Dynamic Scheduling

Why go out of style?

- expensive hardware for the time (actually, still is, relatively)
- register files grew so less register pressure
- early RISCs had lower CPIs

Dynamic Scheduling

Why come back?

- higher chip densities
- greater need to hide other kinds of latencies as:
  - discrepancy between CPU & memory speeds increases
  - branch misprediction penalty increases from superpipelining
  - dynamic scheduling was generalized to cover loads & branches
  - can be implemented with a more general register renaming mechanism
- need to preserve precise interrupts
  - commit instructions in-order
- more need to expolit ILP
  - processors now issue multiple instructions at the same time

2 styles: large physical register file & reorder buffer
(R10000-style) (PentiumPro-style)

Precise Interrupts

Precise interrupts preserve the model that instructions execute in program-generated order, one at a time

- If a recoverable interrupt occurs, the processor can recover from it

What happens on a precise interrupt:

- ***identify the instruction that caused the interrupt***
- ***let the instructions before faulting instruction finish***
- disable writes for faulting & subsequent instructions
- force trap instruction into pipeline
- trap routine
  - save the program state of the executing program
  - correct the cause of the interrupt
  - restore program state
- ***restart faulting & subsequent instructions***

Register Renaming with A Physical Register File

Register renaming provides a **mapping** between 2 register sets

- **architectural registers** defined by the ISA
- **physical registers** implemented in the CPU
  - hold results of the instructions committed so far
  - hold results of subsequent instructions that have executed but have not yet committed
  - more of them than architectural registers
    - ~ issue width * # pipeline stages between register renaming & commit

Register Renaming with A Physical Register File

How does it work?:

- an architectural register is mapped to a physical register during a register renaming stage in the pipeline
  - destination registers create mappings
  - source registers in subsequent instructions use mappings
- After renaming, operands are called by their physical register number
  - values accessed using physical register numbers
  - hazards determined by comparing physical register numbers, not architectural register numbers
  - results are written using physical register numbers

A Register Renaming Example

Code Segment	Register Mapping	Comments
`ld r7,0(r6)`	`r7 -> p1`	**p1** is allocated
`...`		
`add r8, r9, r7`	`r8 -> p2`	use **p1**, not r7
`...`		
`sub r7, r2, r3`	`r7 -> p3`	**p3** is allocated **p1** is deallocated when `sub` commits

Register Renaming with A Physical Register File

Effects:

- eliminates WAW and WAR hazards (*false name* dependences)
- increases ILP

An Implementation (R10000)

Modular design with regular hardware data structures

Structures for register renaming

- 64 **physical registers** (each, for integer & FP)
- **map tables** for the ***current*** architectural-to-physical register mapping (separate, for integer & FP)
  - current means latest defined destination register
  - accessed with the architectural register number of a source operand
  - produces a physical register number for that operand
- a destination register is assigned a new physical register number from a **free register list** (separate, for integer & FP)

An Implementation (R10000)

Instruction "queues" (integer, FP & data transfer)

- contains decoded & mapped instructions with the current physical register mappings
  - instructions entered into free locations in the IQ
  - sit there until they are dispatched to functional units
  - somewhat analogous to Tomasulo reservation stations but no value fields or valid bits & more centralized
- used to determine when operands are available
  - compare physical register numbers of each source operand for instructions in the IQ to physical register numbers of destination values just computed
- determines when an appropriate functional unit is available
- dispatches instructions to functional units

An Implementation (R10000)

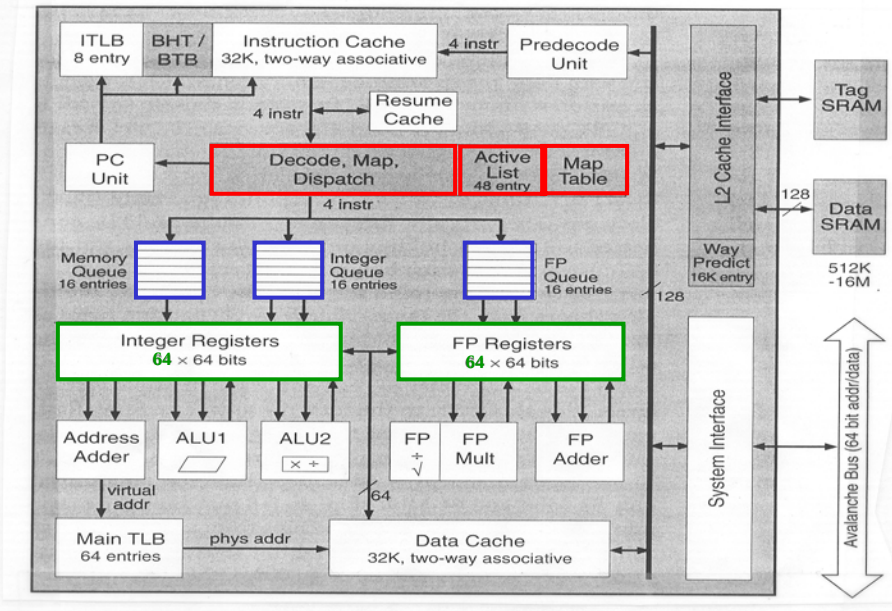
active list for all uncommitted instructions

