Flow Control

Flow Control

- *Flow Control* determines how the resources of a network, such as channel bandwidth and buffer capacity are allocated to packets traversing a network
- Goal is to use resources as efficient as possible to allow a high throughput
- An efficient flow control is a prerequisite to achieve a good network performance

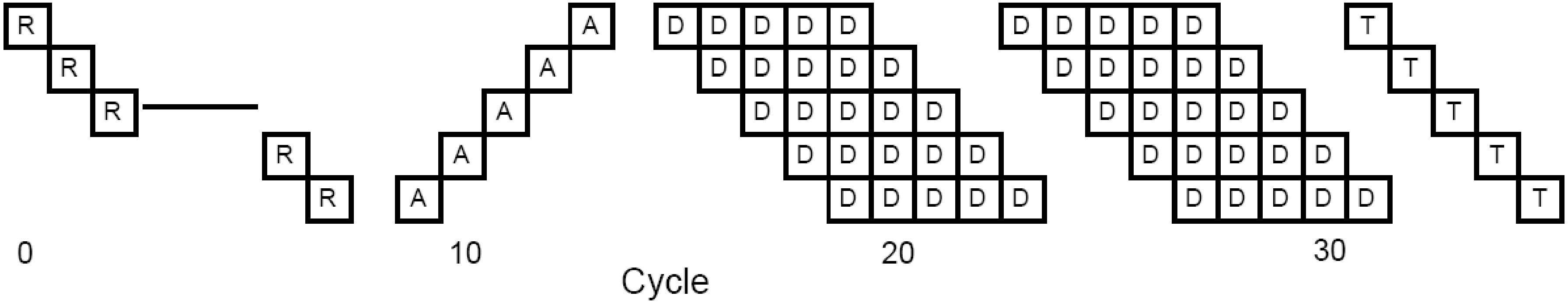
Flow Control

- Flow Control can be viewed as a problem of
  - ➔Resource allocation
  - ➔Contention resolution
- Resources in form of channels, buffers and state must be allocated to each packet
- If two packets compete for the same channel flow control can only assign the channel to one packet, but must also deal with the other packet

Flow Control

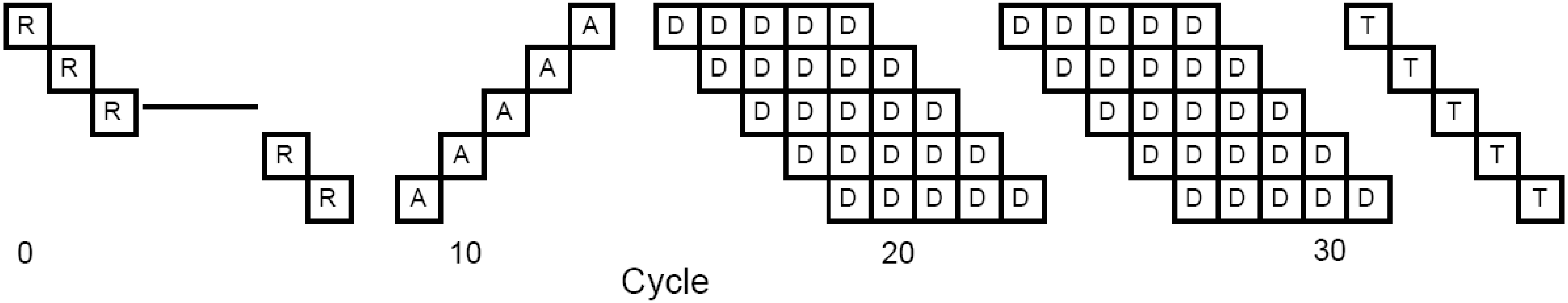
- Flow Control can be divided into
  - Bufferless flow control
    - Packets are either dropped or misrouted
  - Buffered flow control
    - Packets that cannot be routed via the desired channel are stored in buffers

Circuit Switching



- Circuit-Switching is a bufferless flow control, where several channels are reserved to form a circuit
- A request (*R*) propagates from source to destination, which is answered by an acknowledgement (*A*)
- Then data is sent (here two five flit packets (*D*)) and a tail flit (*T*) is sent to deallocate the channels

Circuit Switching



- Circuit-switching does not suffer from dropping or misrouting packets
- However there are two weaknesses
  - ➔ High latency: $T_0 = 3\,H\,t_r + L/b$ (ignoring wire latency)
  - ➔ Low throughput, since channel is used to a large fraction of time for signaling and not for delivery of the payload

