Branch Prediction and Predication

CS 1541
Wonsun Ahn

University of Pittsburgh

Branch Prediction

Solution 3: Branch Prediction

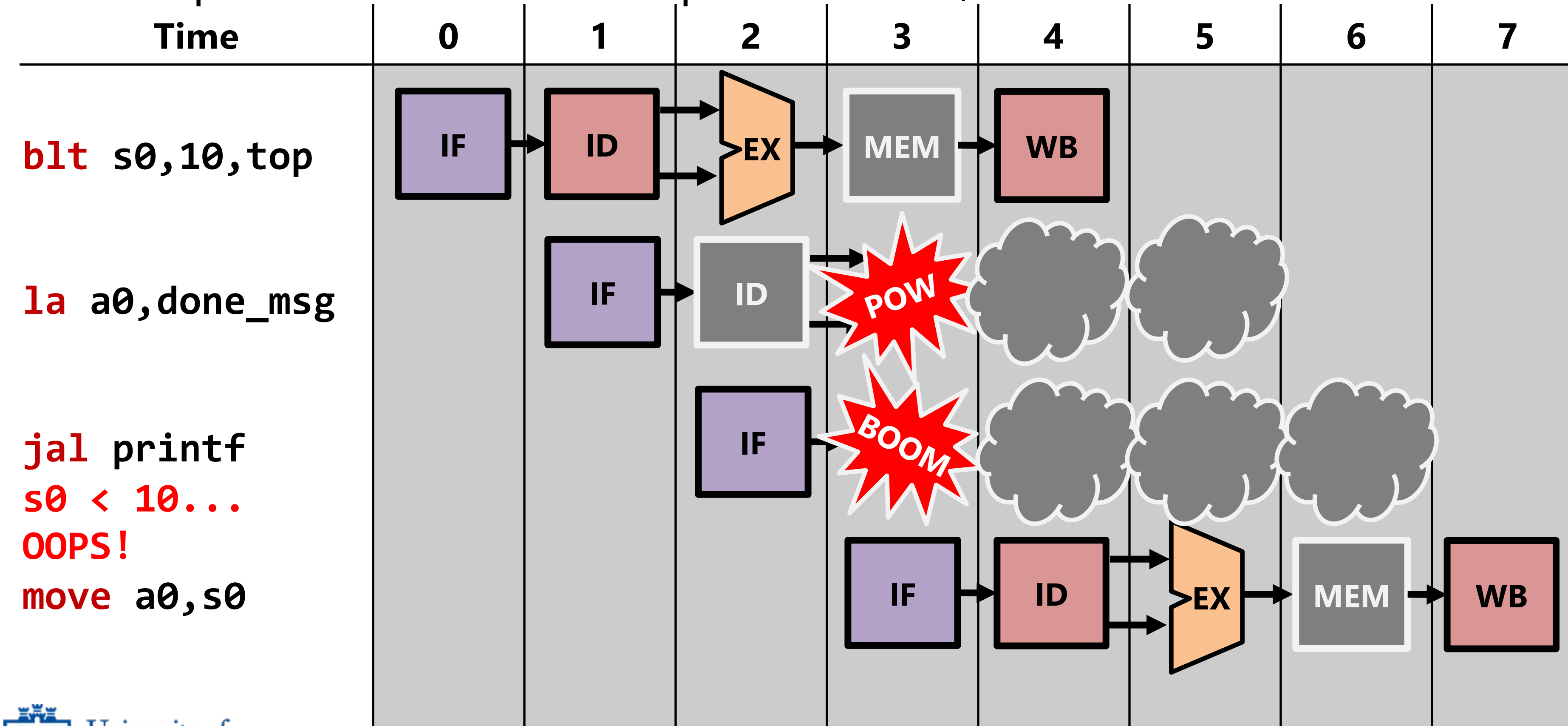
- Wrong path instructions create bubbles and decrease utilization

- What if …
  - We were able to **predict** the branch outcome?
  - Without computing branch outcome at EX stage?

- What if we could make the prediction at **IF** stage?
  - We can start fetching on the correct path at very next cycle!
  - If our prediction turns out incorrect, **flush** at that point.

What if branch is mispredicted?

