EPIC Architectures and Compiler Technology

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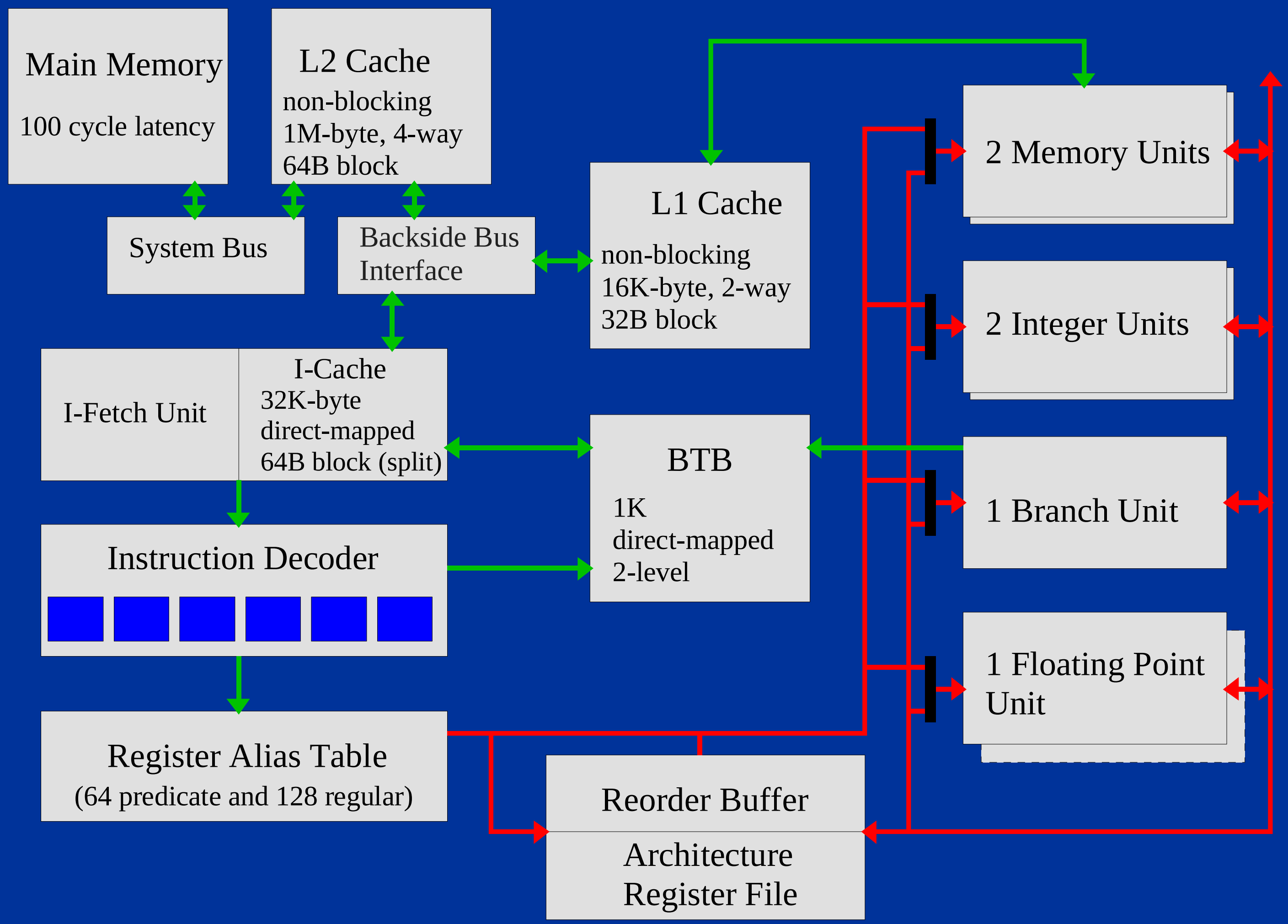
IMPACT Compiler Group
http://www.crhc.uiuc.edu/IMPACT/

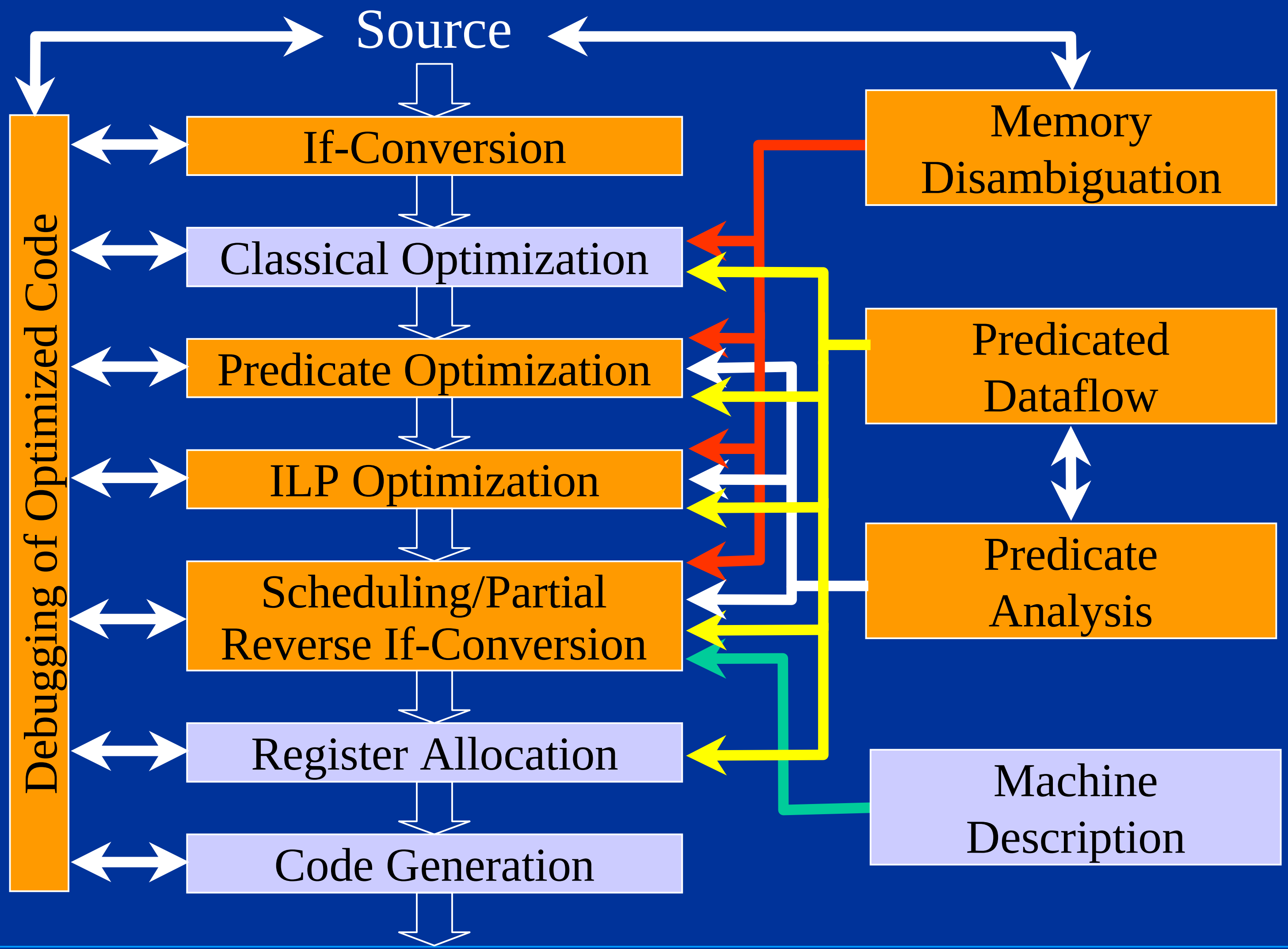
Microprocessor Vision 1999

- UI/HP/Intel research coalition formed in 1992
- Goals
  - ILP architecture features to greatly increase productive IPC
    - eliminate branches and control dependences
    - support software to approach global scheduling
    - control code size explosion
  - Adaptive management of cache and bus hierarchy
    - reduce memory related stall cycles
  - Support software migration
    - support fine-grain mixture of old and new code
  - No compromise on cycle time