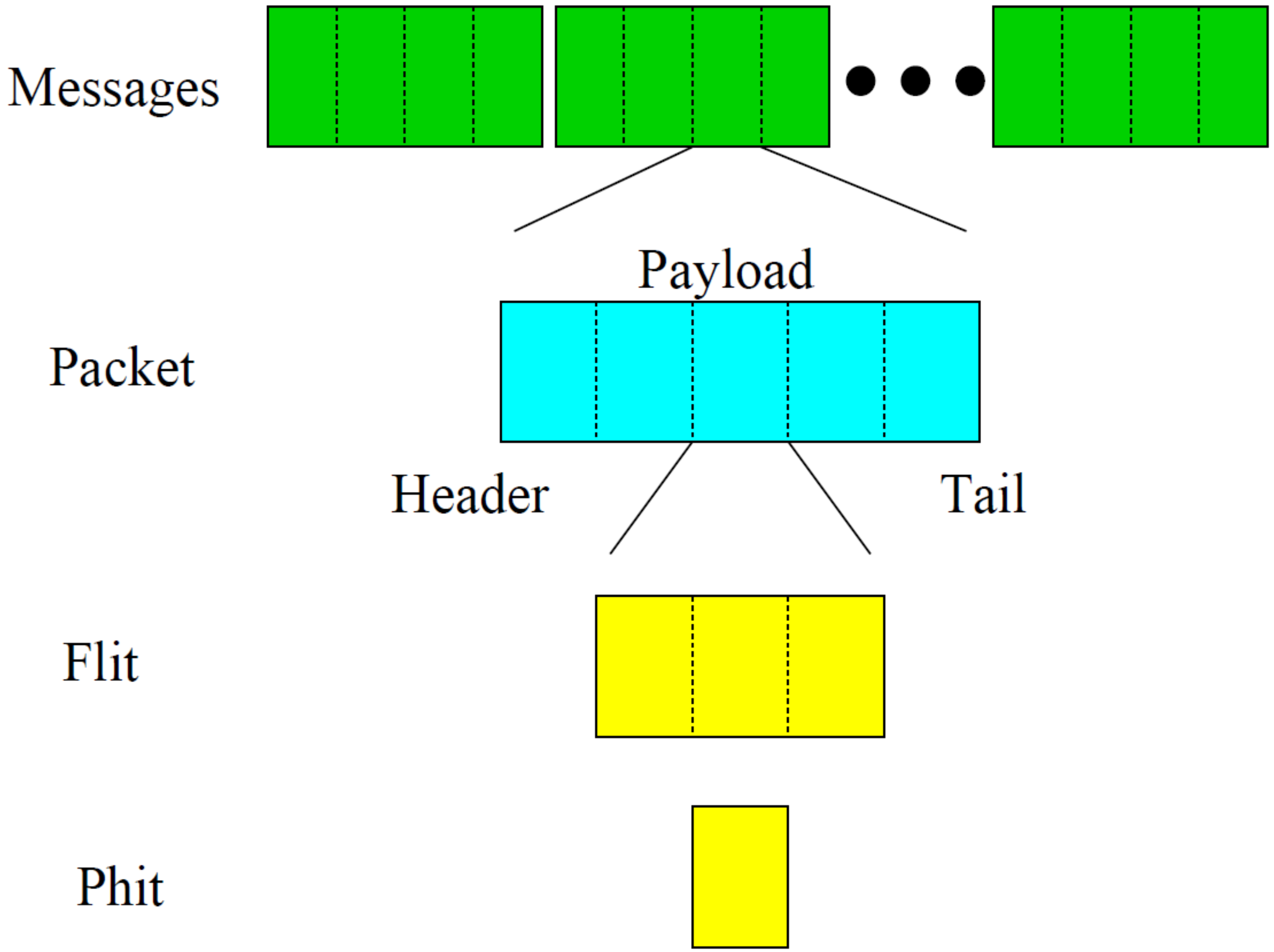
Buffered Flow Control

- More efficient flow control can be achieved by adding buffers
  - ➔ With sufficient buffers packets do not need to be misrouted or dropped, since packets can wait for the outgoing channel to be ready