- HDU can **flush pipeline** of wrong path instructions, just like before
  - Misprediction becomes a performance, **not a correctness issue**



University of Pittsburgh

Taken / Not Taken Branch Prediction

- We have been doing a form of branch prediction all along!
  - We assumed that all branches will be ***not taken***

- Two simple policies:
  - Predict ***not taken***: continue fetching PC + 4, flush if taken
    Pro: Can start fetching the next instruction immediately
    Con: ~67% of branches are taken (due to loops) → many flushes
  - Predict ***taken***: fetch branch target, flush if not taken
    Pro: ~67% of branches are taken (due to loops) → less flushes
    Con: ID stage must decode branch target before fetch → bubble

- Both are non-ideal: there are better ways to predict!

Types of Branch Prediction

- ***Static Branch Prediction***
  - Predicting branch behavior based on code analysis
  - **Compiler** gives hints about branch direction through ISA
  - Not used nowadays due to inaccuracy of compiler predictions

- ***Dynamic Branch Prediction***
  - Predicting branch behavior based on (dynamic) branch history
  - Typically using **hardware** that tracks history information
  - *Premise*: **history repeats itself**
    - Branches not taken in the past → likely not taken in the future (e.g. branches to error handling code)
    - Branches taken in the past → likely taken in the future (e.g. branch back to the next iteration of the loop)

University of Pittsburgh

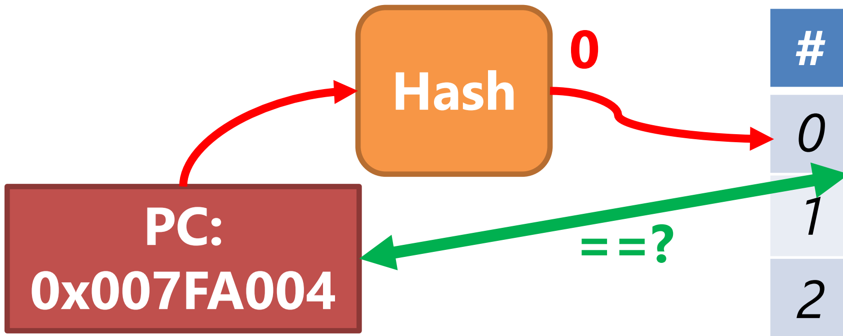
The Branch History Table (BHT)

- BHT stores Taken (**T**) or Not Taken (**NT**) history info for each branch
  - If branch was taken most recently, **T** is recorded
  - If branch was not taken most recently, **NT** is recorded

- BHT is indexed using PC (Program Counter)
  - Each branch has a unique PC, so a unique entry per branch

- BHT, being hardware, is limited in capacity
  - Cannot have a huge table with all PCs possible in a program
  - Besides, not every PC address contains a branch
  - Best to use **hash table** to map branch PCs to (limited) entries

The Branch History Table (BHT)



#	Branch PC	Pred.
0	0x007FA004	T
1	0x007FC60C	NT
2	0x007FA058	T
3	…	NT
4	0x007FC380	T
5	…	T
6	…	NT
7	…	NT

```
entry = Hash(PC)
if(entry.PC == PC
  && entry.pred == T)
  NextPC = inst.target
else
  NextPC = PC+4
```

To filter out conflicts in hash function

University of Pittsburgh

Limitations of Branch History Table (BHT)

- Ideally, we would like know what next to fetch at the **IF** stage
  - So that correct instruction is immediately fetched in next cycle

- BHT can give us branch direction **IF** stage
  - All the information needed is the PC (which is available at IF)

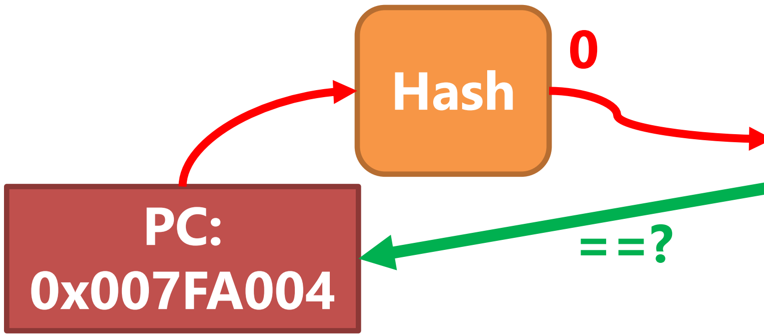
- But also need the **branch target** to know what to fetch
  - Must wait until the **ID** stage for branch target to be decoded
  - If **NT** in BHT: no need to wait (branch target is irrelevant)
    But if **T** in BHT: need to wait until ID stage