Microprocessor Microarchitecture



EPIC Compiler Technology Overview



Predicated Execution

- Conditional execution of instructions based on a Boolean source operand
- Execution model
  - Load r1, r2, r3 <p1>
  - If p1 is TRUE, instruction executes normally
  - If p1 is FALSE, instruction treated as NOP (with some exceptions)
- Provides compiler with an alternative to guarding instruction execution with branches

Instruction Set Support for Predicated Execution

- Full Predication Support
  - Predicate defining instructions
  - Full set of predicated instructions
  - Separate register file
  - Best performance
- Partial Predication Support
  - Limited set of predicated instructions added to existing ISA (CMOV, SELECT)
  - Brings some performance increase to existing ISA's
- Dynamic Predication Support
  - No ISA change needed
  - Smallest performance gain

Predicate Defining Instructions
(HPL PlayDoh Spec)

pred_< *cmp* > P1 < *type* >, P2 < *type* >, src1, src2 (Pin)

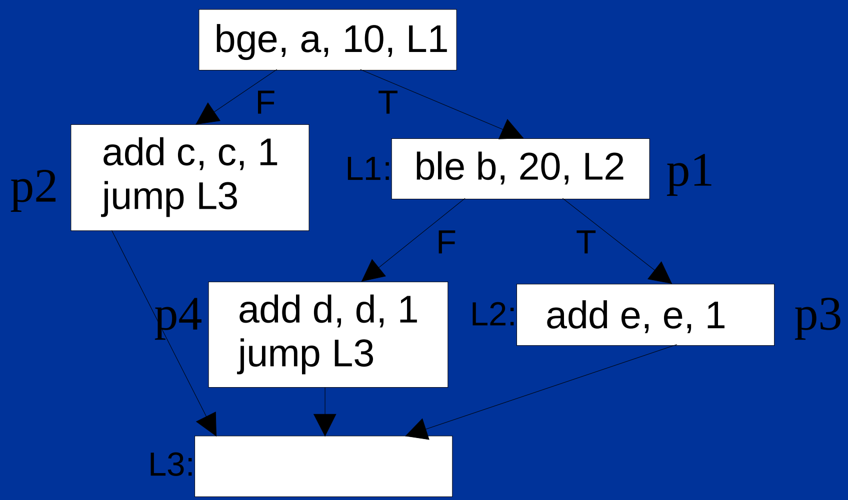
- < *cmp* > - comparison type: =, >, <, etc.
- < *type* >
  - Unconditional (U, U)
  - OR-type (OR, OR)
  - AND-type (AN, AN)
  - Conditional (C, C)

Unconditional Predicate Defines

- Handle blocks executed on one condition

```
if (a < 10)
  c = c + 1
else
  if (b > 20)
    d = d + 1
  else
    e = e + 1
```

pred_ge p1(U), p2($\overline{U}$), a, 10
add c, c, 1 (p2)
pred_le p3(U), p4($\overline{U}$), b, 20 (p1)
add d, d, 1 (p4)
add e, e, 1 (p3)



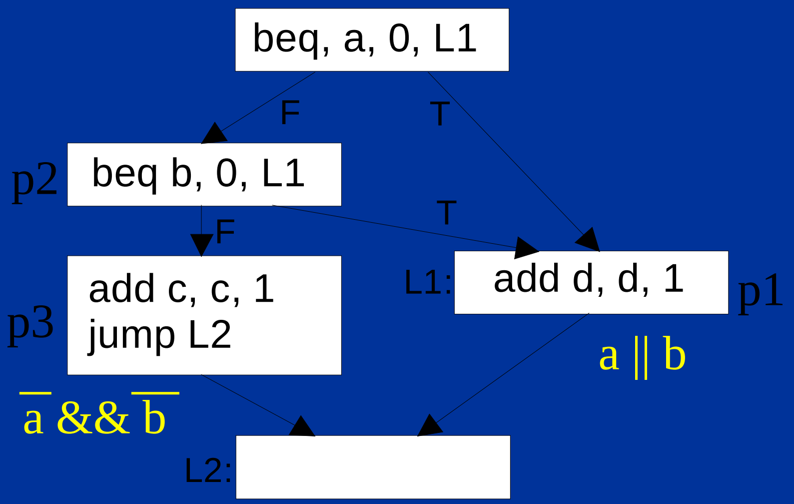
		Pout	
Pin	Comparison	U	$\overline{U}$
0	0	0	0
0	1	0	0
1	0	0	1
1	1	1	0

OR-type Predicate Defines

- Handle blocks executed on multiple conditions

```
if (a && b)
   c = c + 1;
else
   d = d + 1;
```

pred_clr p1
pred_eq p1(OR), p2($\overline{U}$), a, 0
pred_eq p1(OR), p3($\overline{U}$), b, 0 (p2)
add c, c, 1 (p3)
add d, d, 1 (p1)



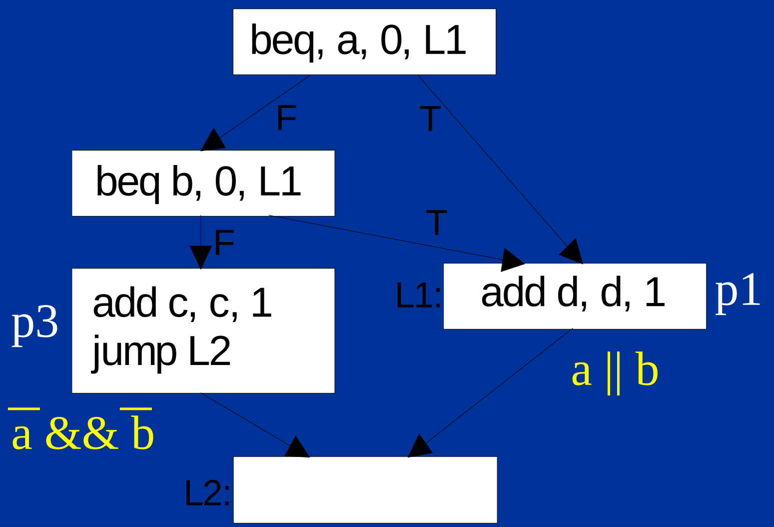
Pin	Comparison	Pout OR	Pout $\overline{OR}$
0	0	-	-
0	1	-	-
1	0	-	1
1	1	1	-

AND-type Predicate Defines

- More efficiently handle blocks executed on multiple conditions

```
if (a && b)
   c = c + 1;
else
   d = d + 1;
```

```
pred_clr p1
pred_set p3
pred_eq p1(OR), p3(AND‾), a, 0
pred_eq p1(OR), p3(AND‾), b, 0
add c, c, 1  (p3)
add d, d, 1  (p1)
```