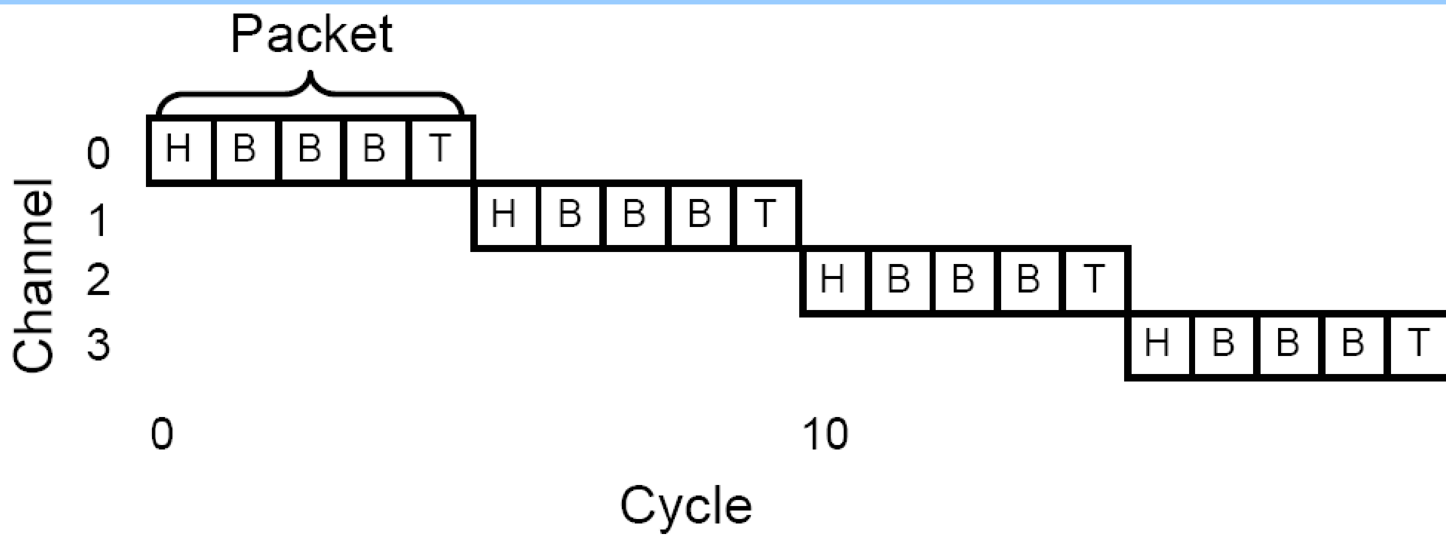
Buffered Flow Control

- Two main approaches
  - Packet-Buffer Flow Control
    - Store-And-Forward
    - Cut-Through
  - Flit-Buffer Flow Control
    - Wormhole Flow Control
    - Virtual Channel Flow Control