- the mechanism for maintaining precise interrupts
  - instructions entered in program-generated order
  - allows instructions to complete in program-generated order
- instructions are removed from the active list:
  - when they are committed - an instruction commits if:
    - the instruction has completed execution
    - all instructions ahead of it have also completed
  - branch is mispredicted
  - an exception occurs
- contains the ***previous*** architectural-to-physical destination register mapping
  - used to recreate the map table for instruction restart after an exception
- instructions in the other hardware structures & the functional units are identified by their active list location

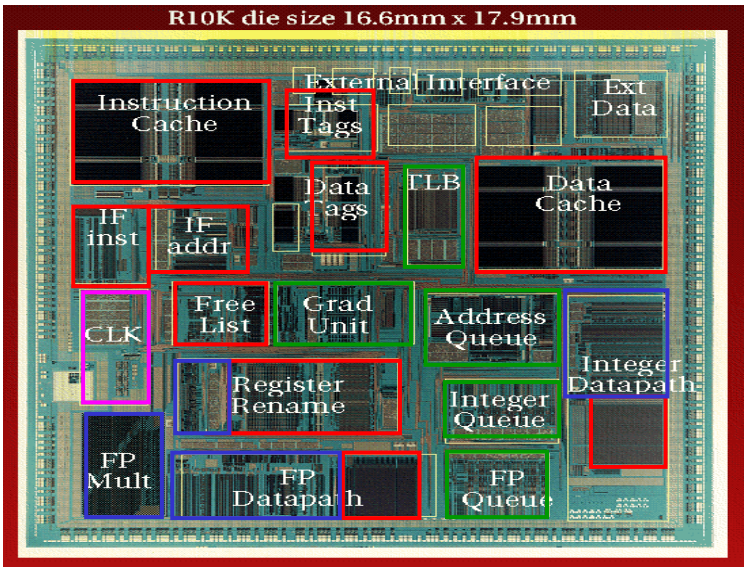
An Implementation (R10000)

busy-register table (integer & FP):

- indicates whether a physical register contains a value
- somewhat analogous to Tomasulo's register status
- used to determine operand availability
  - bit is set when a register is mapped & leaves the free list (not available yet)
  - cleared when a FU writes the register (now there's a value)

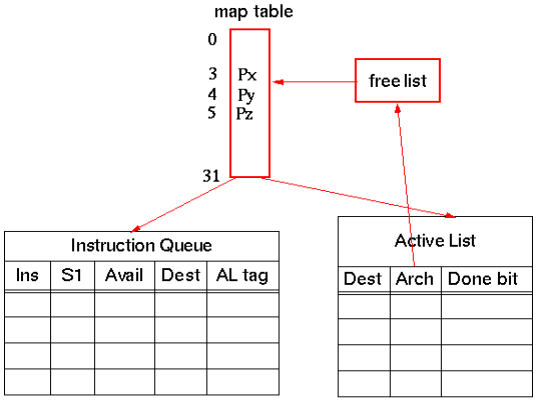


R10000 Die Photo



The R10000 in Action 1

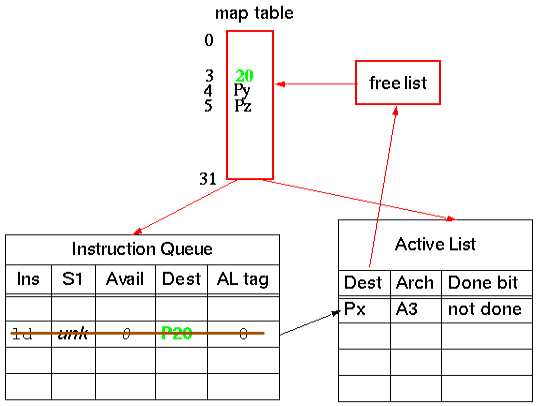
```
ld    A3, #(reg)     arch register A3 defined
                     potential multi-cycle
add   A4, A3, reg    arch register A3 used
sub   A3, reg, reg   arch register A3 redefined
                     name dependence
or    A5, A3, reg    arch register A3 used
```



