Multicores from the Compiler's Perspective

A Blessing or a Curse?

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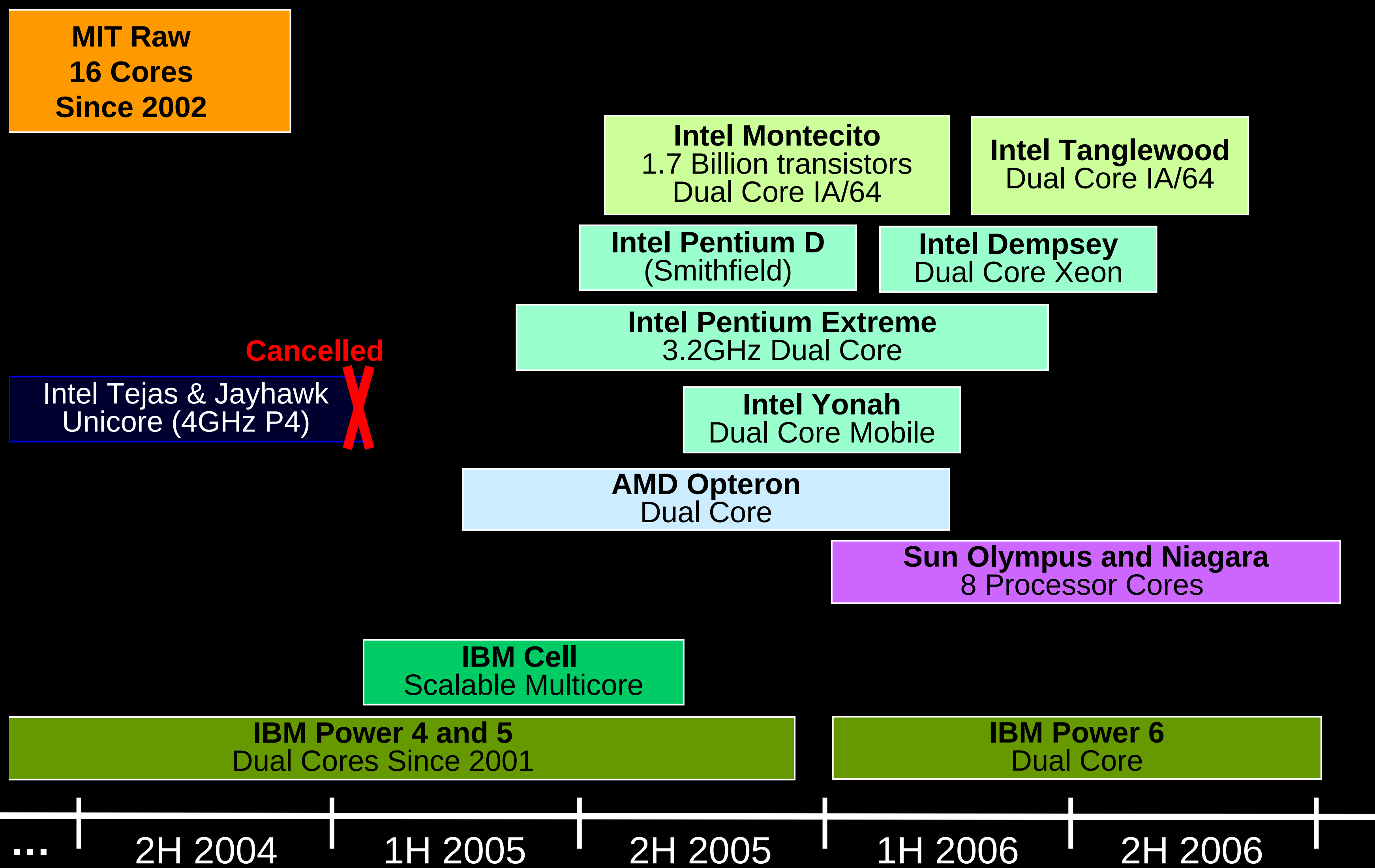
Multicores are coming!



What is Multicore?

- Multiple, externally visible processors on a single die where the processors have independent control-flow, separate internal state and no critical resource sharing.

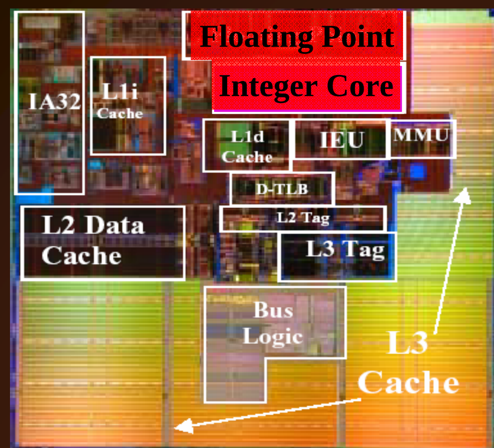
- Multicores have many names…
  - Chip Multiprocessor (CMP)
  - Tiled Processor
  - ….

Why move to Multicores?

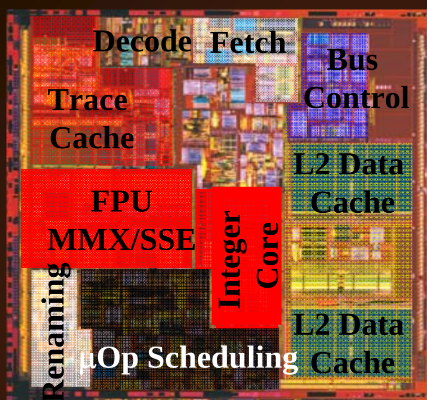
- Many issues with scaling a unicore
  - Power
  - Efficiency
  - Complexity
  - Wire Delay
  - Diminishing returns from optimizing a single instruction stream

Moore’s Law: Transistors Well Spent?

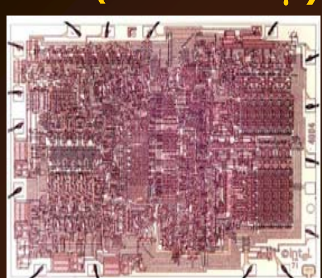
Itanium 2 (421mm² / .18µ)

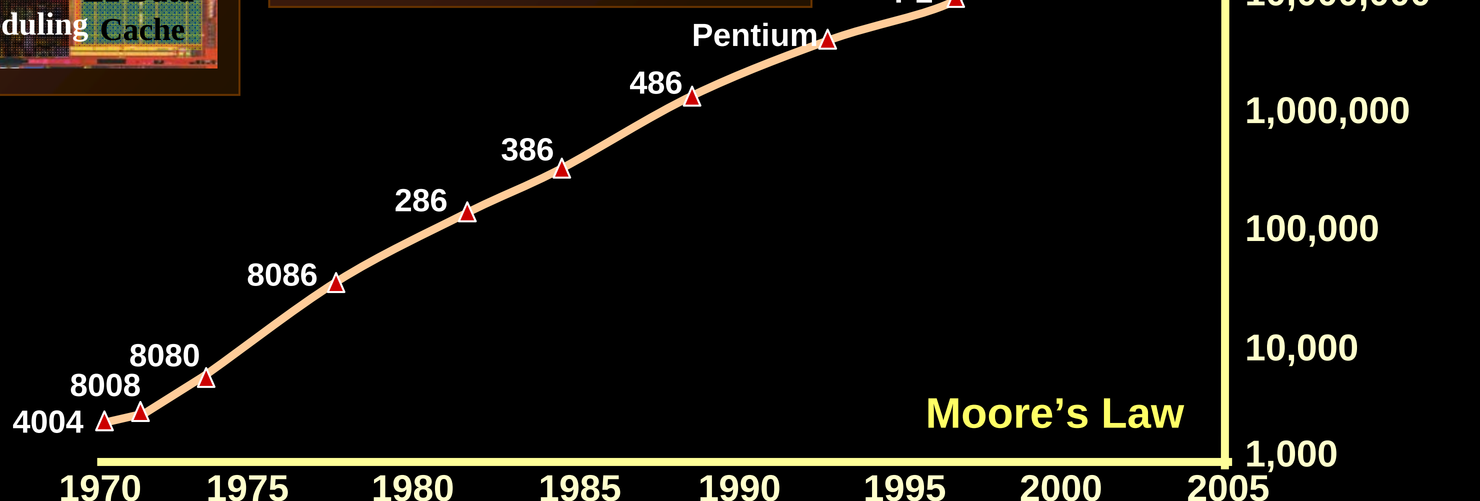


Pentium 4 (217mm² / .18µ)



4004 (12mm² / 8µ)



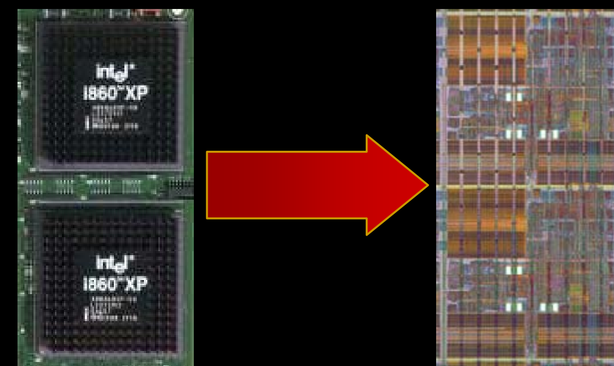


Outline

- Introduction
- Overview of Multicores
- Success Criteria for a Compiler
- Data Level Parallelism
- Instruction Level Parallelism
- Language Exposed Parallelism
- Conclusion

Impact of Multicores

- How does going from Multiprocessors to Multicores impact programs?



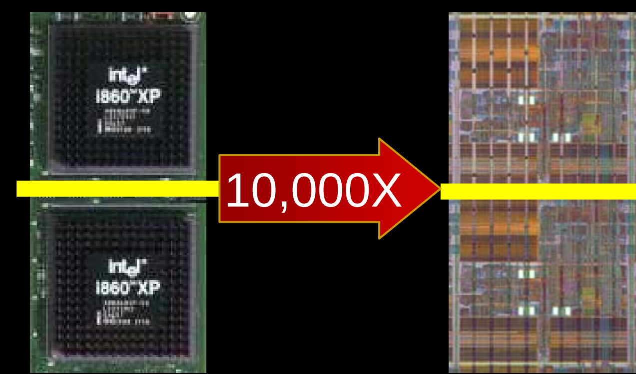
- What changed?
- Where is the Impact?
  - Communication Bandwidth
  - Communication Latency

Communication Bandwidth

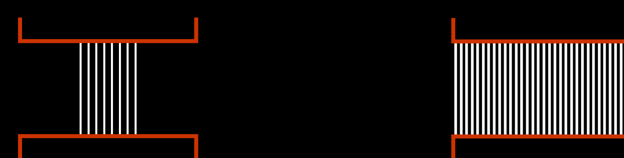
- How much data can be communicated between two cores?