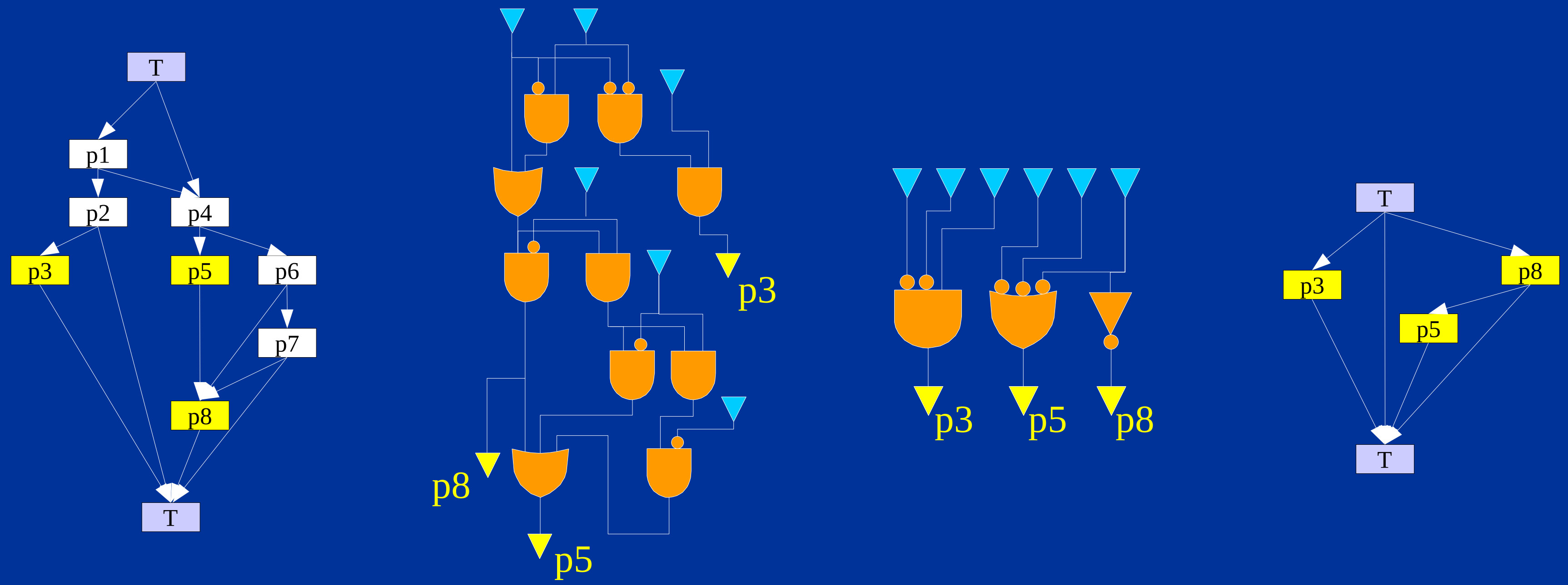


		Pout	
Pin	Comparison	AND	$\overline{AND}$
0	0	-	-
0	1	-	-
1	0	0	-
1	1	-	0

Predication Benefits

- Eliminates branches in exchange for increased resource subscription and/or dependence height
  - Reduction in branch resource consumption
  - Reduction in total branch misprediction penalty
- Aggressive control flow transformations
  - Height reduction and aggressive branch motion
  - Logic minimization of programmatic decision sequence
- Aggressive optimizations in the presence of control flow
  - Simplifies static scheduling and optimization along multiple paths
  - Controls code size explosion, makes some optimizations feasible

Predicate-Domain Control Flow Transformation

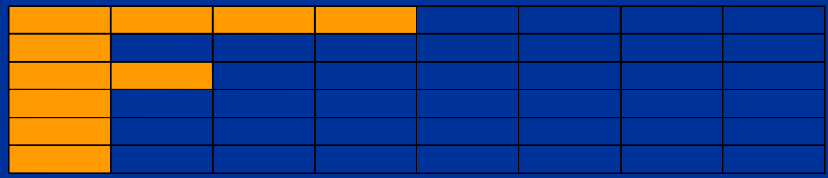


- Predication allow general restructuring of control flow
- Predication allows significant decision height reduction

Path Height Reduction: Concept

- Path classes
  - dependence limited
  - resource limited
- Optimizations can be performed to exchange dependence height for resource usage
- Goal: balance resource height and dependence height to **reduce effective height of path**

Sequential Code

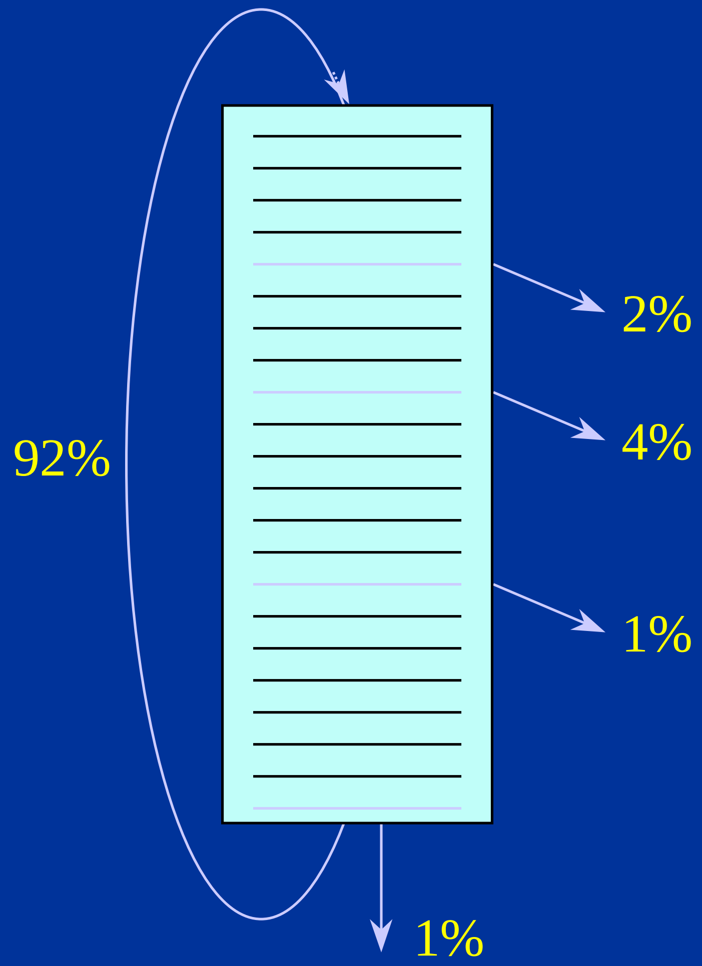


Saturated Code

- Height goes from 6 to 2
- Operation count went from 10 to 14
- Extra operations absorbed by processor width

Fully Resolved Predicates: Motivation

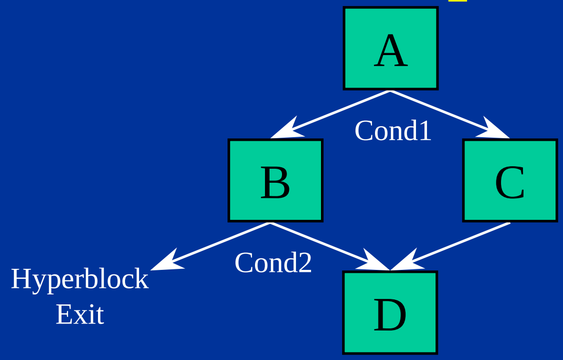
- Typical loops have many infrequently taken exit branches
- Infrequent exit branches
  - Impede code motion
  - Increase length of path to frequently taken branches
  - Consume valuable branch resources
- Goal: Use predication to enhance performance in the presence of **easily predicted branches**



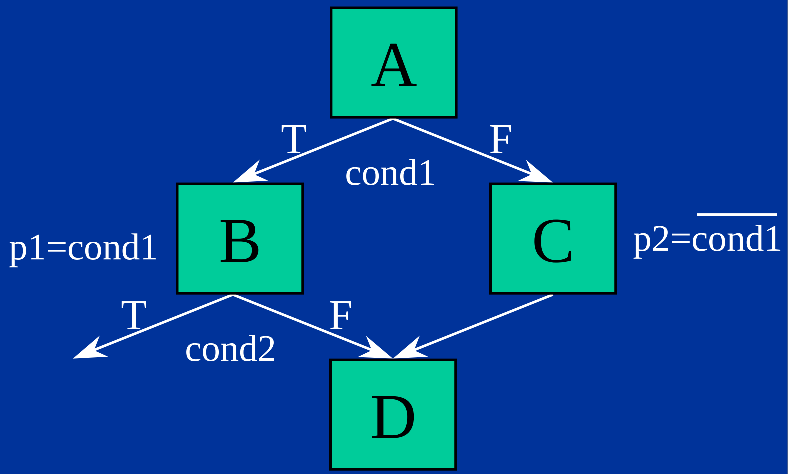
Fully Resolved Predicates: Concept

- Partially Resolved Predicates (PRP)
  - Instruction execution is guarded by predicates or branches.
  - Some control dependencies remain in predicated code.
- Fully Resolved Predicates (FRP)
  - Instructions are guarded by predicates even if guarded by branches.
  - All control dependencies within the region are eliminated.
  - Any instruction can be hoisted above a branch without speculation.