The R10000 in Action 2

```
ld    A3, #(reg)
add   A4, A3, reg
sub   A3, reg, reg

or    A5, A3, reg
```

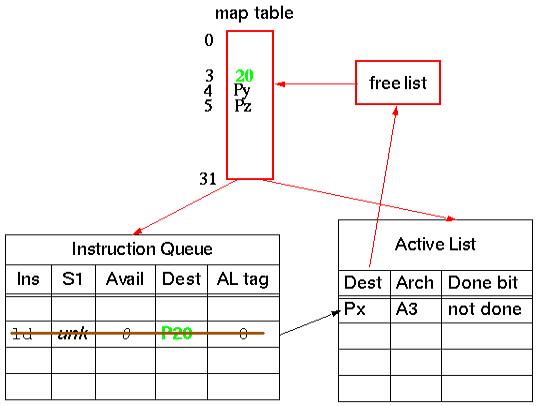
arch register A3 defined
potential multi-cycle



The R10000 in Action 3

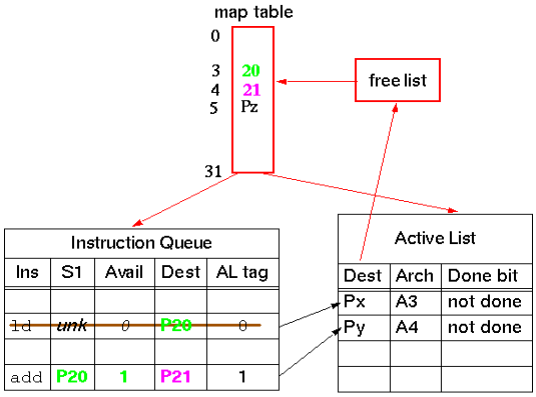
```
ld    A3, #(reg)
add   A4, A3, reg
sub   A3, reg, reg

or    A5, A3, reg
```

arch register A3 defined
potential multi-cycle



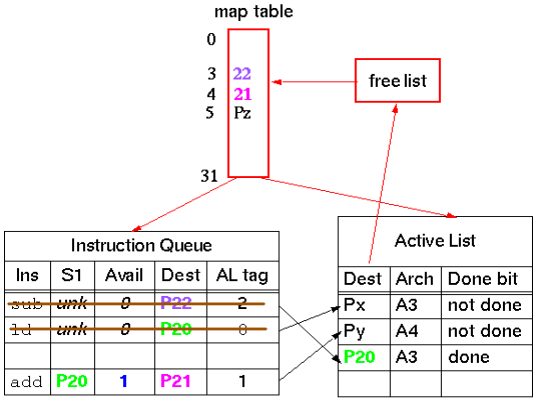
The R10000 in Action 4

```
ld    A3, #(reg)      arch register A3 defined
                      potential multi-cycle
add   A4, A3, reg     arch register A3 used
sub   A3, reg, reg
or    A5, A3, reg
```



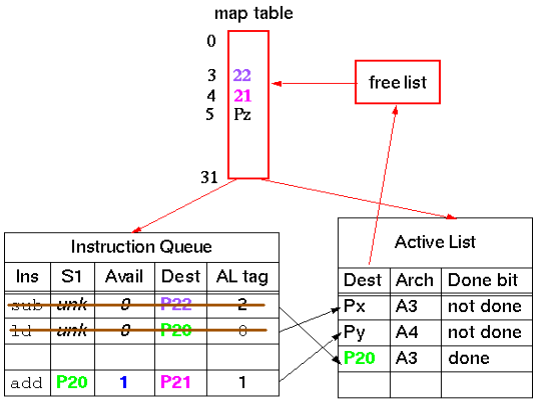
The R10000 in Action 5

```
ld    A3, #(reg)      arch register A3 defined
                      potential multi-cycle
add   A4, A3, reg     arch register A3 used
sub   A3, reg, reg    arch register A3 redefined
                      name dependence
or    A5, A3, reg
```