- What changed?
  - Number of Wires
    - IO is the true bottleneck
    - On-chip wire density is very high
  - Clock rate
    - IO is slower than on-chip
  - Multiplexing
    - No sharing of pins

- Impact on programming model?
  - Massive data exchange is possible
  - Data movement is not the bottleneck → locality is not that important

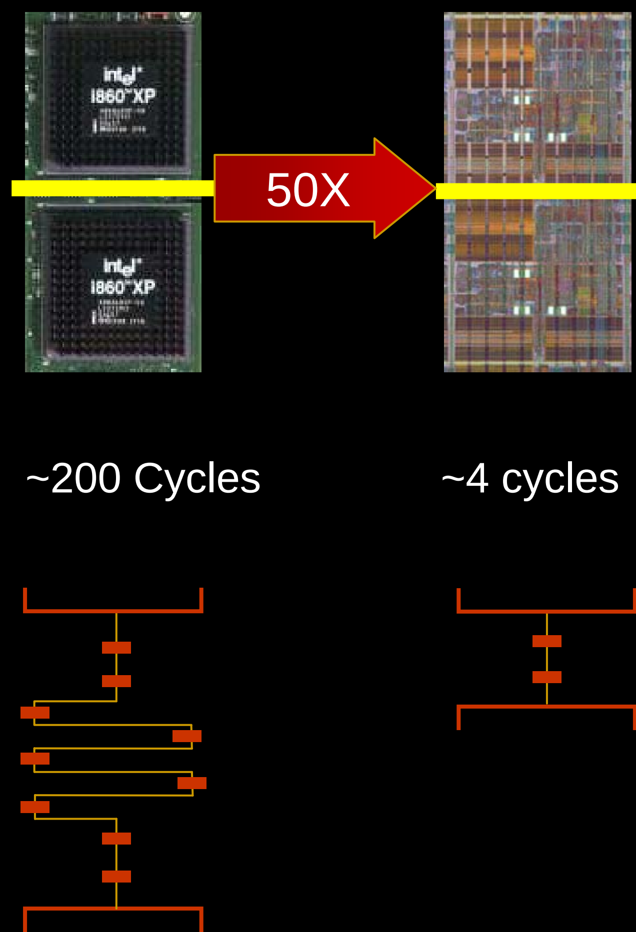


32 Giga bits/sec ~300 Tera bits/sec



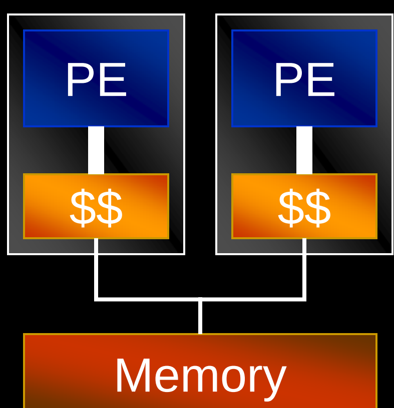
Communication Latency

- How long does it take for a round trip communication?
- What changed?
  - Length of wire
    - Very short wires are faster
  - Pipeline stages
    - No multiplexing
    - On-chip is much closer
- Impact on programming model?
  - Ultra-fast synchronization
  - Can run real-time apps on multiple cores

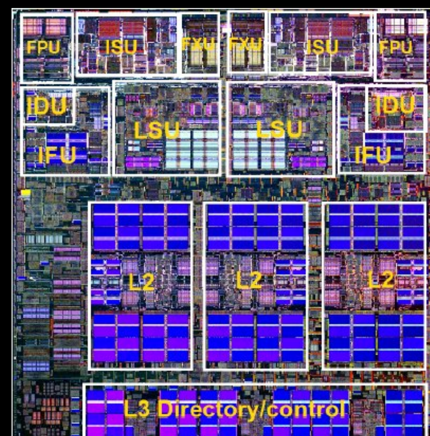


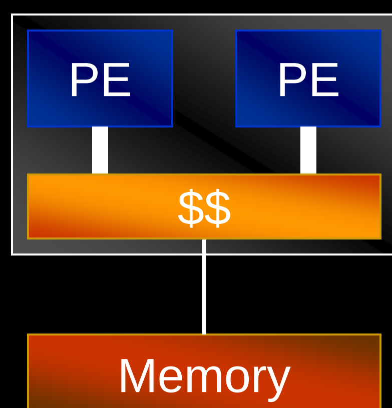
Past, Present and the *Future?*

Traditional Multiprocessor

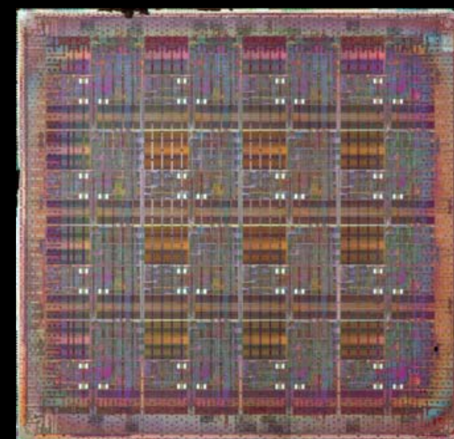


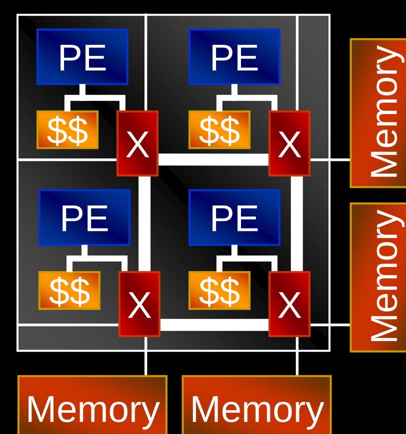
Basic Multicore
IBM Power5





Integrated Multicore
16 Tile MIT Raw





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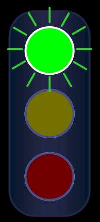
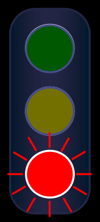
When is a compiler successful as a general purpose tool?

- General Purpose
  - Programs compiled with the compiler are in daily use by non-expert users
  - Used by many programmers
  - Used in open source and commercial settings



- Research / niche
  - You know the names of all the users



Success Criteria

1. Effective
2. Stable
3. General
4. Scalable
5. Simple

1: Effective

- Good performance improvements on most programs

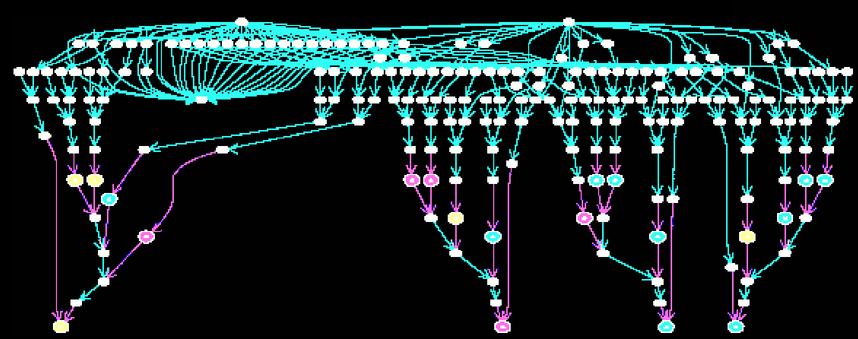
- The speedup graph goes here!

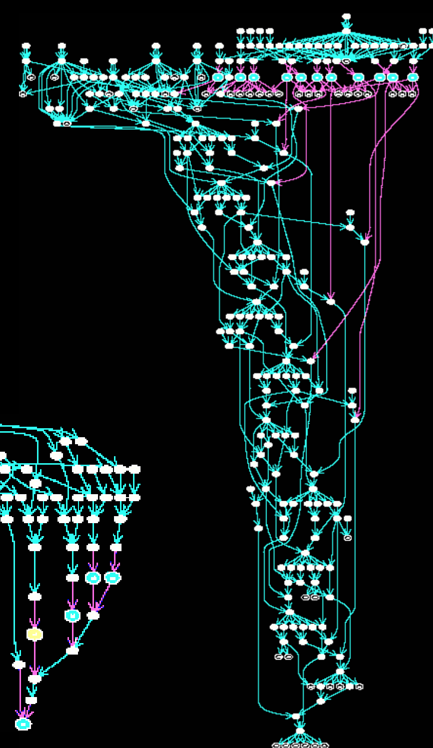
2: Stable

- Simple change in the program should not drastically change the performance!
  - Otherwise need to understand the compiler inside-out
  - Programmers want to treat the compiler as a black box

3: General

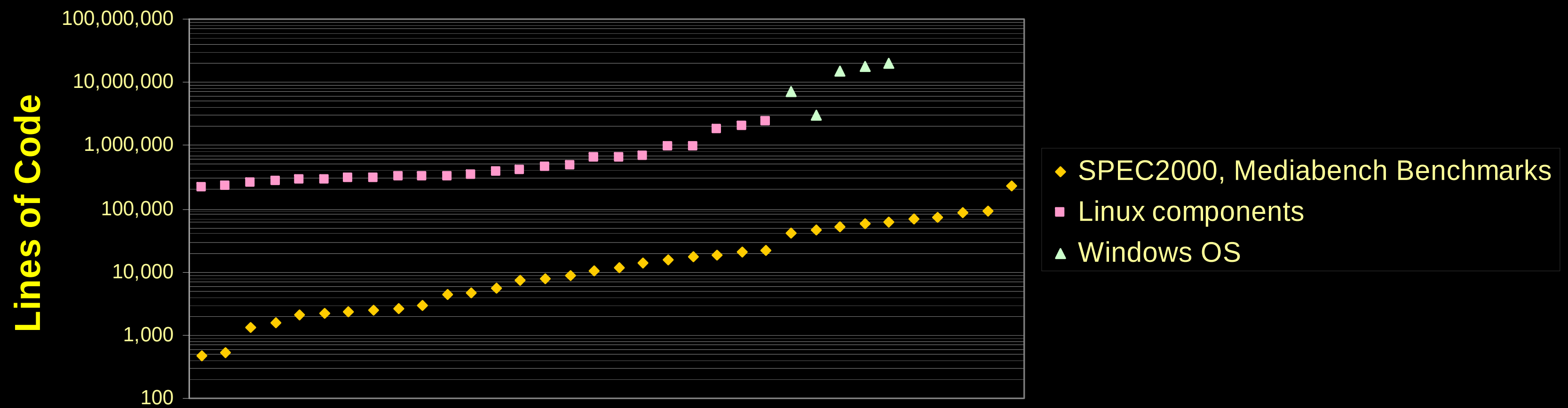
- Support the diversity of programs
  - Support Real Languages: C, C++, (Java)
    - Handle rich control and data structures
    - Tolerate aliasing of pointers
  - Support Real Environments
    - Separate compilation
    - Statically and dynamically linked libraries
- Work beyond an ideal laboratory setting





4: Scalable

- Real applications are large!
  - Algorithm should scale
    - polynomial or exponential in the program size doesn't work
- Real Programs are Dynamic
  - Dynamically loaded libraries
  - Dynamically generated code
- Whole program analysis tractable?



5: Simple

- Aggressive analysis and complex transformation lead to:
  - Buggy compilers!
    - Programmers want to trust their compiler!
    - How do you manage a software project when the compiler is broken?
  - Long time to develop
- Simple compiler $\Rightarrow$ fast compile-times
- Current compilers are too complex!

Compiler	Lines of Code
GNU GCC	~ 1.2 million
SUIF	~ 250,000
Open Research Compiler	~3.5 million
Trimaran	~ 800,000
StreamIt	~ 300,000

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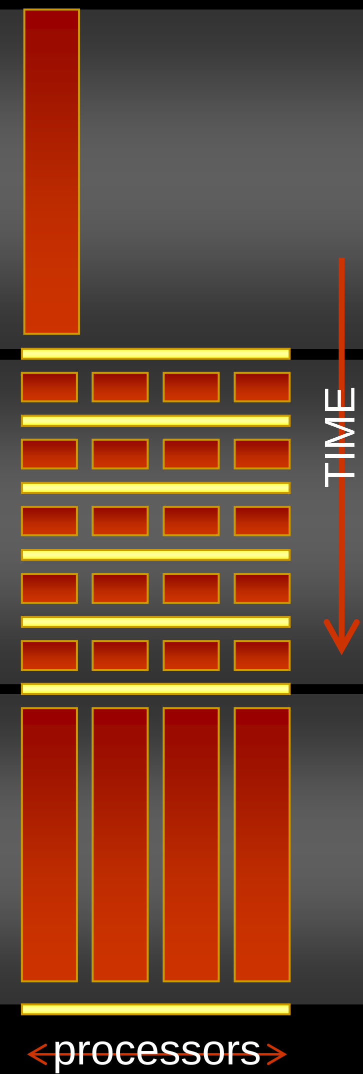
Data Level Parallelism

- Identify loops where each iteration can run in parallel
  - DOALL parallelism
- What affects performance?
  - Parallelism Coverage
  - Granularity of Parallelism
  - Data Locality

```
TDT = DT
 MP1 = M+1
 NP1 = N+1
 EL = N*DX
 PI = 4.D0*ATAN(1.D0)
 TPI = PI+PI
 DI = TPI/M
 DJ = TPI/N
 PCF = PI*PI*A*A/(EL*EL)

 DO 50 J=1,NP1
    DO 50 I=1,MP1
         PSI(I,J) = A*SIN((
         I-.5D0)*DI)*
         SIN((J-.5D0)*DJ)
         P(I,J) = PCF*(COS(2.D0)
CONTINUE

 DO 60 J=1,N
      DO 60 I=1,M
         U(I+1,J) = -(PSI(I+1,J+1)
         -PSI(I+1,J))/DY
         V(I,J+1) = (PSI(I+1,J+1)-
         PSI(I,J+1))/DX
 CONTINUE
```