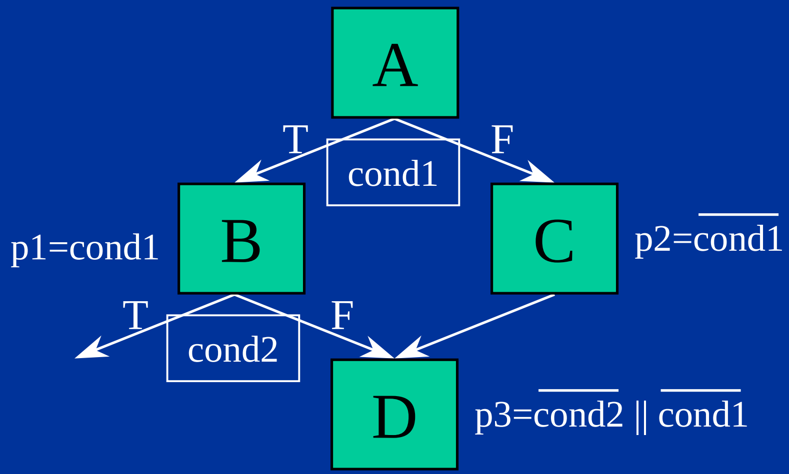
FRP: Computation



Partially Resolved Predicates



Fully Resolved Predicates



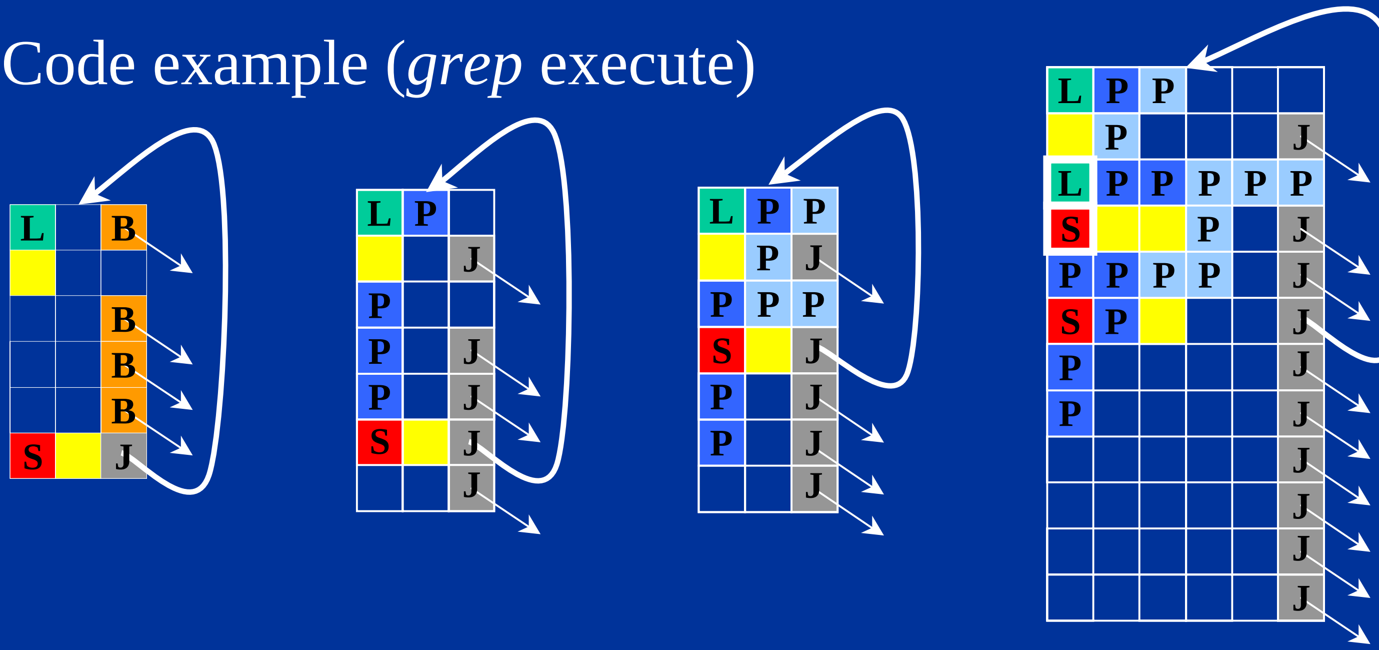
FRP: Case Study

- grep function “execute” inner loop
- Segment accounts for about 40% of total execution time.
- Source:

```
for (;;)
{
   if (p2 >= ebp)
      /* Excluded from Hyperblock */
   if ((c = *p2++) == '\n')
      break;
   if(c)
      if (p1 < &linebuf[1024-1])
         *p1++ = c;
}
```

Height Reduction by Predication and Speculation

Code example (*grep* execute)



Original

Predicated

Predicated and Height Reduced

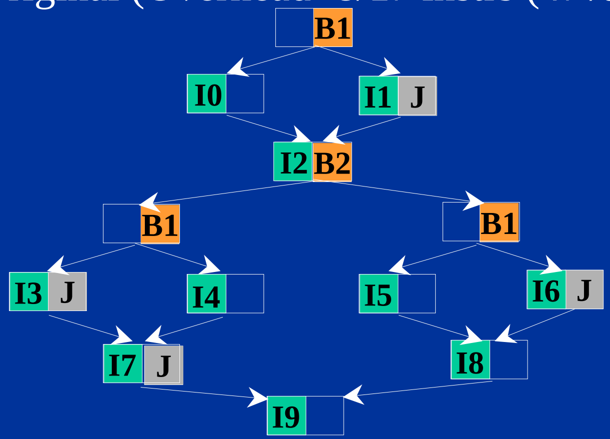
Unrolled with data speculation

- FRP Predication reduced height via control flow restructuring
- Data speculation reduced height via reordering of possibly conflicting loads and stores

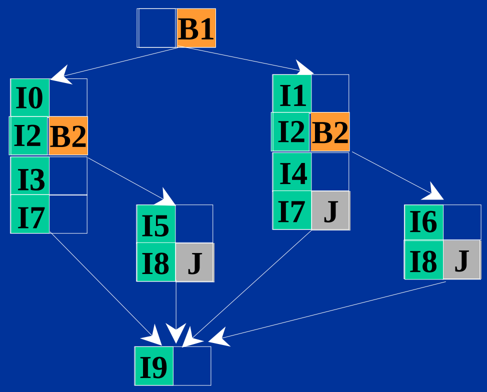
Code Size Control using Predication

Code example *(MediaBench Experimental Image Compression* reflect1):

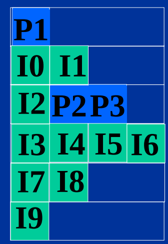
Original (Overhead=8/17 instrs (47%))



Optimized (6/19 (30%))