- That introduces a **bubble** for **taken branches**

The Branch Target Buffer (BTB)

- BTB stores **branch target** for each branch
- BTB is also indexed using PC of branch using a hash table
- BTB allows branch target to be known at the IF stage
  - **No need to wait until ID stage** for branch target to be decoded

The Branch Target Buffer (BTB)



#	Branch PC	Branch Target
0	0x007FA004	0x007FA03C
1	0x007FC60C	0x007FC704
2	0x007FA058	0x007FA040
3	…	…
4	0x007FC380	0x007FC398
5	…	…
6	…	…
7	…	…

```
entry = Hash(PC)
if(entry.PC == PC)
  NextPC = entry.target
else
  NextPC = PC+4
```

BHT + BTB Combined Branch Predictor

Hash

0

PC:
0x007FA004

==?

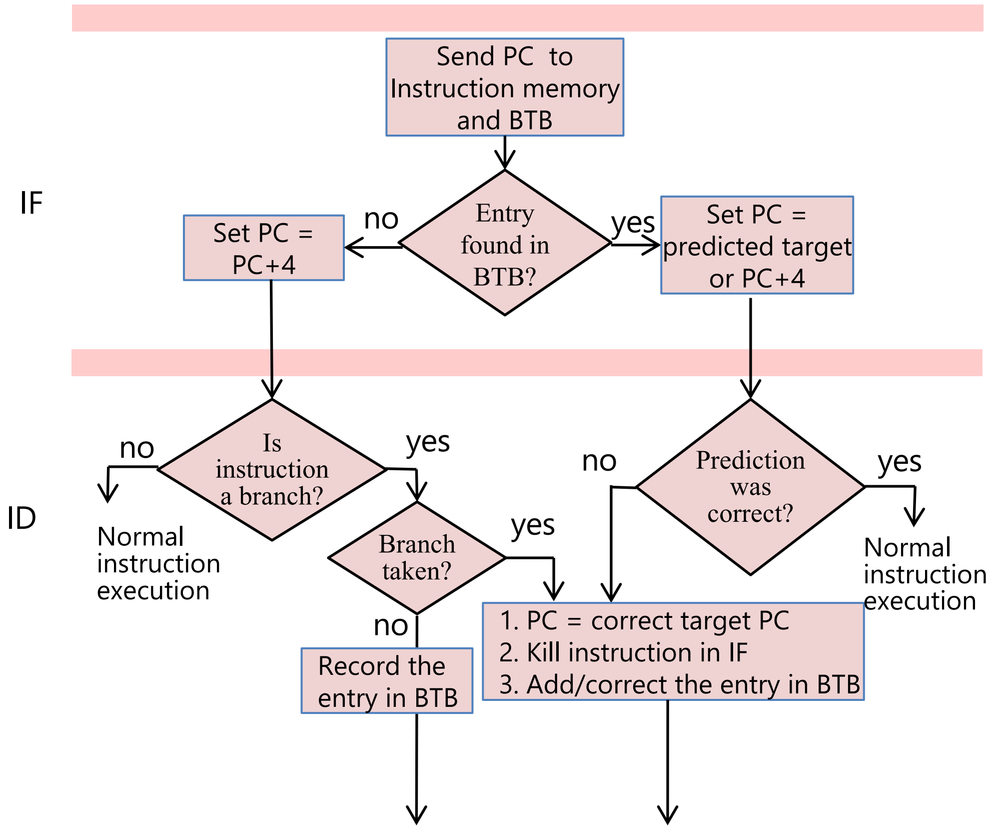
```
entry = Hash(PC)
if(entry.PC == PC
  && entry.pred == T)
  NextPC = entry.target
else
  NextPC = PC+4
```