Data Units



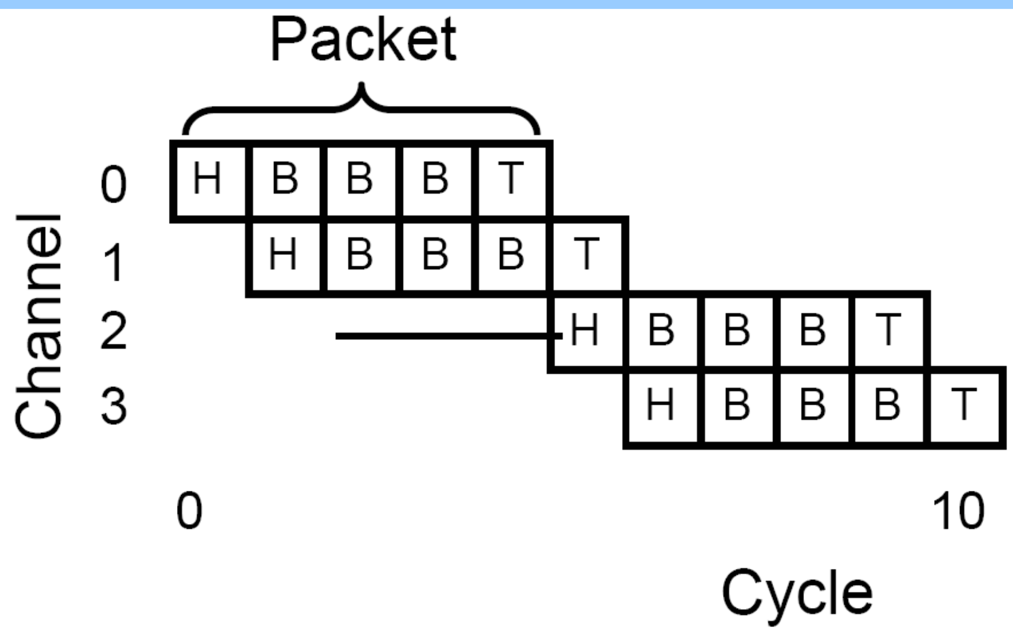
Store and Forward Flow Control



- Each node along a route waits until a packet is completely received (stored) and then the packet is forwarded to the next node
- Two resources are needed
  - ➔ Packet-sized buffer in the switch
  - ➔ Exclusive use of the outgoing channel

$$T_0 = H\,(t_r + L/b)$$

Cut-Through Flow Control



- Transmission on the next channel starts directly when the new header flit is received (otherwise it behaves like Store-Forward)
  - ➔ Channel is released after tail flit