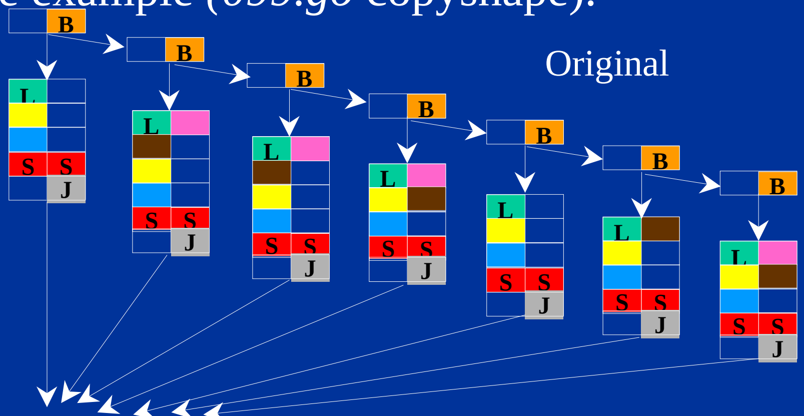


Predicated (3/13 (23%))

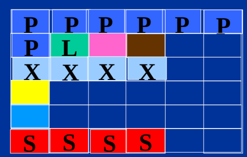


Code example *(099.go* copyshape*):*

Original



Predicated



- Predication reduced code size by instruction merging (in example 35%)

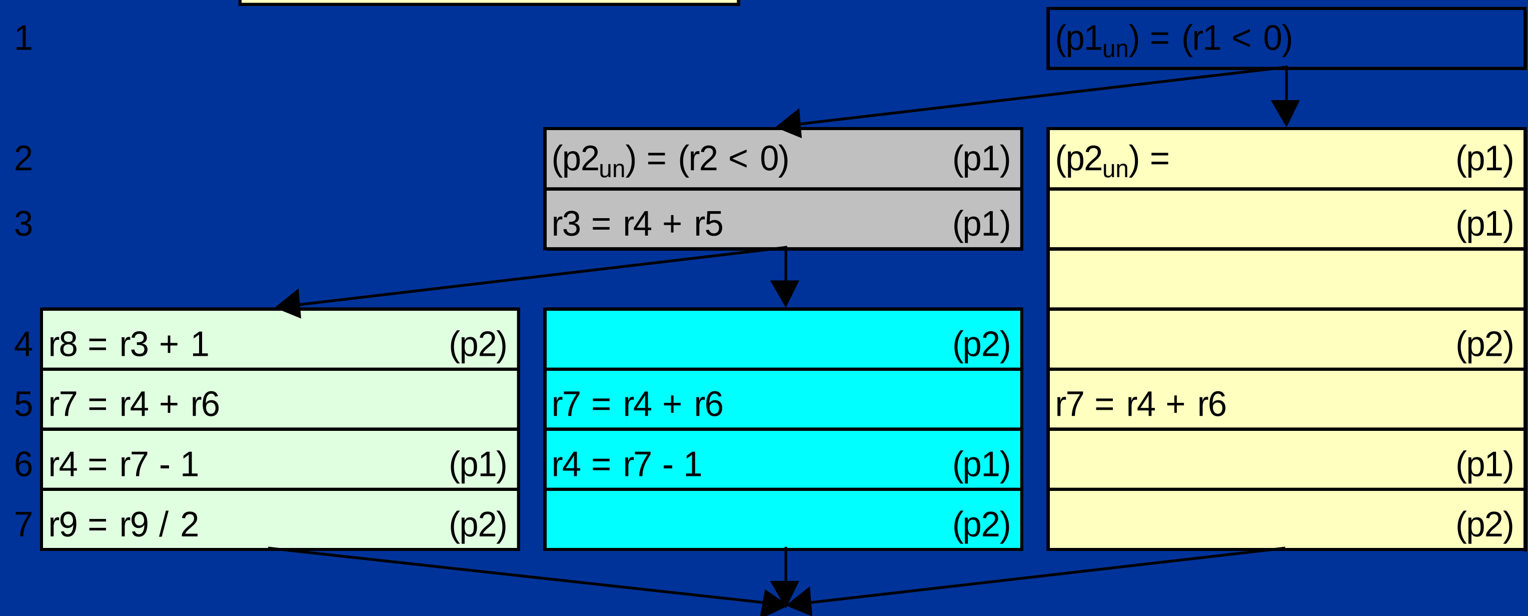
Analysis of Predicated Codes

- Dataflow without regard to predicates can lead to conservative results.
- Live Variable Analysis Example:
  - Without Predicate Aware Dataflow (Only instructions on TRUE predicate can kill.)
    - R7 is defined and killed by instruction 5; R7 is used by instruction 6.
    - R7's live range is (5,6).
    - R3 is not defined and killed by instruction 3 in all cases because it is predicated on P1. R3 is used by instruction 4.
    - R3's live range is (1,2,3,4) and live out the top of the CB.
  - With Predicate Aware Dataflow
    - R7's live range is also (5,6).
    - R3's live range is (3,4) because instruction 3 defines R3 for all uses by instruction 4. This is known by studying the relation of P1 to P2.

1	$(p1_{un}) = (r1 < 0)$	
2	$(p2_{un}) = (r2 < 0)$	(p1)
3	r3 = r4 + r5	(p1)
4	r8 = r3 + 1	(p2)
5	r7 = r4 + r6	
6	r4 = r7 - 1	(p1)
7	r9 = r9 / 2	(p2)

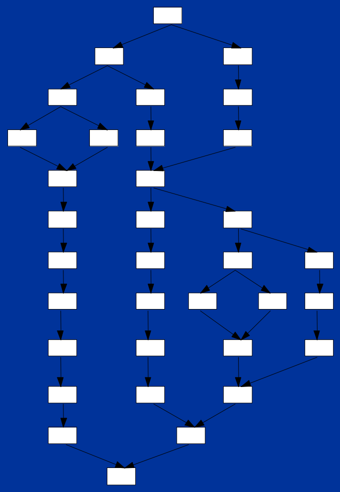
The Predicate Flow Graph

1	$(p1_{un}) = (r1 < 0)$	
2	$(p2_{un}) = (r2 < 0)$	(p1)
3	r3 = r4 + r5	(p1)
4	r8 = r3 + 1	(p2)
5	r7 = r4 + r6	
6	r4 = r7 - 1	(p1)
7	r9 = r9 / 2	(p2)

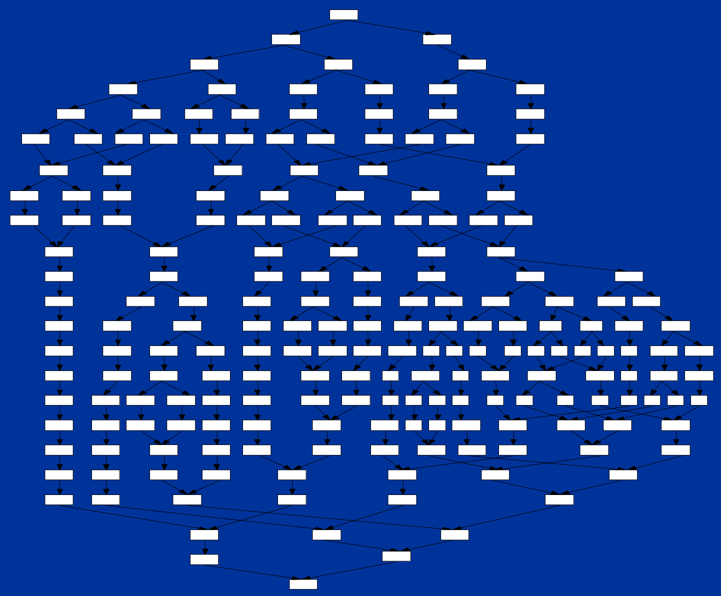


Dataflow Analysis of Predicated Code

Code example (*wc*)