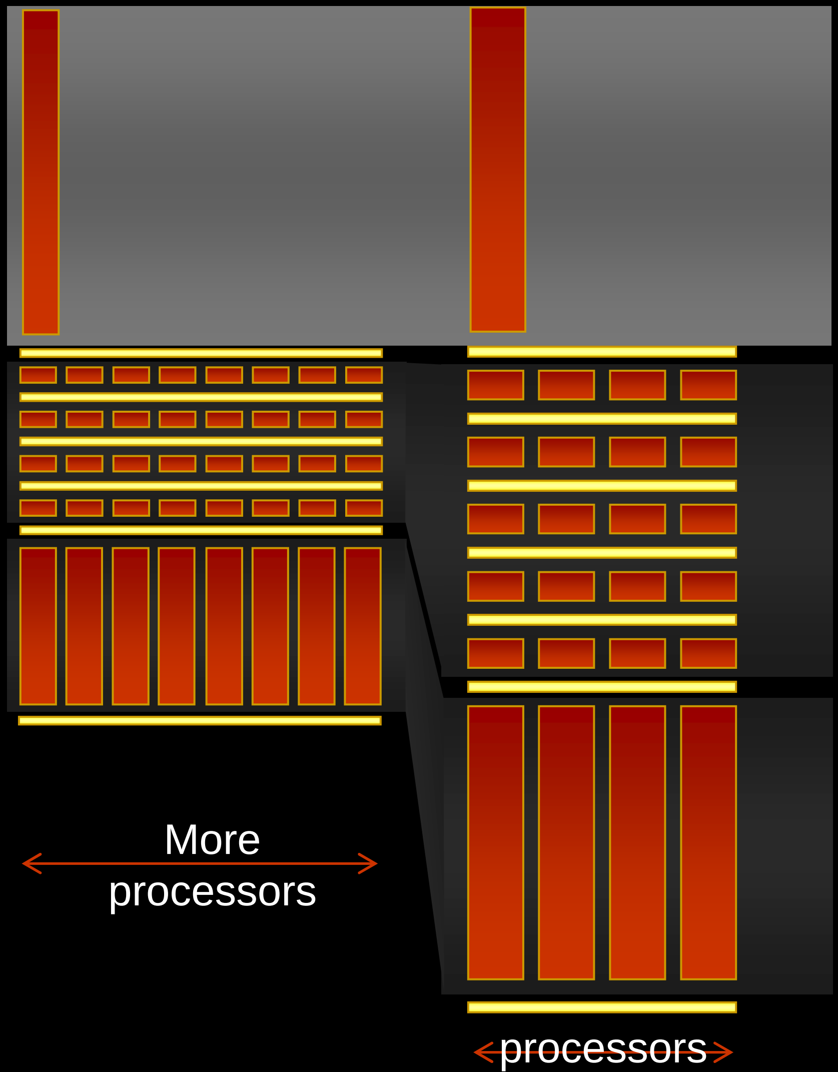
Parallelism Coverage

- Amdahl's Law

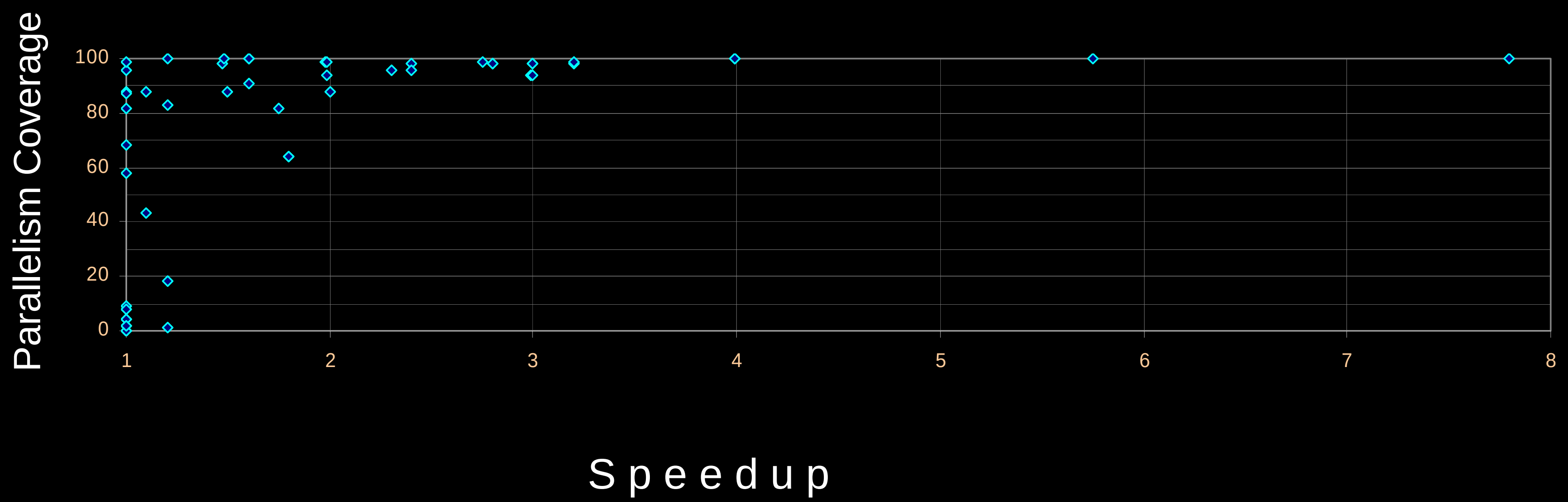
  Performance improvement to be gained from faster mode of execution is limited by the fraction of the time

  the faster mode can be used

- Find more parallelism
  - Interprocedural analysis
  - Alias analysis
  - Data-flow analysis
  - ……



SUIF Parallelizer Results

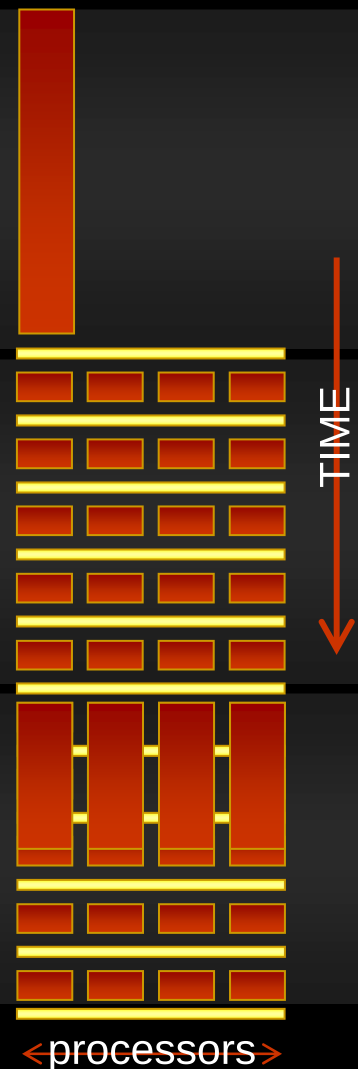


SPEC95fp, SPEC92fp, Nas, Perfect Benchmark Suites
On a 8 processor Silicon Graphics Challenge (200MHz MIPS R4000)

Granularity of Parallelism

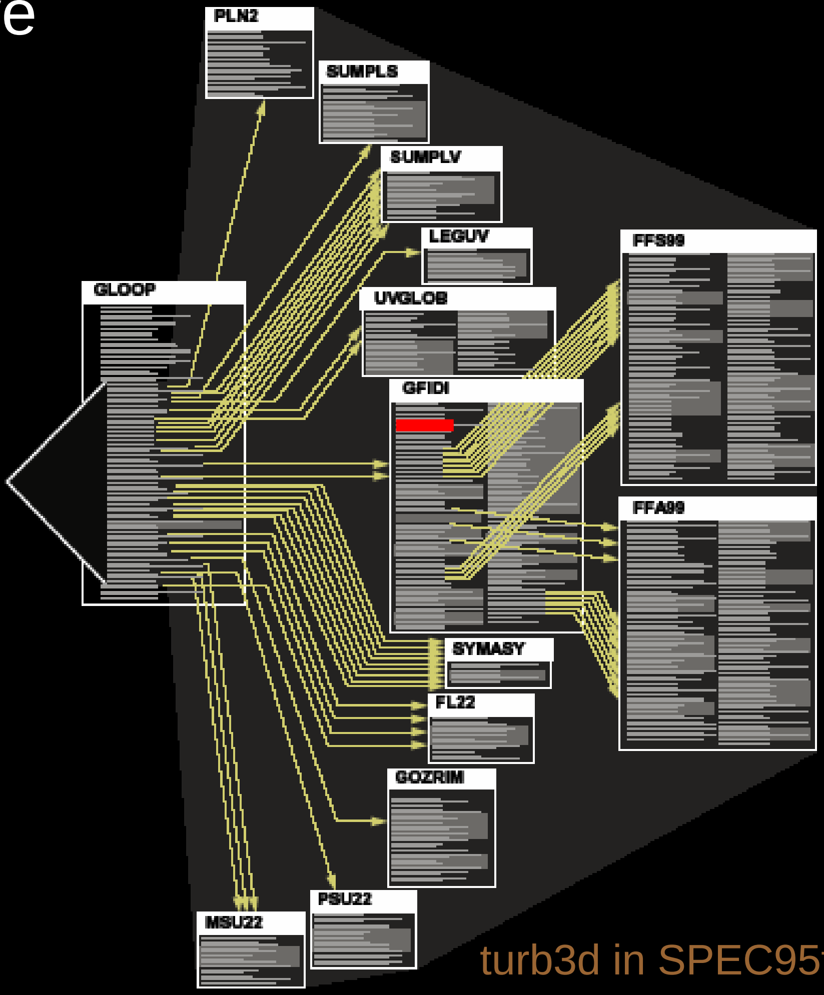
- Synchronization is expensive
- Need to find very large parallel regions → coarse-grain loop nests
- Heroic analysis required

```
TDT = DT
 MP1 = M+1
 NP1 = N+1
 EL = N*DX
 PI = 4.D0*ATAN(1.D0)
 TPI = PI+PI
 DI = TPI/M
 DJ = TPI/N
 PCF = PI*PI*A*A/(EL*EL)

 DO 50 J=1,NP1
    DO 50 I=1,MP1
         PSI(I,J) = A*SIN((
         I-.5D0)*DI)*
         SIN((J-.5D0)*DJ)
         P(I,J) = PCF*(COS(2.D0)
CONTINUE

 DO 60 J=1,N
     DO 60 I=1,M
         U(I+1,J) = -(PSI(I+1,J+1)
         -PSI(I+1,J))/DY
         V(I,J+1) = (PSI(I+1,J+1)-
         PSI(I,J+1))/DX
 CONTINUE
```