$$T_0 = H\, t_r + L/b$$

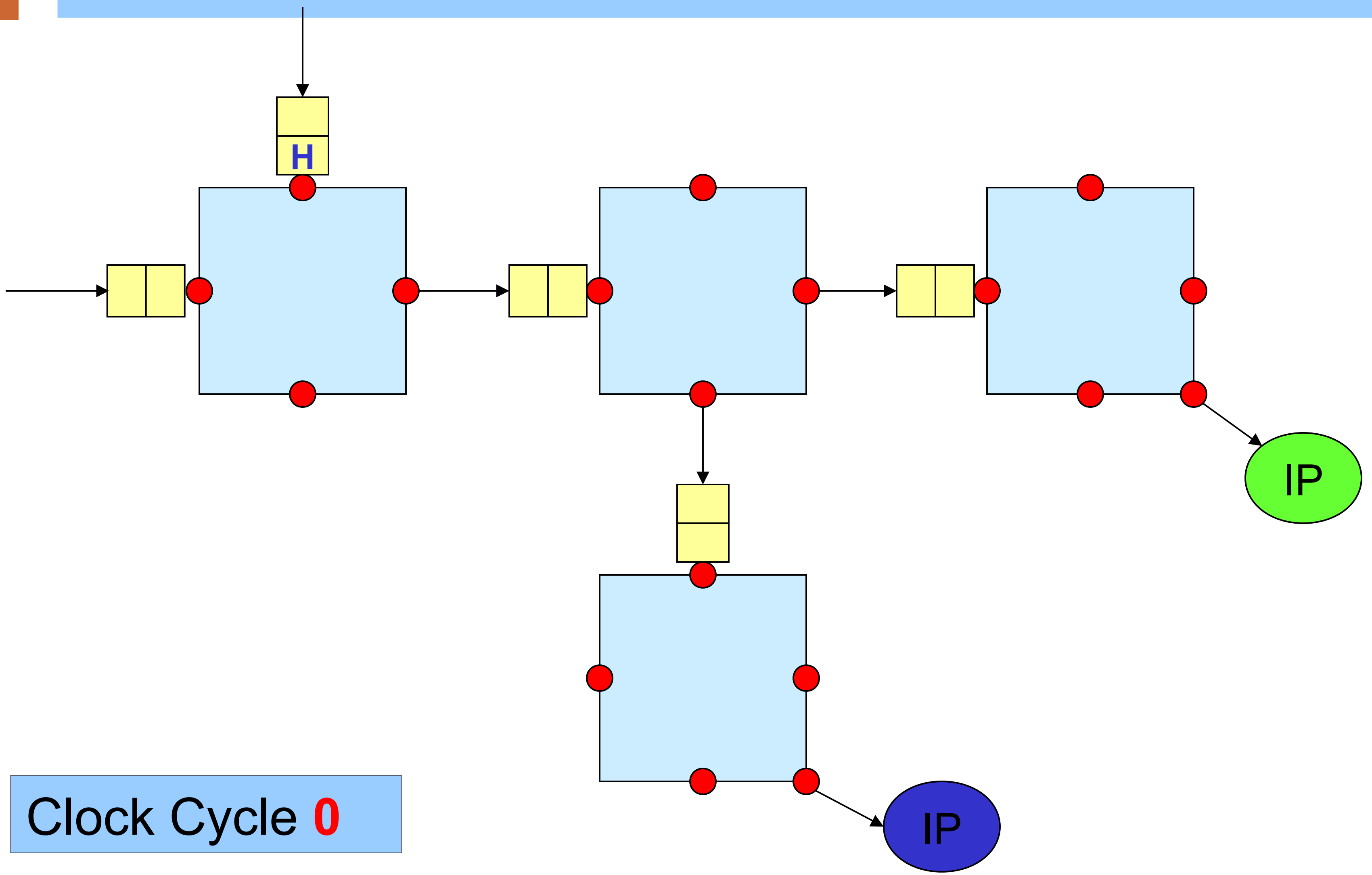
Cut-Through Flow Control

- Shortcomings
  - Very inefficient use of buffer space
    - As buffers are allocated in units of packets
    - Often we need multiple indipendent buffer sets to reduce blocking or provide deadlock avoidance
  - By allocating buffers in units of packets → contention latency is increased
    - E.g., High-priority packet colliding with a low-priority packet