RIC of one iter. (width 5)



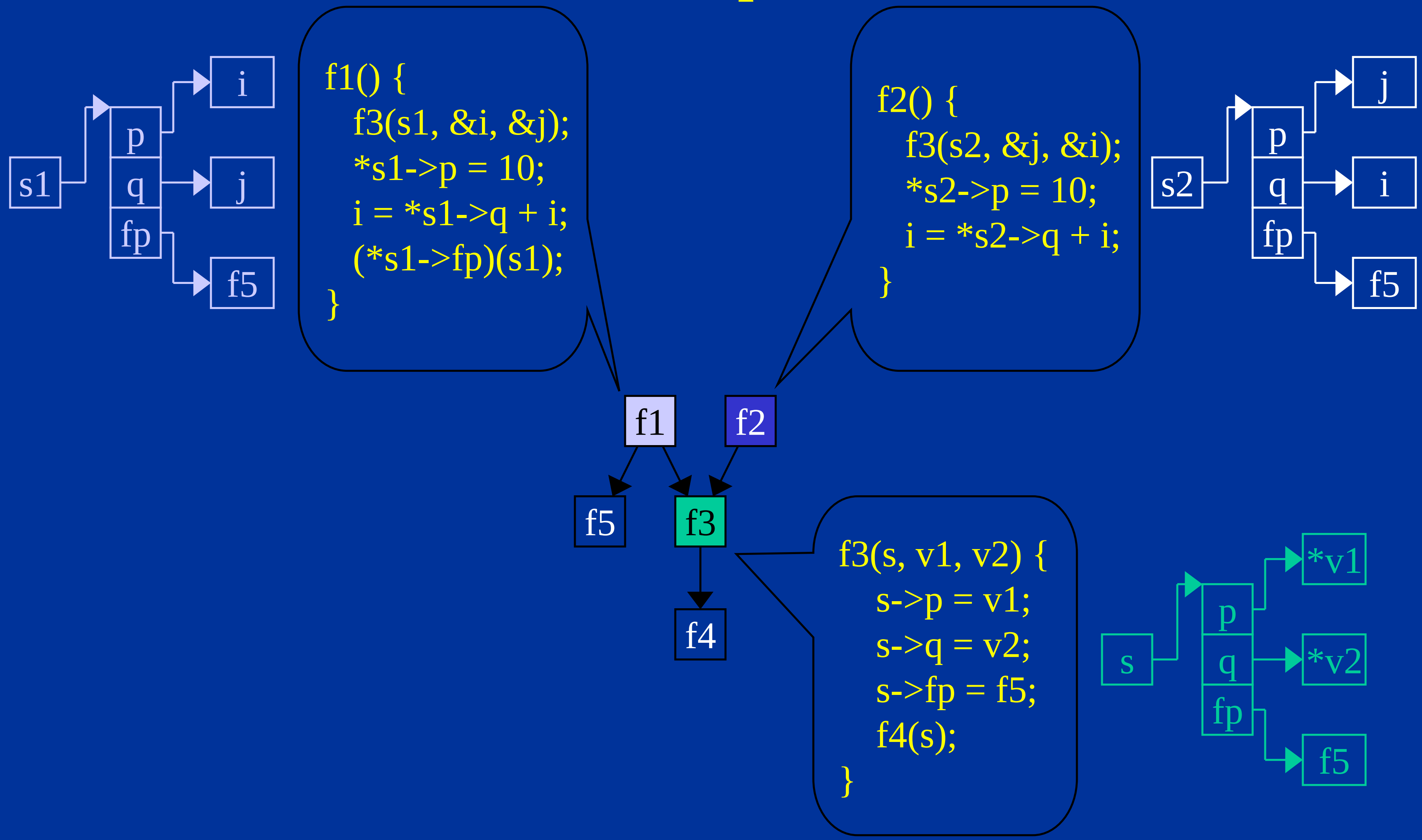
RIC of code with 2x unroll (width 20)

- Traditional dataflow requires reverse if-conversion (RIC)
- RIC of some codes is exponential (*wc*: 5,20,80,240,...)
- Factoring reduces order of complexity (*wc*: 8,15,22,28,...)

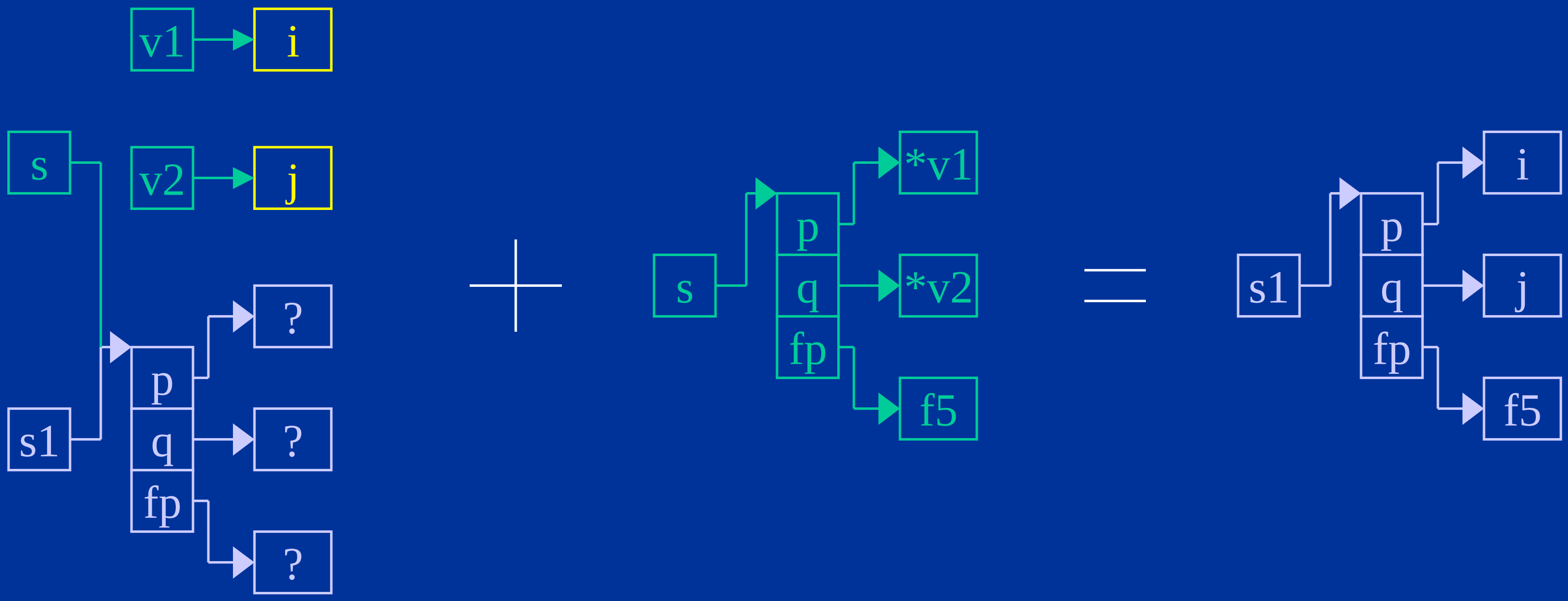
Compile-Time Memory Disambiguation

- Maximize the efficiency of the memory system
  - Eliminate unnecessary loads
  - Reorder loads past independent stores to hide the load latency
  - Instruct the hardware about the possible dependence between loads and stores to prevent run-time mis-speculation
- Indirect memory accesses through pointers
  - Dependence between *p and *q is not obvious
- Function side-effects
  - Analysis between *p and *q difficult when foo(&p, &q) is present
- Efficient and effective interprocedural alias analysis
  - Trade-off between accuracy and complexity
  - Comparable resolution for stack and heap objects

