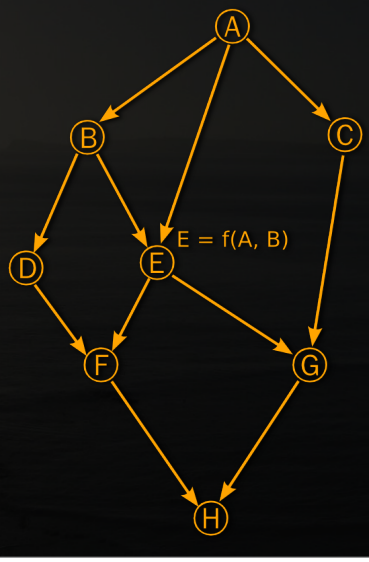
(4) You can write the statements in your program *in any order* within each scope, and it will still run identically – you no longer need to do a *topological sort* in your head to artificially serialize your code (ABDEFCGH)



Back to the drawing board

(5) Next-gen source-code editor: forget text editors, edit the program directly as a DAG!

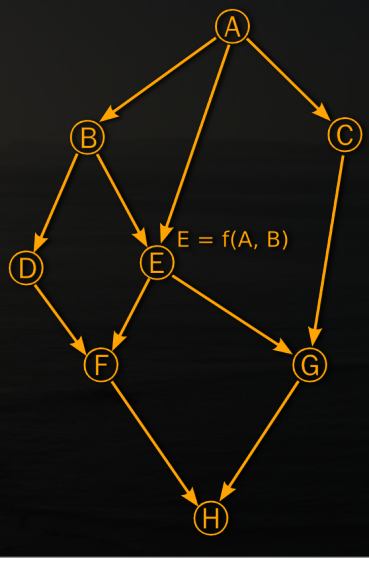
- Why do a topo sort on the source at all? It's completely artificial.
- Tap into the shape recognition power of the human visual system



Back to the drawing board

(6) Next-gen debugging

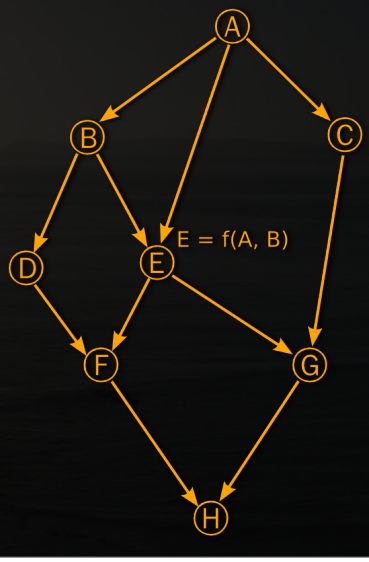
- Watch nodes light up on the DAG as they are computed
- Watch data literally flowing through the pipeline.
- Easy to add checkpointing for stop/restart because you know all data deps
  - Stopped at a breakpoint => run *backwards* one step and re-compute values at a previous node
  - Holy grail of debugging



Back to the drawing board

(7) There is no execution stack in Flow!

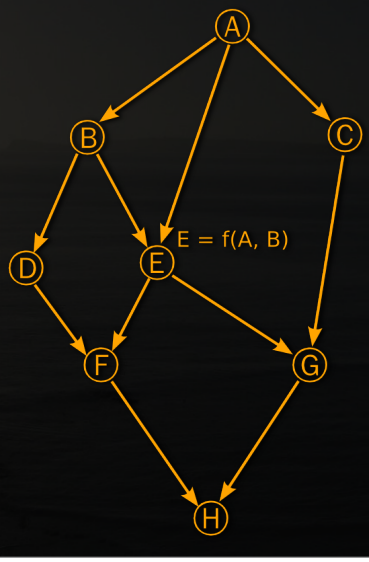
- Weird and rare among programming languages, Prolog is a notable exception
- Stack is conceptually replaced by conditional recursive expansion of sub-lattices within a lattice
- (Compiler will of course generate code that uses CPU stack)



Back to the drawing board

(8) Because each node is effectively a collection (Map/Set/List), we can calculate the big-Oh size of each collection, i.e. the big-Oh time required to compute it

- Every operation can now provide multiple equivalent algorithms or different parallelization strategies with different scaling characteristics, and Flow will switch between them at compiletime or runtime depending on input sizes
  - e.g. switch to single-threaded code for small inputs
- Find CPU bottlenecks and memory hogs before you even run your code (compile-time profiling!)



Category Theory

- **Further optimize implicit parallelization by data reordering and grouping**
  - Uses ***category theory*** for inference over function properties: associativity, commutativity, idempotence, …
  - Each property offers a degree of freedom to parallelize more efficiently
  - e.g. successive applications of functions that are associative and commutative can be reordered/grouped at will:
    (1+(3+(9+(2+(4+7))))) = (1+3+9)+(2+4+7)
    serial → parallel

Iteration and Turing-completeness

- The Structured Program Theorem: *every computable function can be implemented by combining subprograms in only three ways:*

  (1) Executing one subprogram, and then another subprogram (sequence)

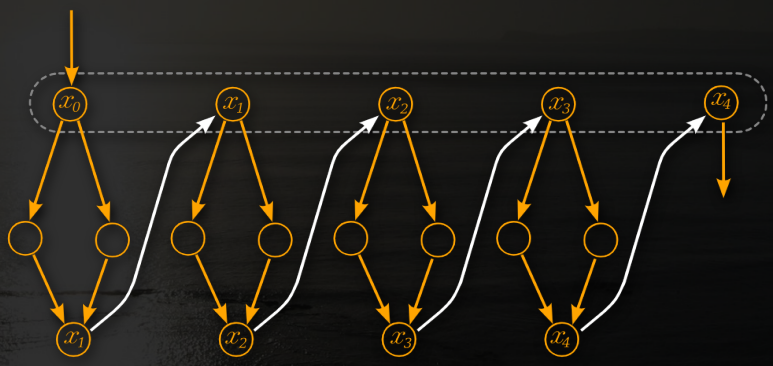
  - Composition of lattices in Flow

  (2) Executing one of two subprograms according to the value of a boolean variable (selection)

  - Trivial boolean function application in Flow

Iteration and Turing-completeness

(3) Executing a subprogram until a boolean variable is true (repetition)



Conclusion

- Flow imposes only the minimally invasive constraint on an imperative programming language to allow implicit parallelization with zero programmer effort
- *Many* different language syntaxes could be built on top of this paradigm (sharing the compiler backend)
- Mere mortal programmers can continue to work (mostly) as normal, the compiler will figure out the hard stuff
  - This (in theory) solves the multicore dilemma – it was a human issue to start with.


flowlang.net
twitter.com/LH