      - Must wait the entire low-priority packet to be transmitted before it can acquire the channel

Wormhole Flow Control

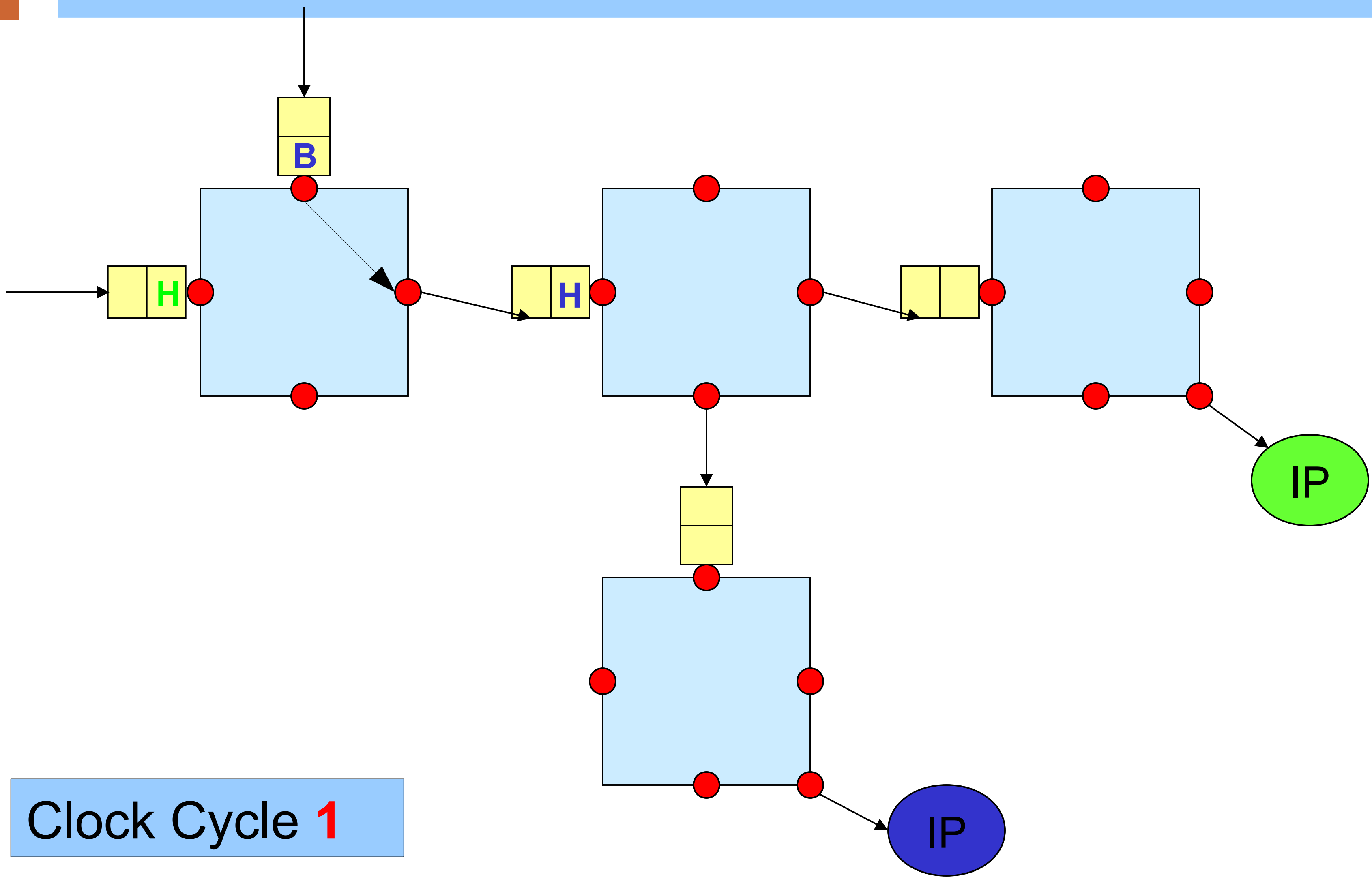
- Wormhole flow control operates like cut-through, but with channel and buffers allocated to flits rather than packets
- Three resources are needed
  - A virtual channel for the packet
    - Body flits of a packet use the VC acquired by the head flit
  - One flit buffer
  - One flit channel bandwidth