Granularity of Parallelism

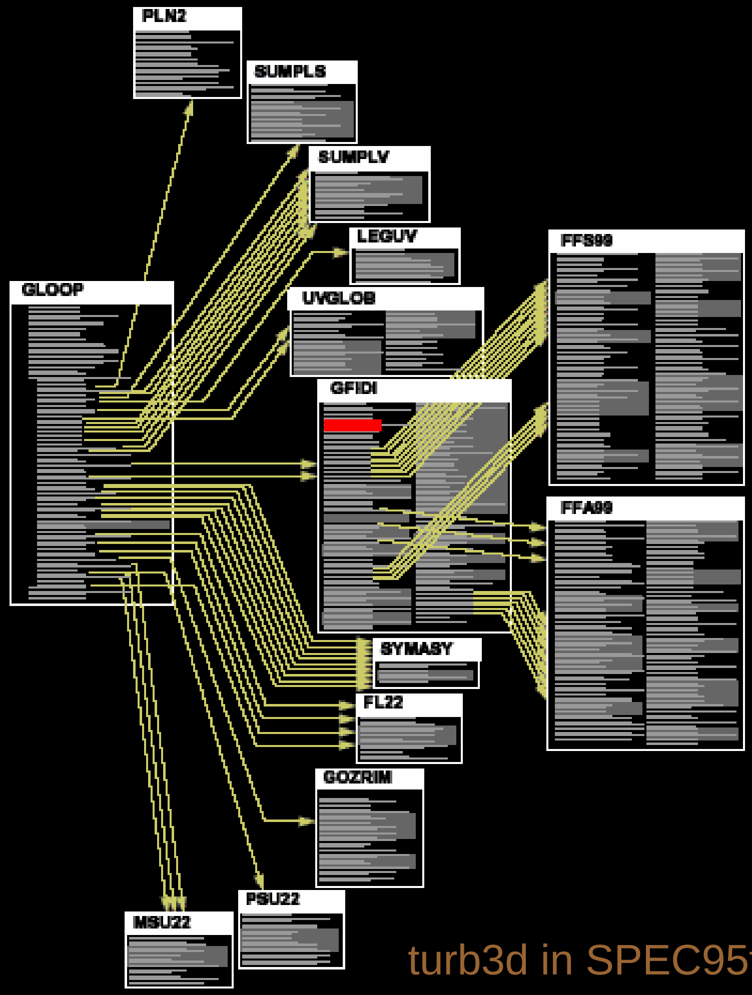
- Synchronization is expensive
- Need to find very large parallel regions → coarse-grain loop nests
- Heroic analysis required
- Single unanalyzable line →



turb3d in SPEC95fp

Granularity of Parallelism

- Synchronization is expensive
- Need to find very large parallel regions → coarse-grain loop nests
- Heroic analysis required
- Single unanalyzable line →
  - Small Reduction in Coverage
  - Drastic Reduction in Granularity



turb3d in SPEC95fp

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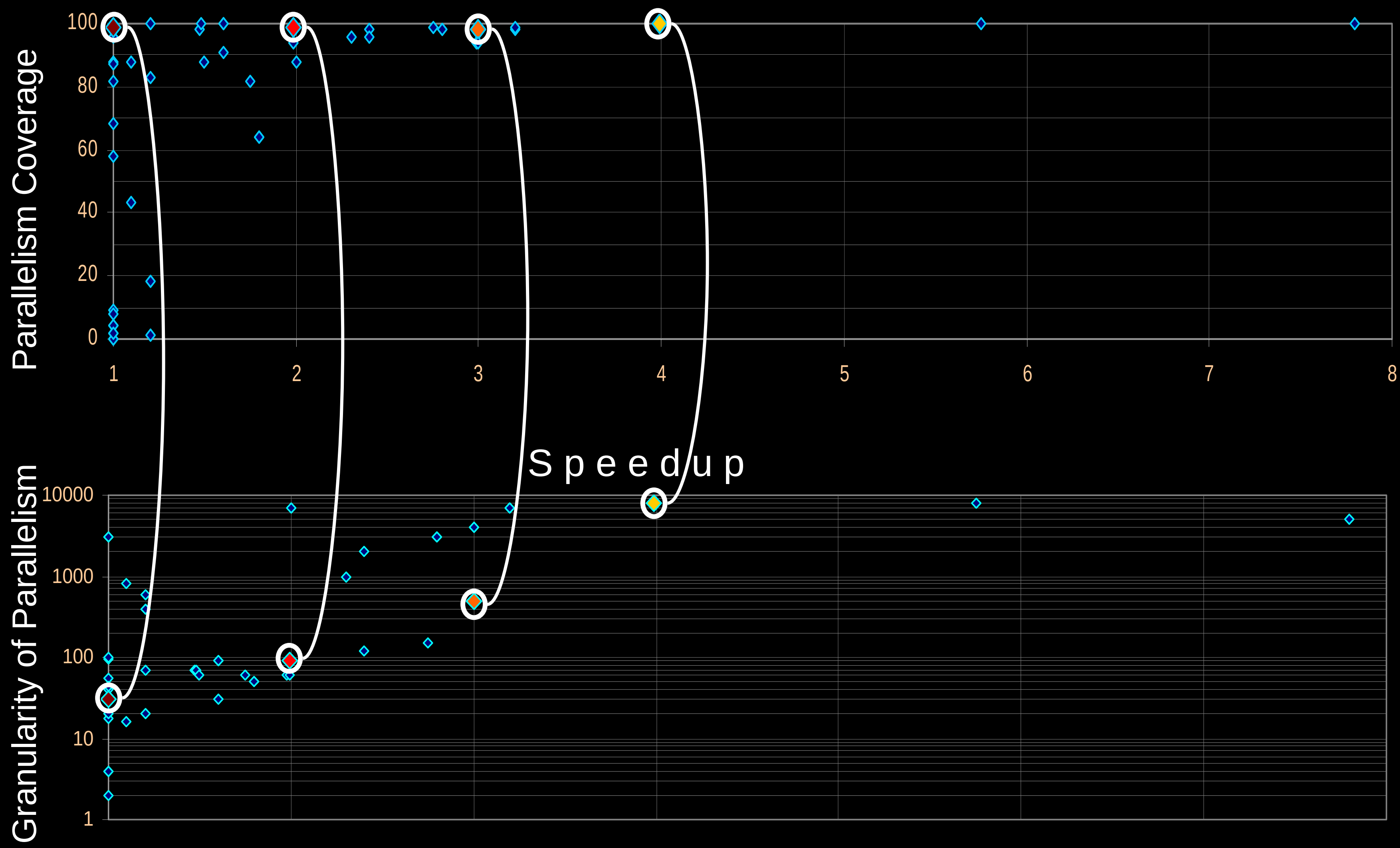
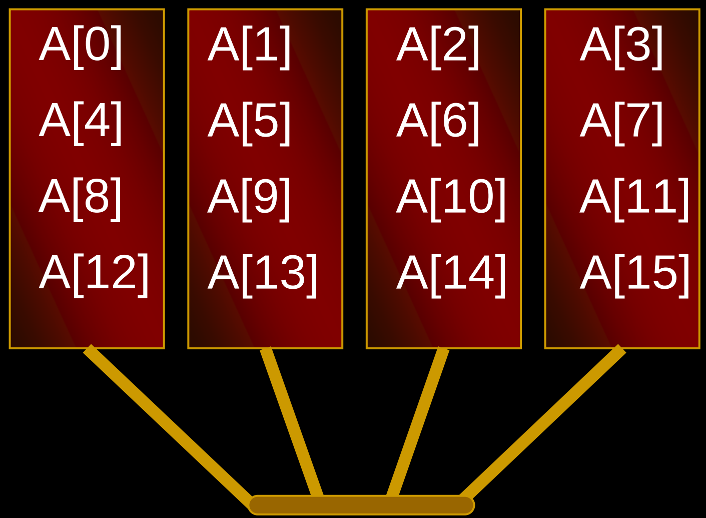


Data Locality

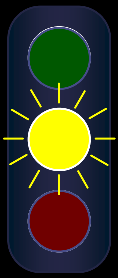
- Non-local data →
  - Stalls due to latency
  - Serialize when lack of bandwidth



- Data Transformations
  - Global impact
  - Whole program analysis

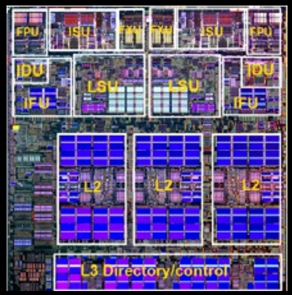
DLP on Multiprocessors: Current State

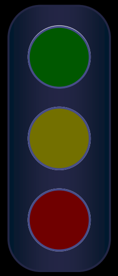
- Huge body of work over the years.
  - Vectorization in the ’80s
  - High Performance Computing in ’90s



- Commercial DLP compilers exist
  - But…only a very small user community

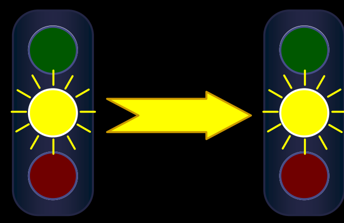
- Can multicores make DLP mainstream?





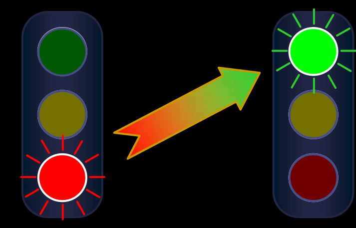
?

Effectiveness



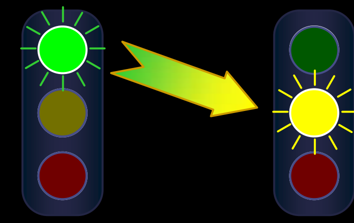
- Main Issue
  - Parallelism Coverage
- Compiling to Multiprocessors
  - Amdahl's law
    - Many programs have no loop-level parallelism
- Compiling to Multicores
  - Nothing much has changed

Stability



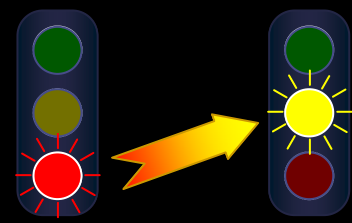
- Main Issue
  - Granularity of Parallelism
- Compiling for Multiprocessors
  - Unpredictable, drastic granularity changes reduce the stability
- Compiling for Multicores
  - Low latency → granularity is less important

Generality



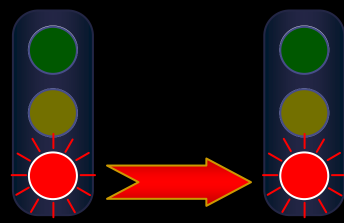
- Main Issue
  - Changes in general purpose programming styles over time impacts compilation
- Compiling for Multiprocessors *(In the good old days)*
  - Mainly FORTRAN
    - Loop nests and Arrays
- Compiling for Multicores
  - Modern languages/programs are hard to analyze
    - Aliasing (C, C++ and Java)
    - Complex structures (lists, sets, trees)
    - Complex control (concurrency, recursion)
    - Dynamic (DLLs, Dynamically generated code)

Scalability



- Main Issue
  - Whole program analysis and global transformations don't scale
- Compiling for Multiprocessors
  - Interprocedural analysis needed to improve granularity
  - Most data transformations have global impact
- Compiling for Multicores
  - High bandwidth and low latency → no data transformations
  - Low latency → granularity improvements not important

Simplicity



- Main Issue
  - Parallelizing compilers are exceedingly complex
- Compiling for Multiprocessors
  - Heroic interprocedural analysis and global transformations are required because of high latency and low bandwidth
- Compiling for Multicores
  - Hardware is a lot more forgiving…
  - But…modern languages and programs make life difficult

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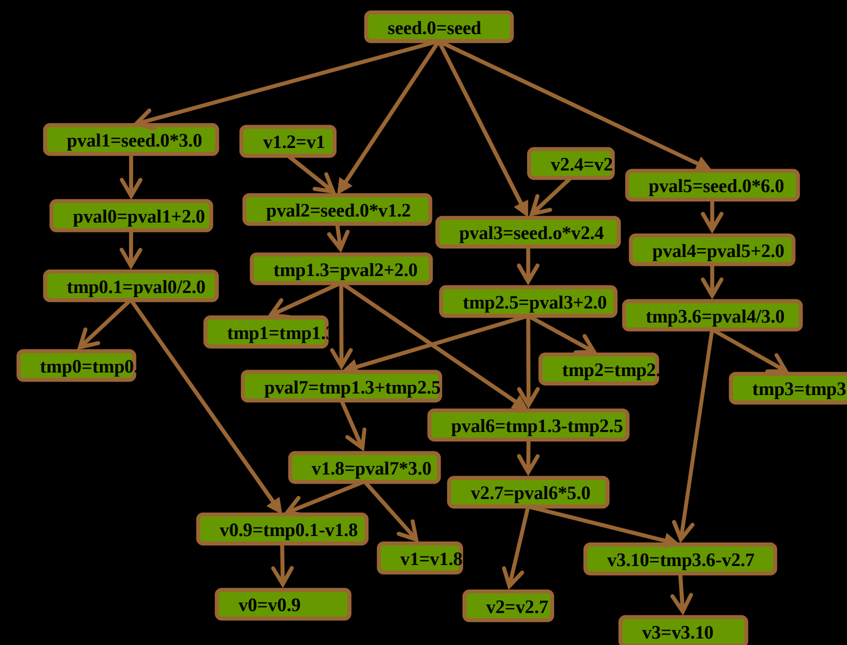
Instruction Level parallelism on a Unicore