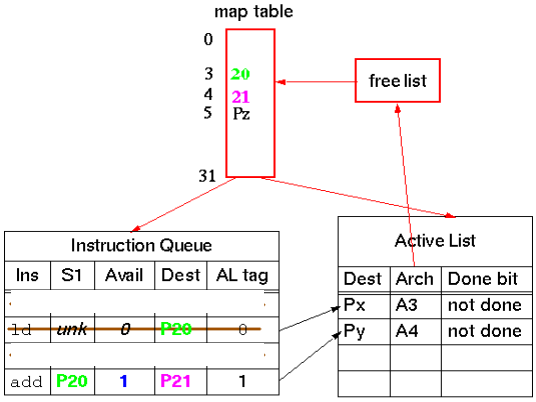
The R10000 in Action 5 : Interrupts 1

```
ld    A3, #(reg)      arch register A3 defined
                      potential multi-cycle
add   A4, A3, reg     arch register A3 used
sub   A3, reg, reg    arch register A3 redefined
                      name dependence
or    A5, A3, reg
```



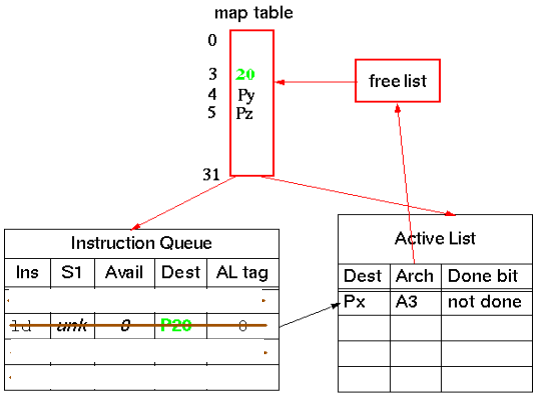
The R10000 in Action: Interrupts 2

```
ld    A3, #(reg)      arch register A3 defined
                      potential multi-cycle
add   A4, A3, reg     arch register A3 used
sub   A3, reg, reg    arch register A3 redefined
                      name dependence
or    A5, A3, reg     arch register A3 used
```



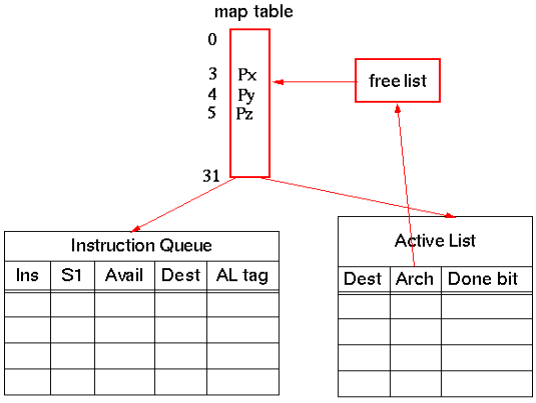
The R10000 in Action: Interrupts 3

```
ld    A3, #(reg)      arch register A3 defined
                      potential multi-cycle
add   A4, A3, reg     arch register A3 used
sub   A3, reg, reg    arch register A3 redefined
                      name dependence
or    A5, A3, reg     arch register A3 used
```



The R10000 in Action: Interrupts 4

```
ld    A3, #(reg)      arch register A3 defined
                      potential multi-cycle
add   A4, A3, reg     arch register A3 used
sub   A3, reg, reg    arch register A3 redefined
                      name dependence
or    A5, A3, reg     arch register A3 used
```



R10000 Execution

In-order issue (have already fetched instructions)

- rename architectural registers to physical registers via a map table
- detect structural hazards for instruction queues (integer, memory & FP) & active list
- issue up to 4 instructions to the instruction queues

Out-of-order execution (to increase ILP)

- instruction queues that indicate when an operand has been calculated
  - each instruction monitors the setting of the busy-register table
- set busy-register table entry for the destination register
- detect functional unit structural & RAW hazards
- dispatch instructions to functional units & execute them

In-order commit (to preserve precise interrupts)

- this & previous program-generated instructions have completed
- physical register in previous mapping returned to free list
- rollback on interrupts

Limits

Limits on out-of-order execution

- amount of ILP in the code
- scheduling window size (instruction queues)
  - need to do associative searches & its effect on cycle time
  - relatively few instructions in window
- number & types of functional units
- number of locations for values
- number of ports to memory
- Issue width