Wormhole - Example



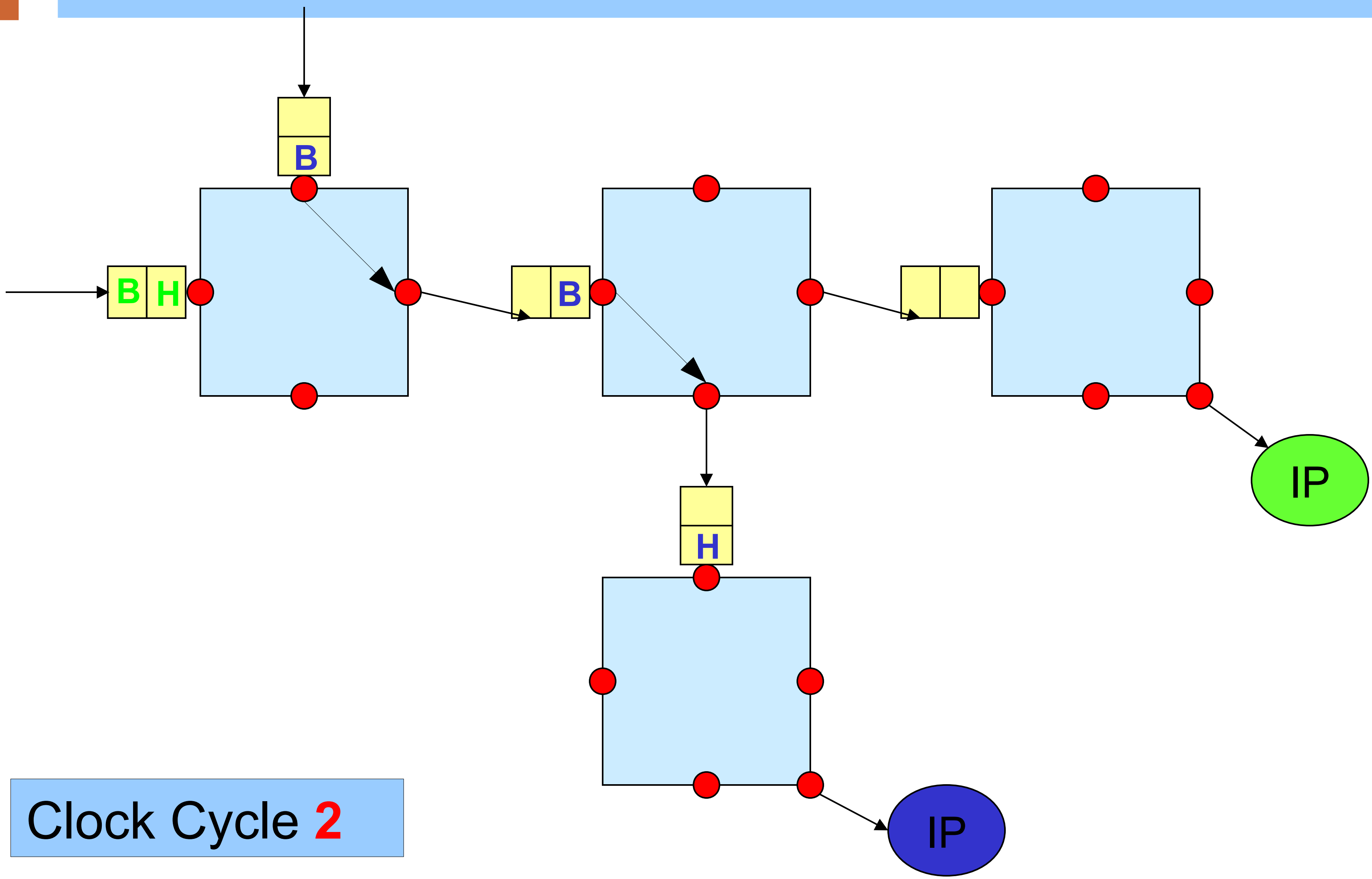
Clock Cycle **0**

Wormhole - Example



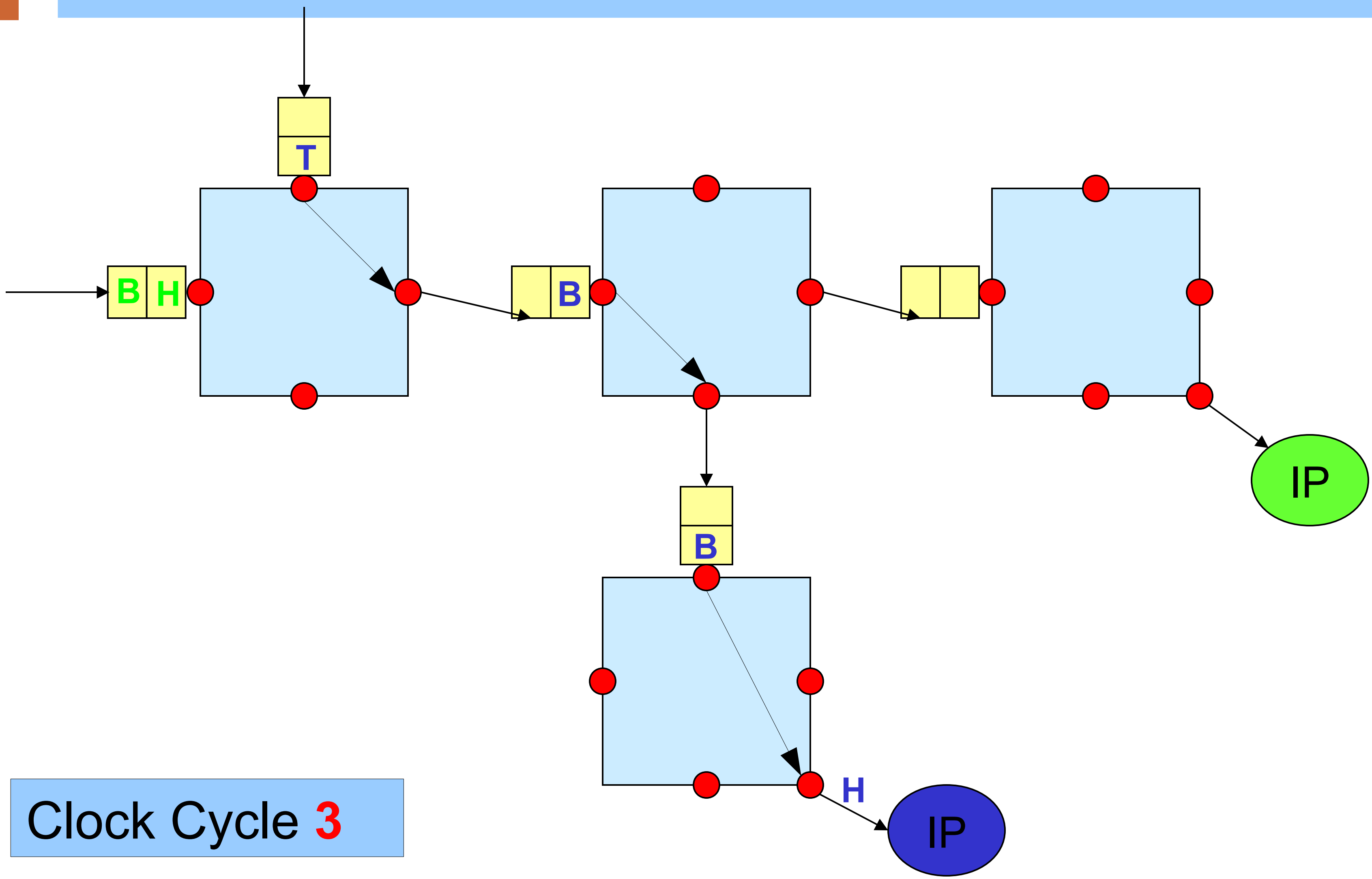