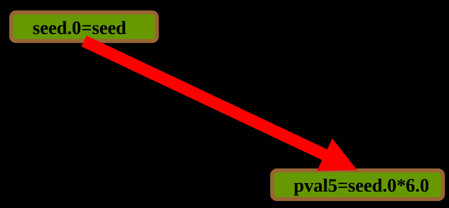
```
tmp0 = (seed*3+2)/2
tmp1 = seed*v1+2
tmp2 = seed*v2 + 2
tmp3 = (seed*6+2)/3
v2 = (tmp1 - tmp3)*5
v1 = (tmp1 + tmp2)*3
v0 = tmp0 - v1
v3 = tmp3 - v2
```

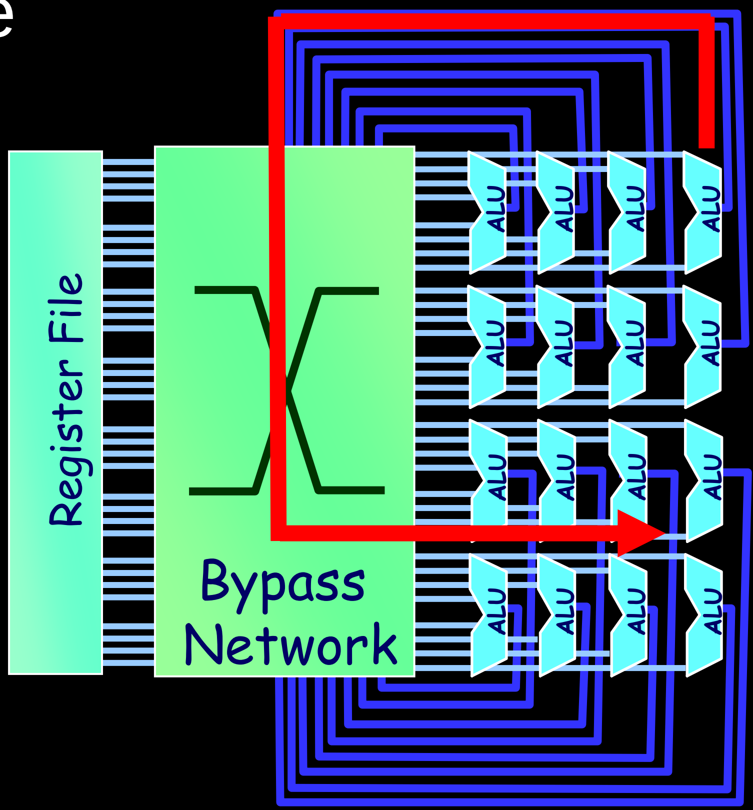


- Programs have ILP
- Modern processors extract the ILP
  - Superscalars → Hardware
  - VLIW → Compiler

Scalar Operand Network (SON)

- Moves results of an operation to dependent instructions
- Superscalars → in Hardware
- What makes a good SON?





Scalar Operand Network (SON)

- Moves results of an operation to dependent instructions
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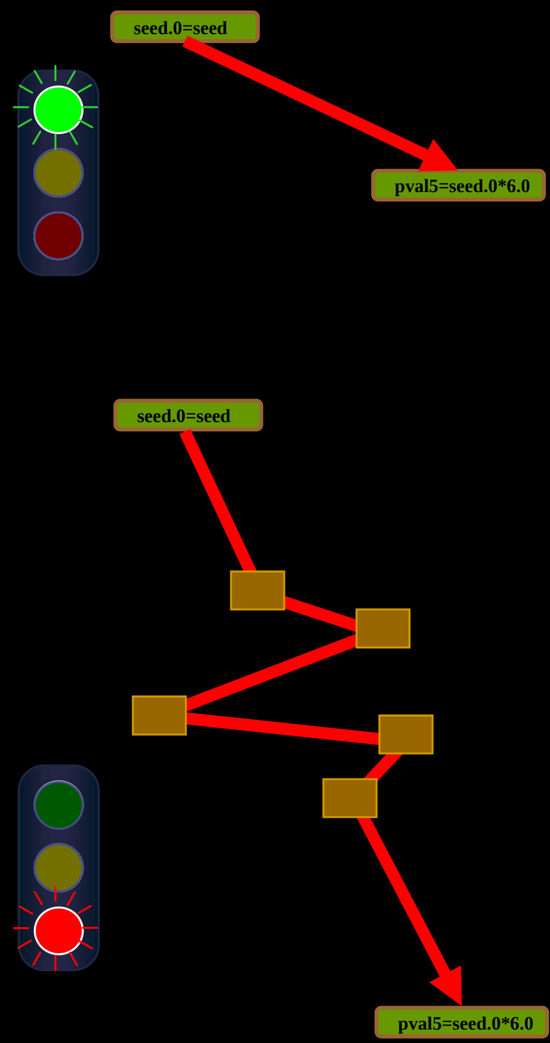
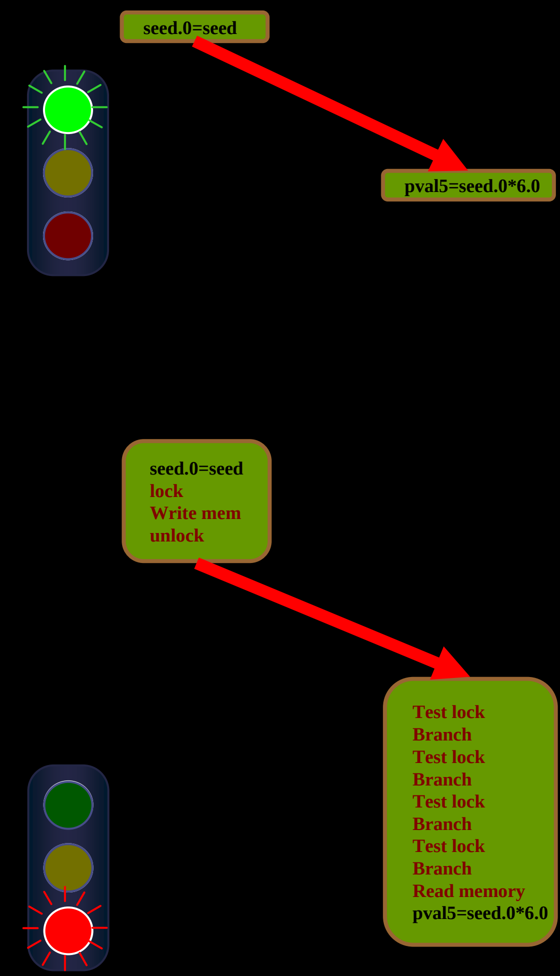
- What makes a good SON?
  - Low latency from producer to consumer



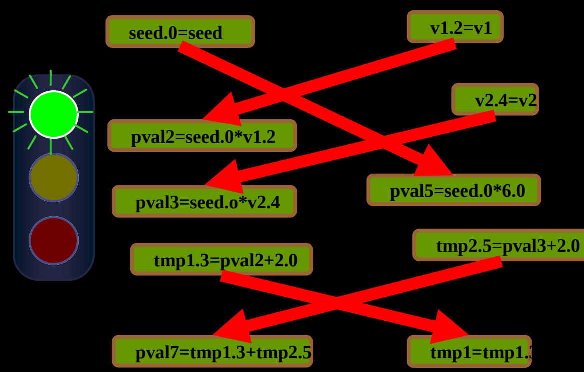
Scalar Operand Network (SON)

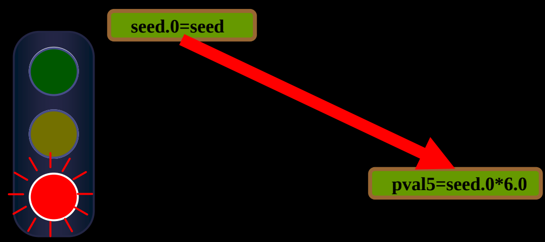
- Moves results of an operation to dependent instructions
- Superscalars → in Hardware
- What makes a good SON?
  - Low latency from producer to consumer
  - Low occupancy at the producer and consumer



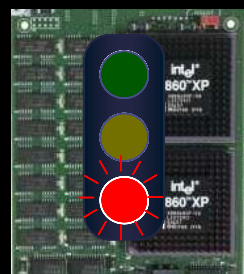
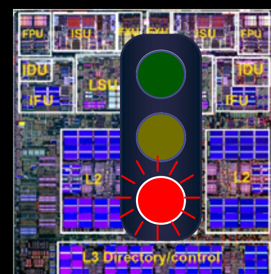
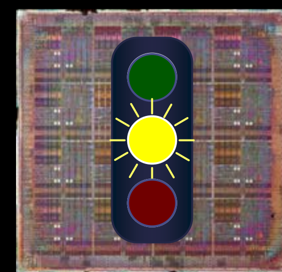
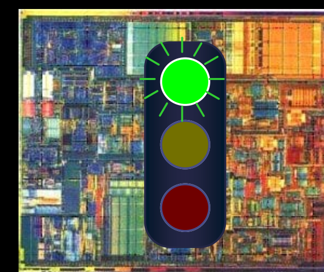
Scalar Operand Network (SON)

- Moves results of an operation to dependent instructions
- Superscalars → in Hardware
- What makes a good SON?
  - Low latency from producer to consumer
  - Low occupancy at the producer and consumer
  - High bandwidth for multiple operations





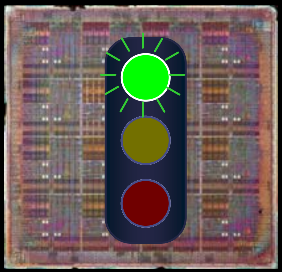
Is an Integrated Multcore Reedy to be a Scalar Operand Network?

	Traditional Multiprocessor	Basic Multicore	Integrated Multicore	VLIW Unicore
				
Latency (cycles)	60	4	3	0
Occupancy (instructions)	50	10	0	0
Bandwidth (operands/cycle)	1	2	16	6

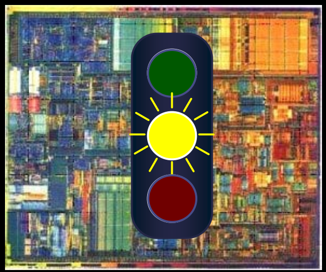
Scalable Scalar Operand Network?

- Unicores
  - N2 connectivity
  - Need to cluster → introduces latency
- Integrated Multicores
  - No bottlenecks in scaling

Integrated Multicore

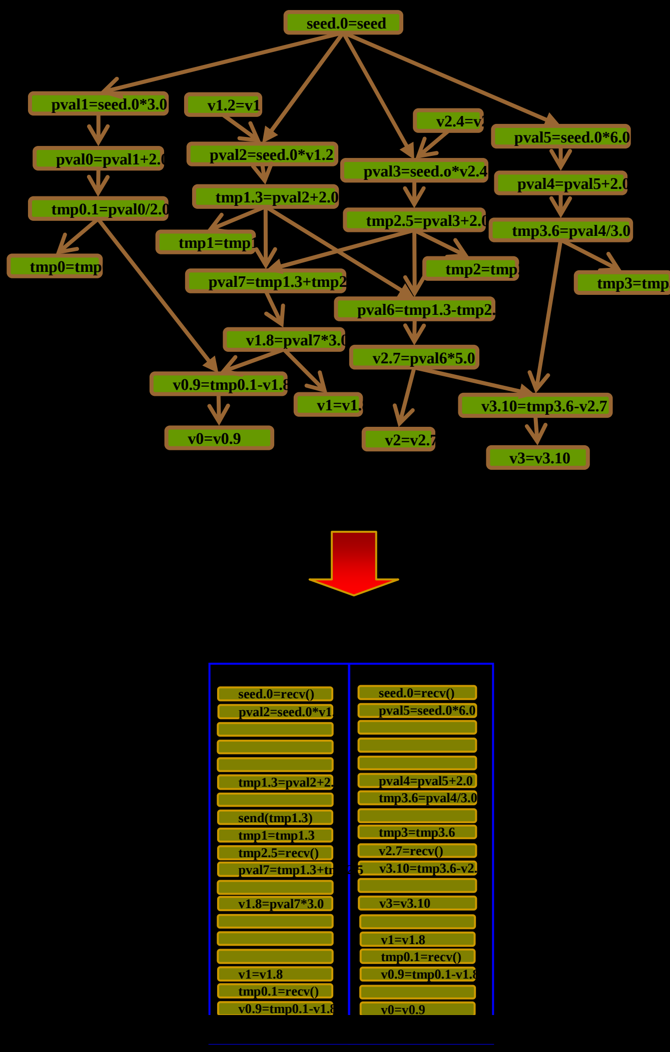


Unicore



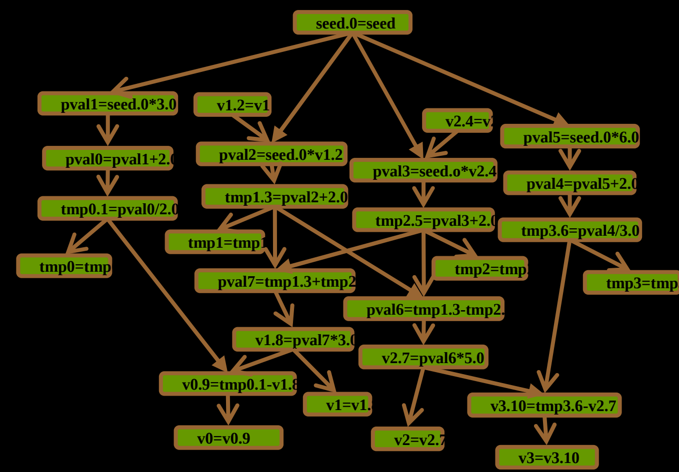
Compiler Support for Instruction Level Parallelism