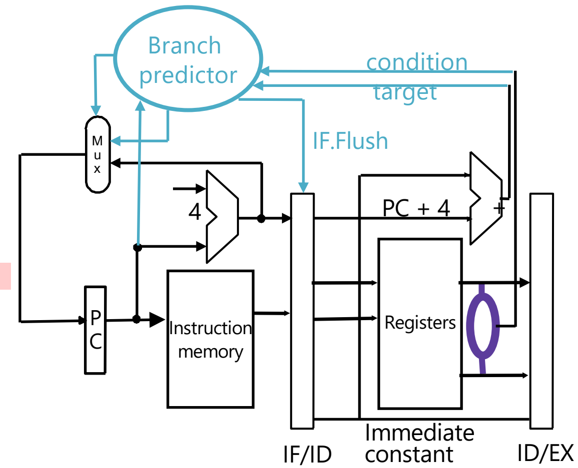
#	Branch PC	Pred.	Branch Target
0	**0x007FA004**	**NT**	**0x007FA03C**
1	**0x007FC60C**	**NT**	**0x007FC704**
2	**0x007FA058**	**T**	**0x007FA040**
3	**…**	**NT**	**…**
4	**0x007FC380**	**T**	**0x007FC398**
5	**…**	**T**	**…**
6	**…**	**NT**	**…**
7	**…**	**NT**	**…**

University of Pittsburgh

Branch Prediction Decision Tree

Assuming that branch condition and target are resolved in ID stage





Limitations of 1-bit BHT Predictor

- Is 1-bit (T / NT) enough history to make a good decision?

- Take a look at this example:

```
for (j=0; j<100; j++) {
  for (i=0; i< 5; i++) {
    A[i] = B[i] * C[i];
    D[i] = E[i] / F[i];
  }
}
```

Predicted	-	T	T	T	**T**	**NT**	T	T	T	**T**	**NT**	T	T
Actual	T	T	T	T	NT	T	T	T	T	NT	T	T	T

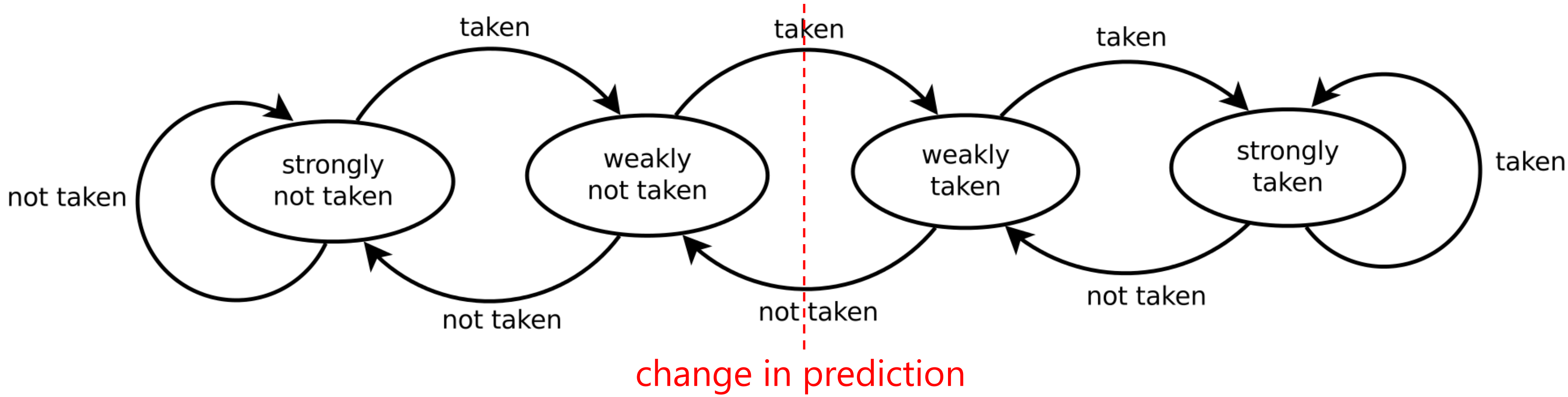
this branch is predicted wrong
twice every inner loop
invocation (every 5 branches)

- It would have been better to stay with T than flip back and forth!

- Idea behind the 2-bit predictor: make predictions more stable
  - So that predictions don't flip immediately

2-bit BHT Predictor

- State transition diagram of 2-bit predictor:



- Can be implemented using a 2-bit saturating counter
  - Strongly not taken: 00
  - Weakly not taken: 01
  - Weakly taken: 10
  - Strongly taken: 11

University of Pittsburgh

2-bit BHT Predictor

- How well does the 2-bit predictor do with our previous example?