Example


s1
p
q
fp
i
j
f5
f1() {
f3(s1, &i, &j);
*s1->p = 10;
i = *s1->q + i;
(*s1->fp)(s1);
}
f2() {
f3(s2, &j, &i);
*s2->p = 10;
i = *s2->q + i;
}
s2
p
q
fp
j
i
f5
f1
f2
f5
f3
f4
f3(s, v1, v2) {
s->p = v1;
s->q = v2;
s->fp = f5;
f4(s);
}
s
p
q
fp
*v1
*v2
f5

Interprocedural Points-to Analysis

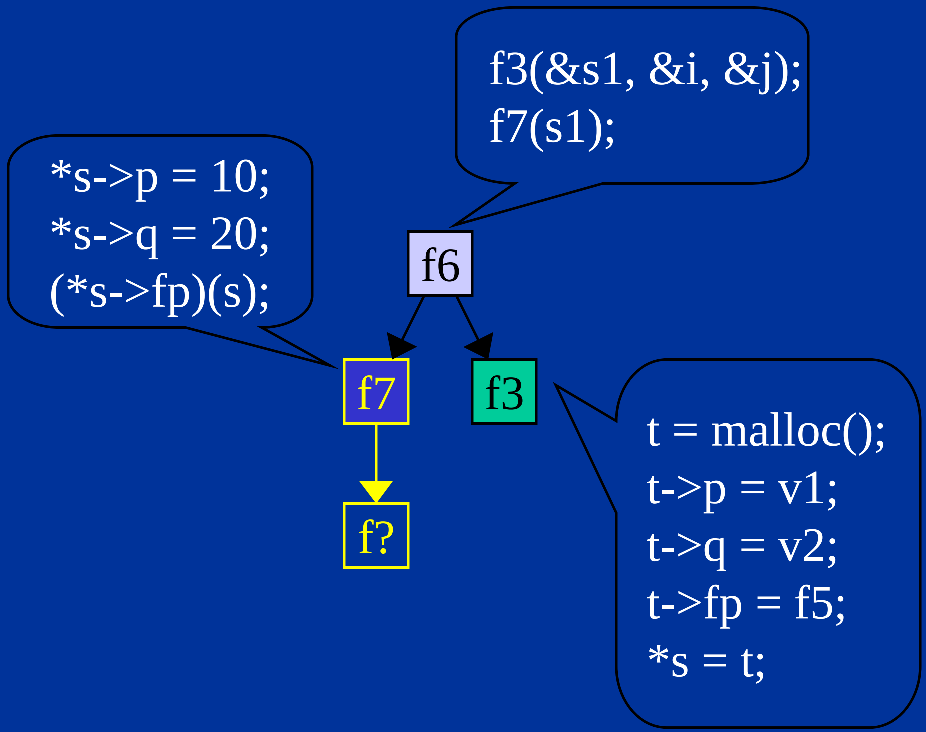


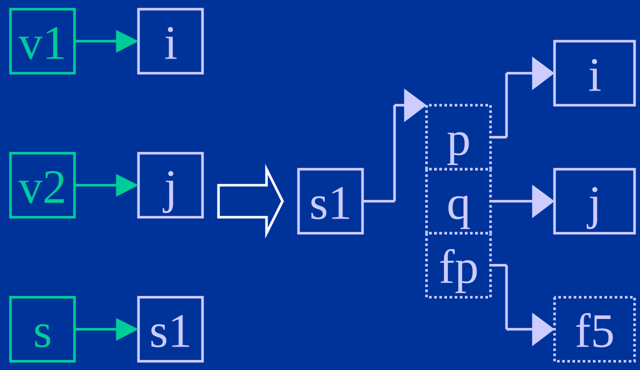
- Flow-Insensitive function-level points-to templates
- Context-Sensitive exchange of function-level points-to templates

Object Elevation

- Report interprocedurally accessed callee objects to the caller
- Not all accessible objects are visible
  - Heap objects allocated in the callee
  - Indirectly accessed non-local variables
- Objects accessed in the callee and accessible in the caller are mapped to the caller with encoded object name
- Object names are encoded by the access path
  - *s => s*
  - s->p => s*.offset_of_p
  - s->p->q => s*.offset_of_p*.offset_of_q

Working Example - 132.ijpeg in SPEC95





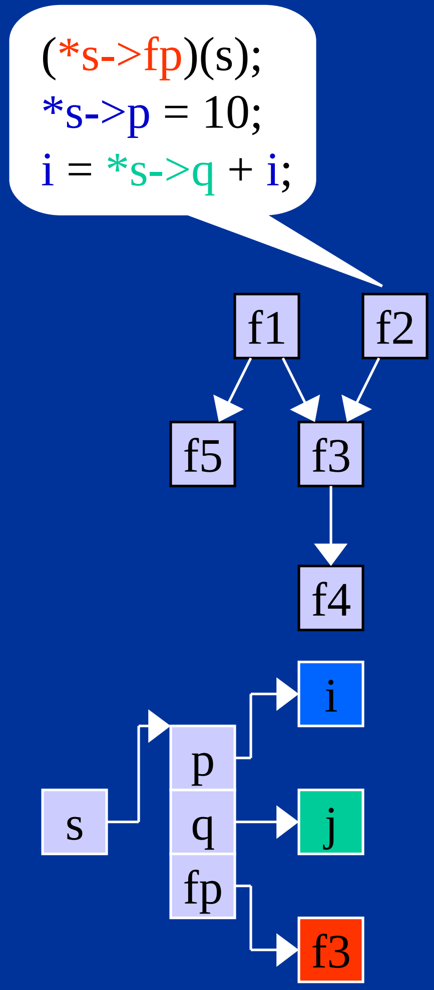
Prior to object elevation

After object elevation

- Contains 477 functions and 25,889 lines of code
- Spends 200 seconds and 18MB of memory in analysis
- 229 of 266 indirect call-sites are converted into direct ones

Compile-Time Memory Disambiguation

- Potential performance enhancements
  - Eliminates redundant loads (*s->fp)
  - Reorders loads past independent stores (*s->q and *s->p)
  - Prevents run-time mis-speculation (i and *s->p)
- Challenges of interprocedural pointer analysis
  - Maintaining both efficiency and accuracy
    - Flow-insensitive and context-sensitive
  - Providing comparable results for stack- and heap-pointers
    - Object elevation
- Working example - ijpeg in SPEC95
  - 477 functions and 25,889 lines of code
  - Analysis consumes 200 seconds and 18MB of memory
  - 229 of 266 indirect call-sites converted into direct ones
  - 30% performance improvement observed



Debugging optimized code

- Motivation
  - optimization becomes default when compiling EPIC code
  - software validation issue: what is debugged is what gets shipped
- Provide meaningful information without misleading users
  - truthful behavior
    - make the user aware of optimization effects and surprising outcomes
  - expected behavior
    - hide the effects of optimization
    - current focus of most research and development efforts