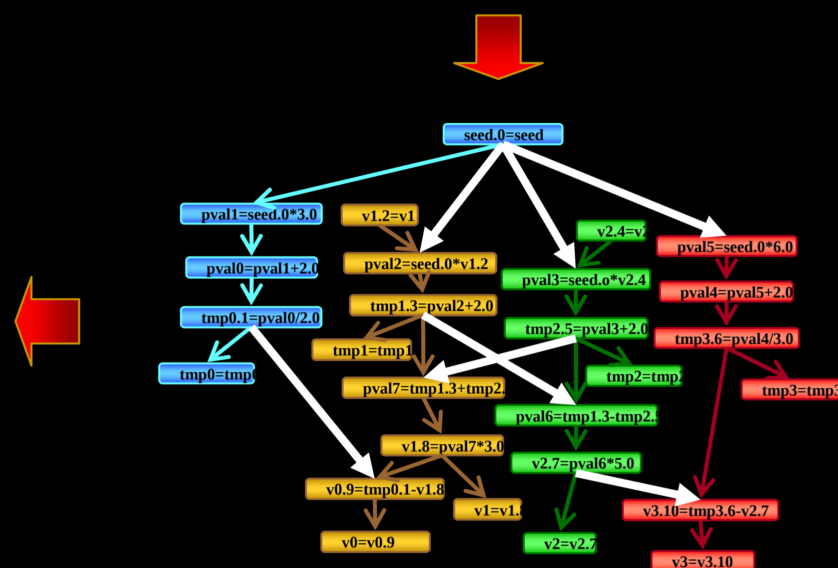
- Accepted general purpose technique
  - Enhance the performance of superscalars
  - Essential for VLIW
- Instruction Scheduling
  - List scheduling or Software pipelining

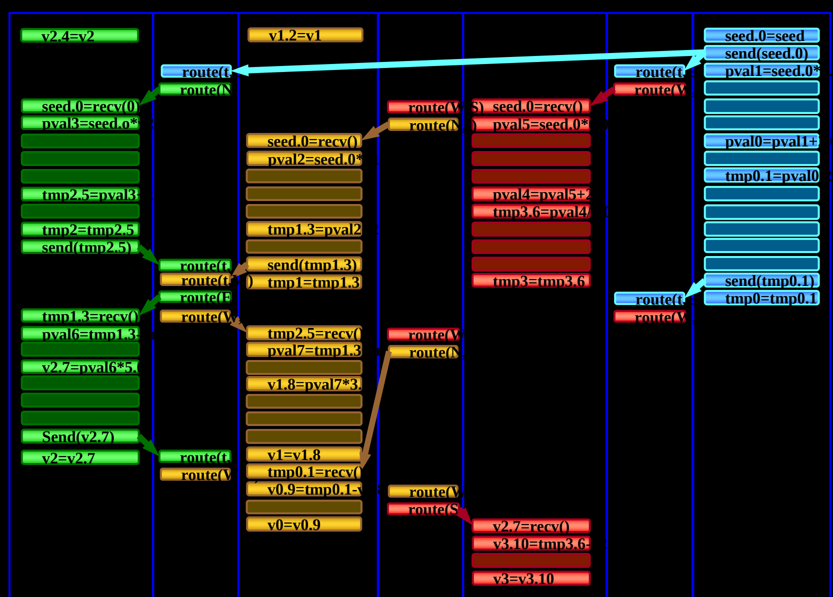


ILP on Integrated Multicores:
Space-Time Instruction Scheduling

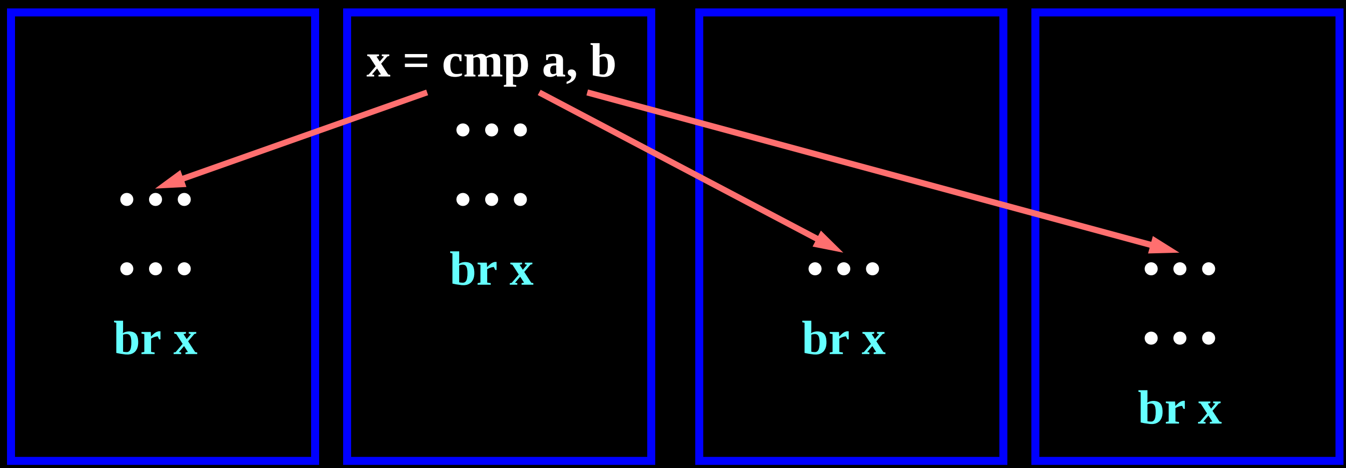
- Partition, placement, route and schedule
- Similar to Clustered VLIW





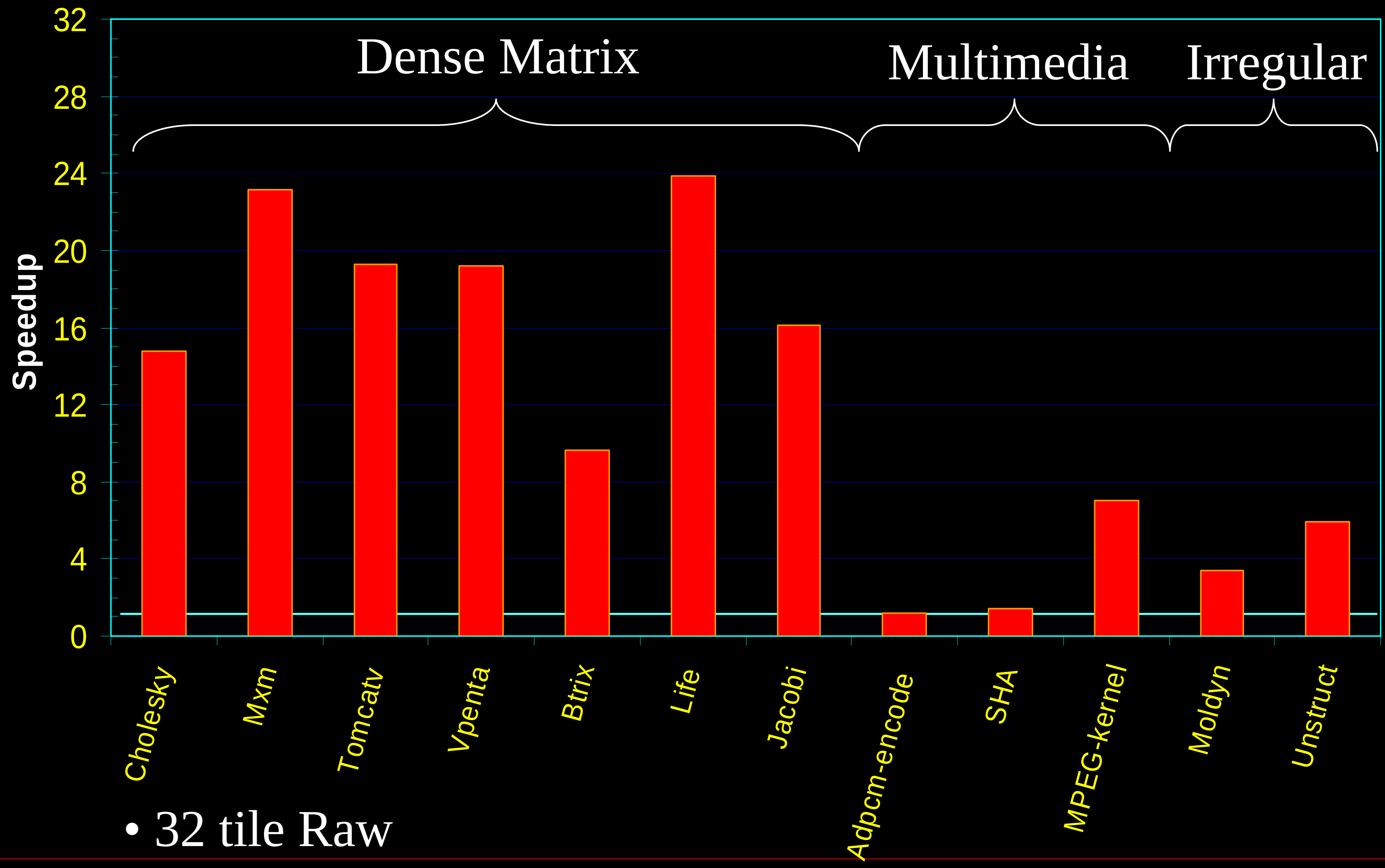


Handling Control Flow



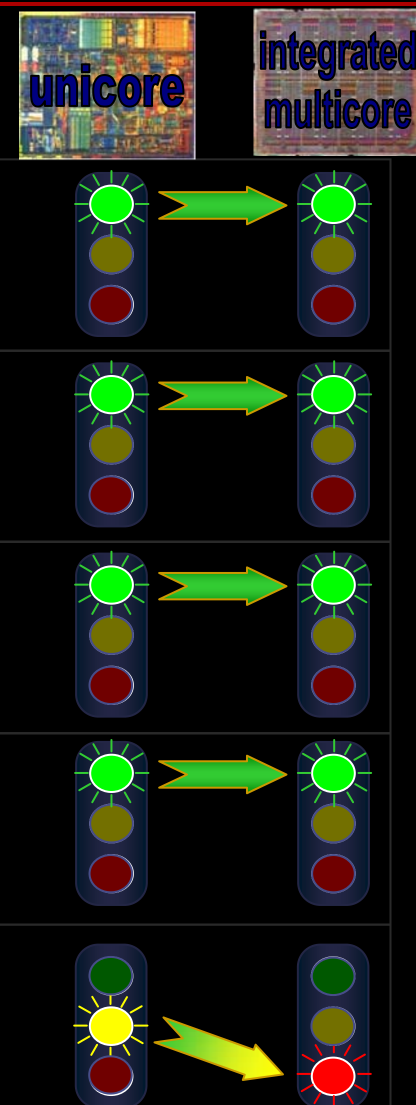
- Asynchronous global branching
  - Propagate the branch condition to all the tiles as part of the basic block schedule
  - When finished with the basic block execution asynchronously switch to another basic block schedule depending on the branch condition