- Our previous example:

```
for (j=0; j<100; j++) {
  for (i=0; i< 5; i++) {
    A[i] = B[i] * C[i];
    D[i] = E[i] / F[i];
  }
}
```

		Weakly Taken	Strongly Taken	Strongly Taken	Strongly Taken	Weakly Taken	Strongly Taken	Strongly Taken	Strongly Taken	Strongly Taken	Weakly Taken	Strongly Taken	Strongly Taken
Predicted	-	T	T	T	**T**	T	T	T	T	**T**	T	T	T
Actual	T	T	T	T	NT	T	T	T	T	NT	T	T	T

this branch is predicted wrong **only once** every inner loop invocation (every 5 branches)

- Does it help beyond 2 bits? (e.g. 3-bit predictor, or 4-bit predictor)
  - Empirically, no. 2 bits already cover loop which is most common.
  - 2 bits + large BHT gets you **~93% accuracy**

- We need other tricks to improve accuracy!

University of Pittsburgh

Limitations of 2-bit BHT Predictor

- Here is an example where 1-bit BHT predictor fails miserably

```
for (j=0; j<100; j++) {
  if (j % 2) {
  }
}
```

You get the prediction **wrong every single time**!

Predicted	-	**NT**	**T**	**NT**	**T**	**NT**	**T**	**NT**	**T**	**NT**	**T**	**NT**	**T**
Actual	NT	T	NT	T	NT	T	NT	T	NT	T	NT	T	NT

- And a 2-bit predictor doesn't do very well either

```
for (j=0; j<100; j++) {
  if (j % 2) {
  }
}
```

You get the prediction **wrong every other time**!

Predicted	-	**NT**	NT	**NT**	NT	**NT**	NT	**NT**	NT	**NT**	NT	**NT**	NT
Actual	NT	T	NT	T	NT	T	NT	T	NT	T	NT	T	NT

  - Would a 3-bit predictor do any better?
- Idea: Base prediction on a **pattern** found in history of branches!
  - Rather than relying on a single prediction for a branch
  - If History: T → predict NT, if History: NT → predict T

Correlating Predictors leverage patterns

- **Correlating Predictor**: Uses patterns in past branches for prediction
  - Often branch behavior more complex than just taken or not taken
  - Often correlates to a pattern of past branches
- Pattern may exist in two ways:
  - Pattern in **local** branch history (history of only current branch)
  - Pattern in **global** branch history (history of all branches)
- Maintaining longer history allows detection of longer patterns
  - Local branch history for each branch maintained at all times
  - One global branch history maintained at all times

University of Pittsburgh

Local Branch History Correlating Predictor

- With a local branch history of 1, can predict perfectly!

```
for (j=0; j<100; j++) {
  if (j % 2) {
  }
}
```

Predict with branch PC + 1 local branch history

Predicted	-	-	-	T	NT	T	NT	T	NT	T	NT	T	NT
Actual	NT	T	NT	T	NT	T	NT	T	NT	T	NT	T	NT

- Local branch history changes as such:
  - **NT** → **T** → **NT** → **T** → **NT** → **T** → **NT** → **T** → **NT** → **T** → **...**
- Prediction based on branch PC and local branch history:
  - PC: if (j % 2) + History: **NT** → Prediction: **T**
  - PC: if (j % 2) + History: **T** → Prediction: **NT**

University of Pittsburgh

Local Branch History Correlating Predictor

- You need a local branch history of 2 for this one.

```
for (j=0; j<100; j++) {
  if (j % 3) {
  }
}
```

Predict with branch PC + 2 local branch history

Predicted	-	-	-	-	-	T	NT	T	T	NT	T	T	NT
Actual	NT	T	T	NT	T	T	NT	T	T	NT	T	T	NT

- Local branch history changes as such:
  - **NT, T** → **T, T** → **T, NT** → **NT, T** → **T, T** → **T, NT** → **NT, T** → **...**
- Prediction based on branch PC and local branch history:
  - PC: if (j % 3) + History: **NT, T** → Prediction: **T**
  - PC: if (j % 3) + History: **T, T** → Prediction: **NT**
  - PC: if (j % 3) + History: **T, NT** → Prediction: **T**
  - PC: if (j % 3) + History: **NT, NT** → No prediction

Global Branch History Correlating Predictor

- Knowing the result of other branches in your history also helps

```
If (j == 0) {
}
...
If (j != 0) {
}
```

previous

current

Knowing result of a **previous different branch** in your history helps in predicting **current** branch!