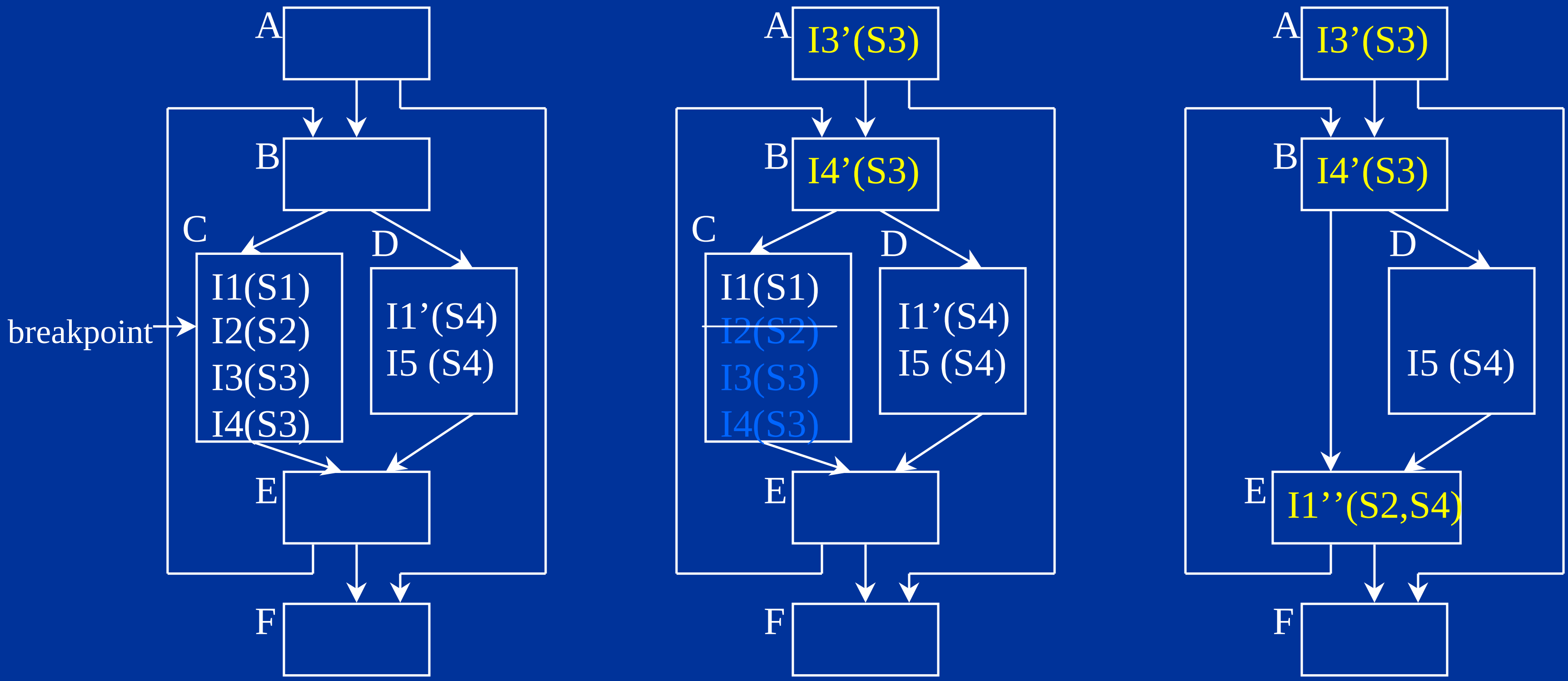
Basic idea of recovering expected behavior

- Unexpected behavior caused by
  - program states updated prematurely or too late
  - program states not available
- Basic idea
  - suspend the execution early
  - control the execution of all the instructions necessary for the recovery (*forward recovery*)
  - compile required program states

```
  S1: a = b + c
→ S2: x = 2
  S3: y = z * 3
```

```
                             i1: ld r1, b          <1>
                             i2: ld r2, c          <1>
suspend execution         →  i3: ld r5, z          <3>
                             i4: mul r6, r5, 3     <3>
                          →  i5: mov r4, 2         <2>
Should have been executed →  i6: add r3, r1, r2    <1>
```

Issues need to be addressed



- When to take over execution and when to stop forward recovery?
  - original execution order of instructions has to be tracked
  - instructions might be moved up to different paths leading to the breakpoint or down to different paths starting from the breakpoint

Issues need to be addressed (continued)

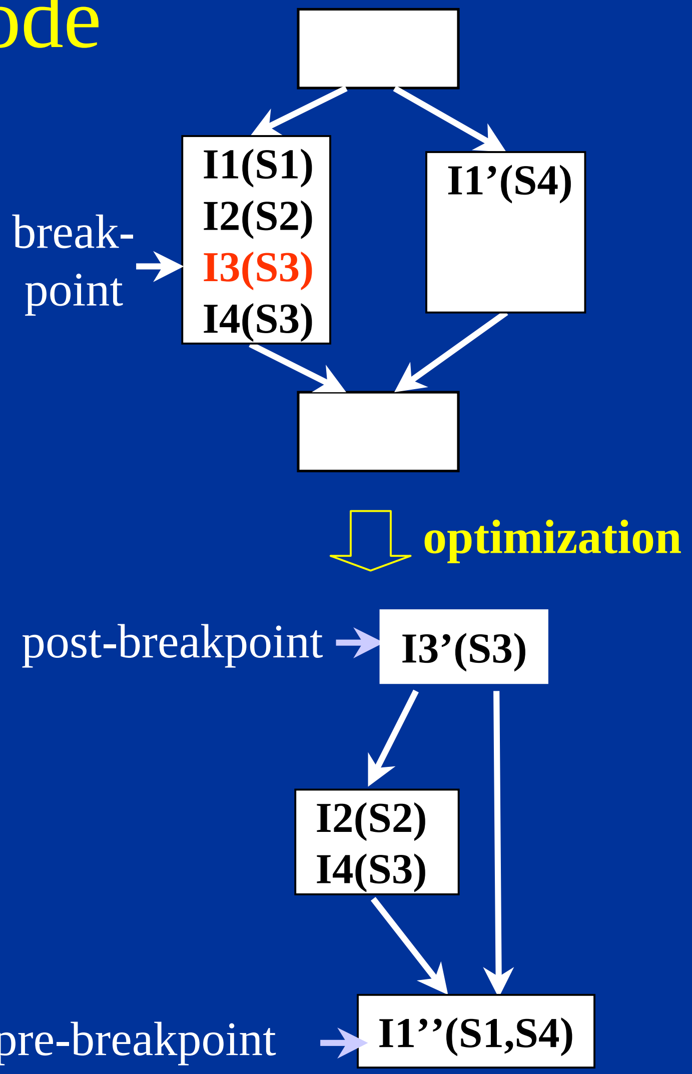
- How does the debugger confirm a source breakpoint?
  - some object locations which are control equivalent to the breakpoint need to be identified
  - boolean conditions have to be incorporated sometimes
- How does forward recovery work?
  - executing everything or selectively
  - breakpoints and exceptions need to be reported in the expected order
- Where are the locations of variables at run-time?
  - run-time location of a variable may vary or not exist at all at different points of the program

Summary of a new debugging paradigm

- The compiler needs to preserve and maintain (besides the traditional debugging information)
  - original execution order of instructions
  - source statement instance information
  - breakpoint confirmation information
  - variable run-time location information
- The debugger needs to determine (using the above information)
  - when to suspend the normal execution
  - what instructions should be executed
  - where to find the variable values
  - how to ensure the program behavior consistent with what the user expects

Debugging of Optimized Code

- Increased importance due to EPIC
  - optimization essential in EPIC code
  - need to debug software while under test
- Solution must not mislead users
  - expected behavior or truthful behavior
- Keys to providing expected behavior
  - mappings between source breakpoints and object code locations
  - tracking run-time locations of variables
  - recovery of the expected variable values



Outlook

- Compilers critical to the performance of EPIC uP's
  - Use of predication and speculation is a serious challenge
  - Any misuse will lead to performance loss.
  - Brand new algorithms will be deployed in the EPIC compilers.
  - Existing software development models must be supported.
- Expect performance robustness issues
  - Awesome performance leap seen for some applications.
  - Less for others due to limitations of analyses and optimizations.
  - It can take years for the performance gain to be universal.
  - A lot of research activities needed, www.trimaran.org.
- Evolution of EPIC architectures
  - Revisions of architectures are likely as compilers mature.
  - Code size and power consumption are critical for embedded EPICs.