Raw Performance



- 32 tile Raw

Success Criteria

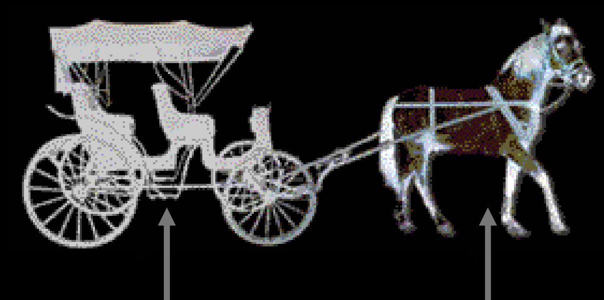


1. Effective
   - If ILP exists → same
2. Stable
   - Localized optimization → similar
3. General
   - Applies to same type of applications
4. Scalable
   - Local analysis → similar
5. Simple
   - Deeper analysis and more transformations

Outline

- Introduction
- Overview of Multicores
- Success Criteria for a Compiler
- Data Level Parallelism
- Instruction Level Parallelism
- Language Exposed Parallelism
- Conclusion

Languages are out-of-touch with Architecture



C ⇔ von-Neumann machine

Modern architecture

- Two choices:
  - Develop cool architecture with complicated, ad-hoc language
  - Bend over backwards to support old languages like C/C++

Supporting von Neumann Languages

- Why C (FORTRAN, C++ etc.) became very successful?
  - Abstracted out the differences of von Neumann machines
    - Register set structure
    - Functional units and capabilities
    - Pipeline depth/width
    - Memory/cache organization
  - Directly expose the common properties
    - Single memory image
    - Single control-flow
    - A clear notion of time
  - Can have a very efficient mapping to a von Neumann machine
  - "C is the portable machine language for von Numann machines"
- Today von Neumann languages are a curse
  - We have squeezed out all the performance out of C
  - We can build more powerful machines
  - But, cannot map C into next generation machines
  - Need better languages with more information for optimization

New Languages for Cool Architectures

- Processor specific languages
  - Not portable
- Increase the burden on programmers
  - Many more tasks for the programmer (parallelism annotations, memory alias annotations)
  - But, no software engineering benefits
- Assembly hacker mentality
  - Worked so hard on putting architectural features
  - Don't want compilers to squander it away
  - Proof-of-concept done in assembly
- Architects don't know how to design languages

What Motivates Language Designers

- Primary Motivation → Programmer Productivity
  - Raising the abstraction layer
  - Increasing the expressiveness
  - Facilitating design, development, debugging, maintenance of large complex applications

- Design Considerations
  - Abstraction → Reduce the work programmers have to do
  - Malleablility → Reduce the interdependencies
  - Safety → Use types to prevent runtime errors
  - Portability → Architecture/system independent

- No consideration given for the architecture
  - For them, performance is a non-issue!

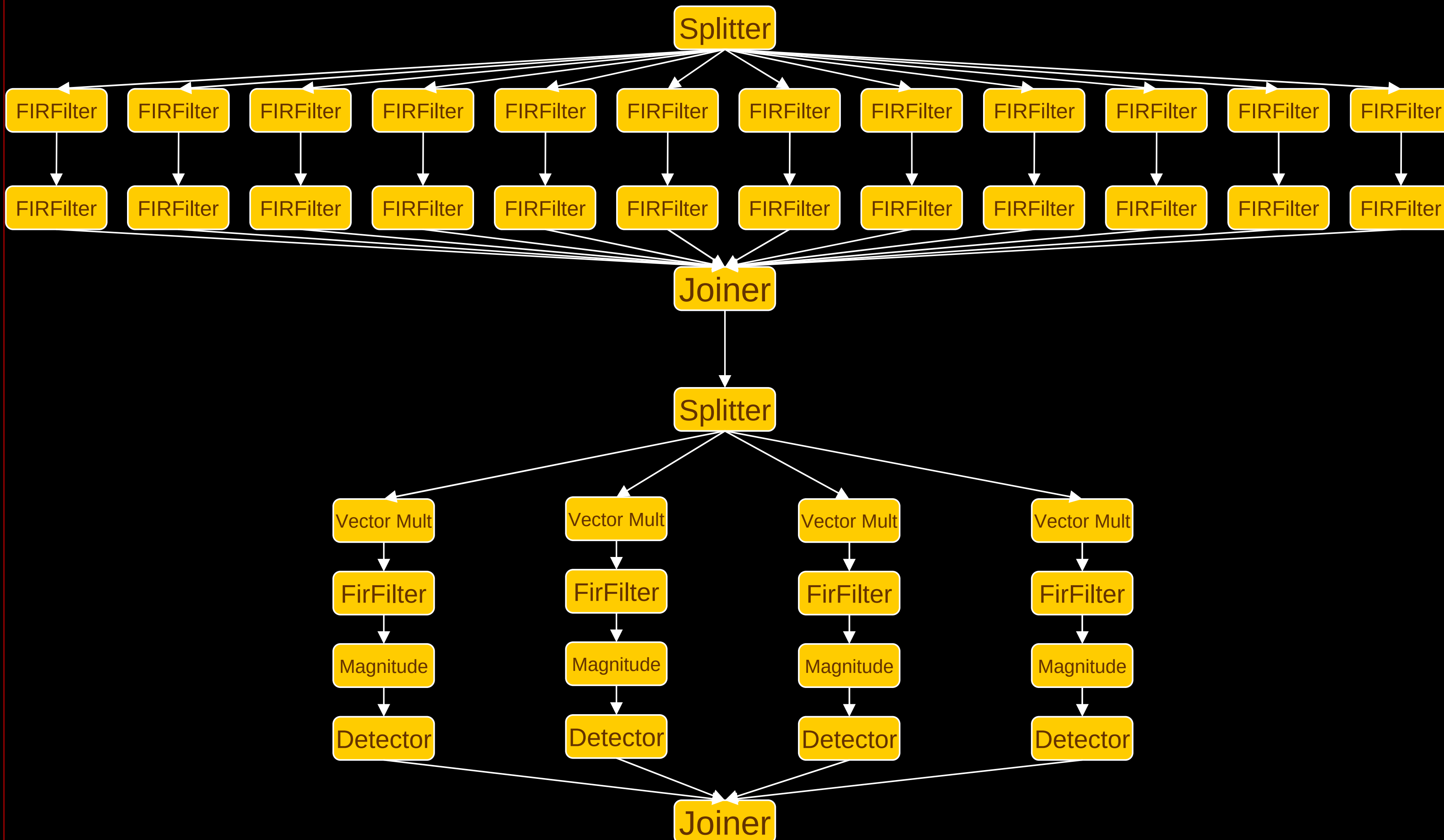
Is There a Win-Win Solution

- Languages that increase programmer productivity while making it easier to compile

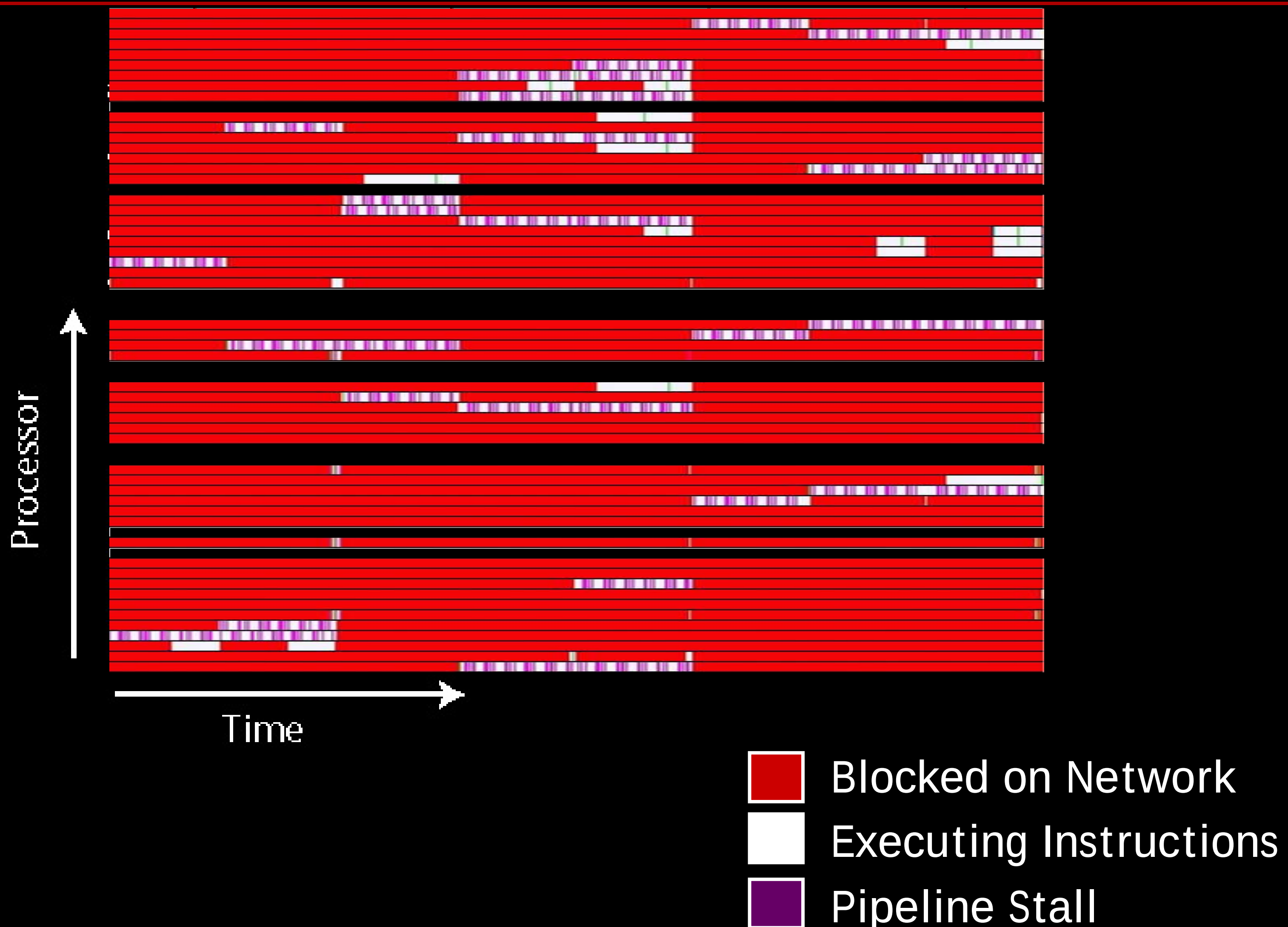
Example: StreamIt, A spatially-aware Language

- A language for streaming applications
  - Provides high-level stream abstraction
    - Exposes Pipeline Parallelism
  - Improves programmer productivity
- Breaks the von Neumann language barrier
  - Each filter has its own control-flow
  - Each filter has its own address space
  - No global time
  - Explicit data movement between filters
  - Compiler is free to reorganize the computation