- This is called **global branch history** (involves all branches).

- Can be helpful when local branch history can't capture pattern.

Unified Correlating Predictor

- **Correlates** prediction with branch **history** as well as branch PC
  - Local branch history + Global branch history
  - An entry with matching history gives more precise prediction!

- Now, instead of indexing into BHT by branch PC only
  - Use hash(PC, Local branch history, Global branch history)

- History is stored in register called Branch History Shift Register (BHR)
  - T/NT bit is shifted on to BHR whenever branch is encountered

1. One Global BHR (there is just one global history)
2. Multiple Local BHRs (local histories for each branch PC)

University of Pittsburgh

Correlating Predictors

Hash

0

PC

#	Tags	Local BHRs
0	PC	T, NT, NT, T, ...
1	PC	T, T, NT, T, ...
2	PC	T, T, T, T, ...
3	...	...

Global BHR
T, NT, NT, T, T, NT, ...

#	Tags	Pred.	Branch Target
0	PC+History	01	0x007FA03C
1	PC+History	00	0x007FC704
2	PC+History	11	0x007FA040
3	...	01	...
4	PC+History	10	0x007FC398
5	...	00	...
6	...	10	...
7	...	11	...

- Can reach up to **97% accuracy!**

University of Pittsburgh

How about function returns?

- **jal funcAddr**: function call
  - Stores PC+4 to **$ra** and jumps to funcAddr

- **jr $ra**: function return
  - Jumps to function return address stored in **$ra**

- **jr $ra** makes life difficult for the BTB
  - Unlike other branches, branch target is not an immediate value! (Jumping to a variable target is called an ***indirect branch***)
  - **$ra** can change dynamically depending on call site
  - BTB which relies on jump target being constant

- Target of **jr** is predicted using the ***Return Stack Buffer***
  - Not the Branch Target Buffer (BTB)

The Return Stack Buffer

- Since functions return to where they were called every time, it makes sense to cache the return addresses in a stack

```
4AB33C jal someFunc
4AB340 beq v0, $0, blah
       ...
       someFunc:
           ...
           jr $ra
```

When we encounter the jal, push the return address.

When we encounter the jr $ra, pop the return address. Easy!

40CC00
46280C
4AB108
4AB340
000000
000000
000000
000000

- On misprediction or stack overflow, empty stack
  - Not a problem since this is for prediction anyway

Performance Impact with Branch Prediction

- Now, CPI = $CPI_{nch} + \alpha * \pi * K$
  - CPI_{nch} : CPI with no control hazard
  - α : fraction of branch instructions in the instruction mix
  - π : **probability a branch is mispredicted**
  - K : penalty per pipeline flush

- With deep pipelines, mispredictions can have outsized impact

Example: If 20% of instructions are branches and the misprediction rate is 5%, and pipeline flush penalty 20 cycles, then:

$$CPI = CPI_{nch} + 0.2 * 0.05 * 20 = CPI_{nch} + 0.2 \text{ cycles per instruction}$$

- Problem is a small percentage of hard to predict branches
  - How do we deal with these?

Predication

Branch Mispredictions have Outsized Impact

- Assume a deep pipeline and `if(s1 >= 0)` is hard to predict

```
if(s1 >= 0)
    s2 = 0;
```

```
    blt  s1, 0, top
    li   s2, 0
```

Mispredict

```
for(s0 = 0 .. 10)
    s3 = s3 + s0;
```

```
top:
    add  s3, s3, s0
    addi s0, s0, 1
    blt  s0, 10, top
```

Flush!