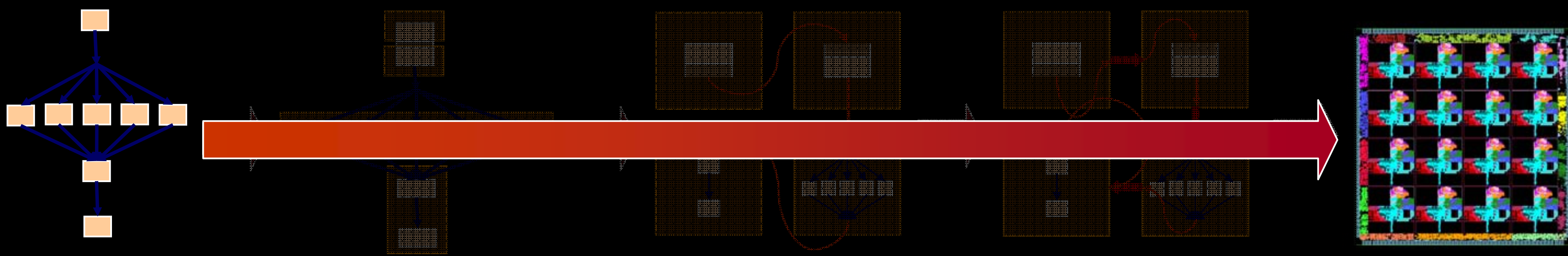
Example: Radar Array Front End



Radar Array Front End on Raw

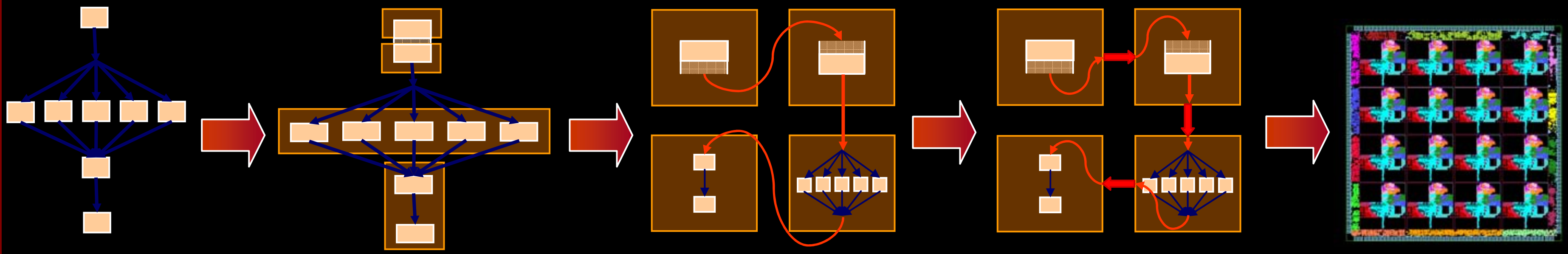


Bridging the Abstraction layers



- StreamIt language exposes the data movement
  - Graph structure is architecture independent
- Each architecture is different in granularity and topology
  - Communication is exposed to the compiler
- The compiler needs to efficiently bridge the abstraction
  - Map the computation and communication pattern of the program to the tiles, memory and the communication substrate

Bridging the Abstraction layers



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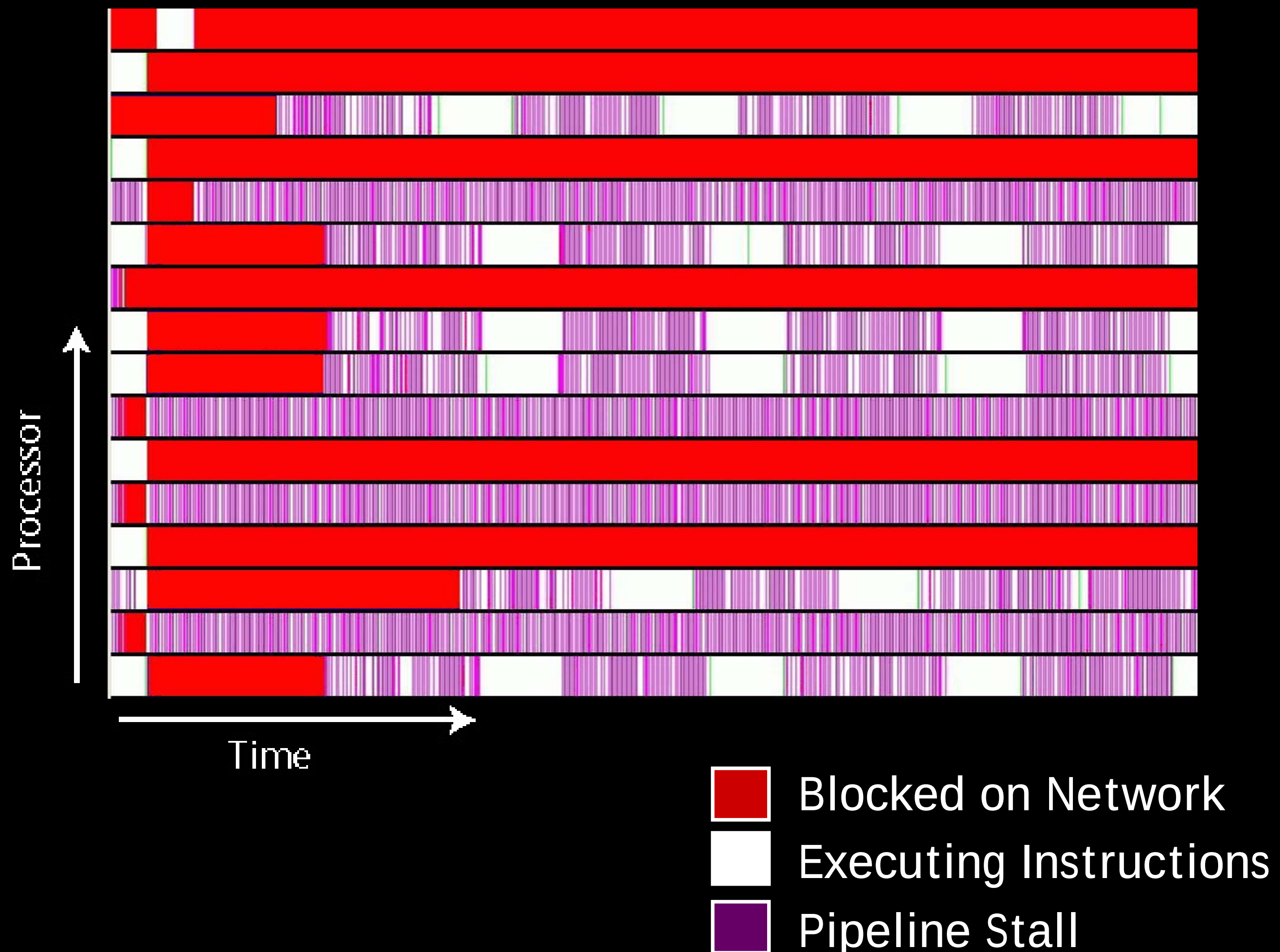
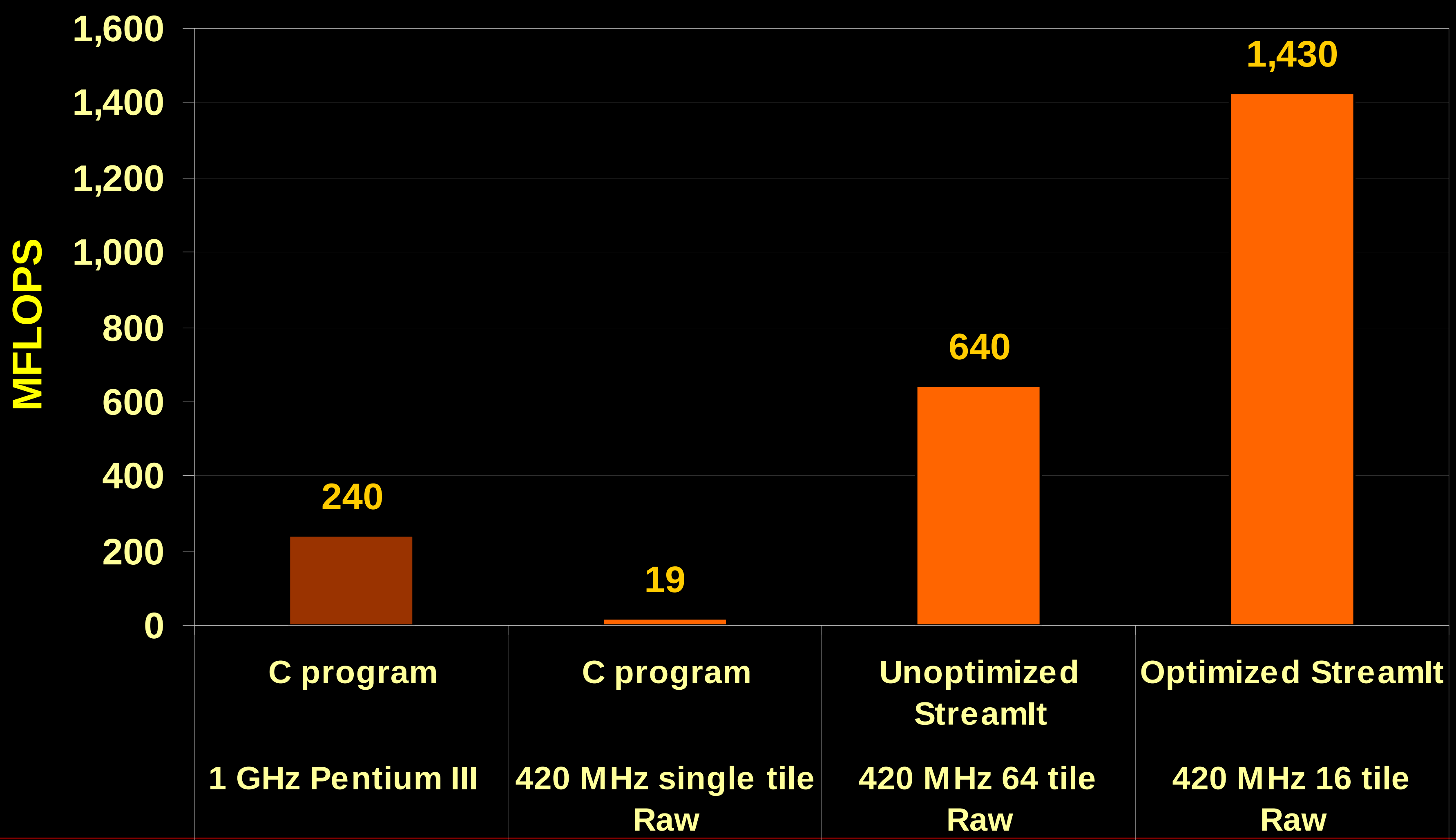
  - Communication is exposed to the compiler
- The compiler needs to efficiently bridge the abstraction
  - Map the computation and communication pattern of the program to the tiles, memory and the communication substrate
- The StreamIt Compiler
  - Partitioning
  - Placement
  - Scheduling
  - Code generation

Optimized Performance for Radar Array Front End on Raw



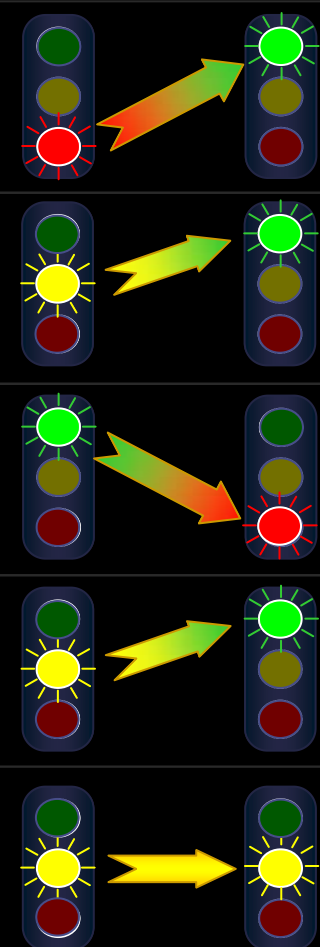
Performance



Success Criteria

Compiler for: **Von Neumann Languages** | **Stream Language**

1. Effective
   - Information available for more optimizations
2. Stable
   - Much more analyzable
3. General
   - Domain-Specific
4. Scalable
   - No global data structures
5. Simple
   - Heroic analysis vs. more transformations



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Overview of Success Criteria

	Data Level Parallelism		Instruction Level Parallelism		Language Exposed Parallelism on Multicore	
	multi processor	basic multicore	unicore	integrated multicore	Von Neumann Languages	Stream Language
1. Effective						
2. Stable						
3. General						
4. Scalable						
5. Simple						

Can Compilers take on Multicores?

- Success Criteria is Somewhat Mixed
- But….
  - Don’t need to compete with unicores
  - Multicores will be available regardless
- New Opportunities
  - Architectural advances in integrated multicores
  - Domain specific languages
  - Possible compiler support for using multicores for other than parallelism
    - Security Enforcement
    - Program Introspection
    - ISA extensions

http://cag.csail.mit.edu/commit
http://www.determina.com