- On a misprediction, every following instruction is flushed
  - Not only the control dependent instructions (`li s2, 0`)
  - But also multiple iterations of the “bystander” loop that were fetched

University of Pittsburgh

Solution 4: Predication

- ***Predicate***: a Boolean value used for conditional execution
  - Instructions that use predicates are said to be ***predicated***
  - A predicated instruction will modify state only if predicate is true
  - ISA is modified to add predicated versions for all instructions

- Example of code generation using predication:

```
pge   p1, s1, 0      # Store boolean s1 >= 0 to predicate p1
li.p s2, 0, p1       # Assign 0 to s2 if p1 is true
sw.p s3, 0(s4), p1 # Store s3 to address 0(s4) if p1 is true
```

- Now there is no branch. It is just straight-line code!
  - Control dependencies have been converted to data dependencies

Code with predication

- Now there are no branches!

```
if(s1 >= 0)
    s2 = 0;
```

```
    pge  p1, 0, s1
    li.p s2, 0, p1
```

```
for(s0 = 0 .. 10)
    s3 = s3 + s0;
```

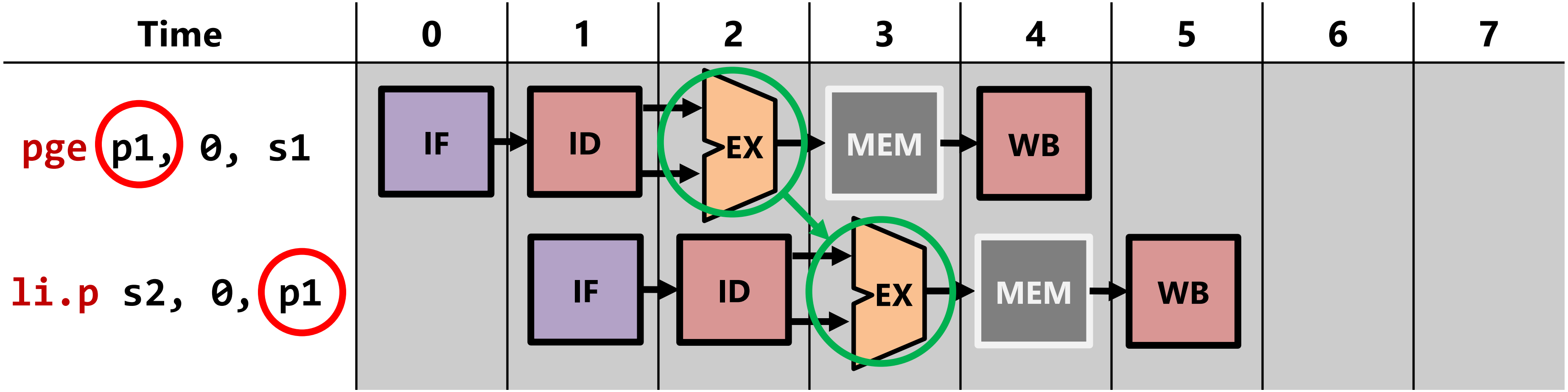
```
top:
    add  s3, s3, s0
    addi s0, s0, 1
    blt  s0, 10, top
```

- Drawback: even if branch not taken, `li.p` fetched (acts like a bubble)
  - But often worth it for hard to predict branches!
  - For easy to predict branches, often not worth it.

University of Pittsburgh

What does predication mean for the pipeline?

- Again, predicates are registers just like any other register
- Predicate dependencies work just like other data dependencies



- With data forwarding, no stalls required!
  - Predicate forwarded to **`li.p`** EX stage
  - Later predicate enables/disables regwrite control in **`li.p`** WB stage

University of Pittsburgh

What does predication mean for the compiler?

- Compiler can schedule instruction more freely!

```
if(s1 >= 0)
      s2 = 0;

for(s0 = 0 .. 10)
      s3 = s3 + s0;
```

```
      pge  p1, 0, s1

top:
      add  s3, s3, s0
      addi s0, s0, 1
      blt  s0, 10, top

      li.p s2, 0, p1
```

- Low-power compiler-scheduled processors often support predicates

Predication in the Real World

- Predication is only beneficial for hard to predict branches

- So how does the compiler figure out the hard to predict branches?
  - Through code analysis
  - Through software profiling (model a branch predictor)

- Supported in various ISAs
  - ARM allows most instructions to be predicated
  - Intel x86 has conditional move instructions (cmov)
  - SIMD architectures use predication in the form of a logical mask
    - Only data items that are not masked are updated
    - Intel AVX vector instructions
    - GPU instructions (e.g. CUDA)