Clock Cycle 1

Wormhole - Example



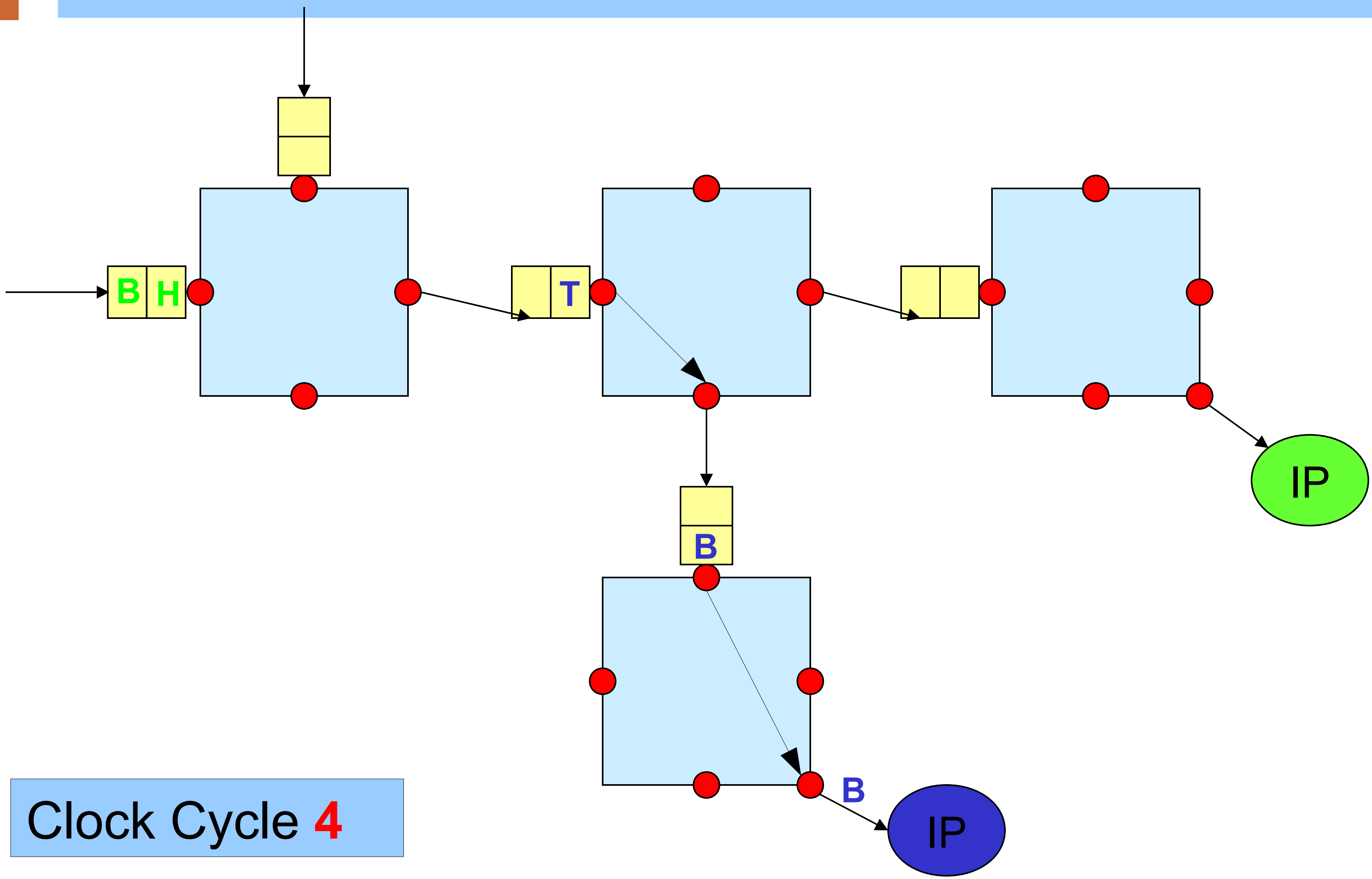
Clock Cycle 2

Wormhole - Example



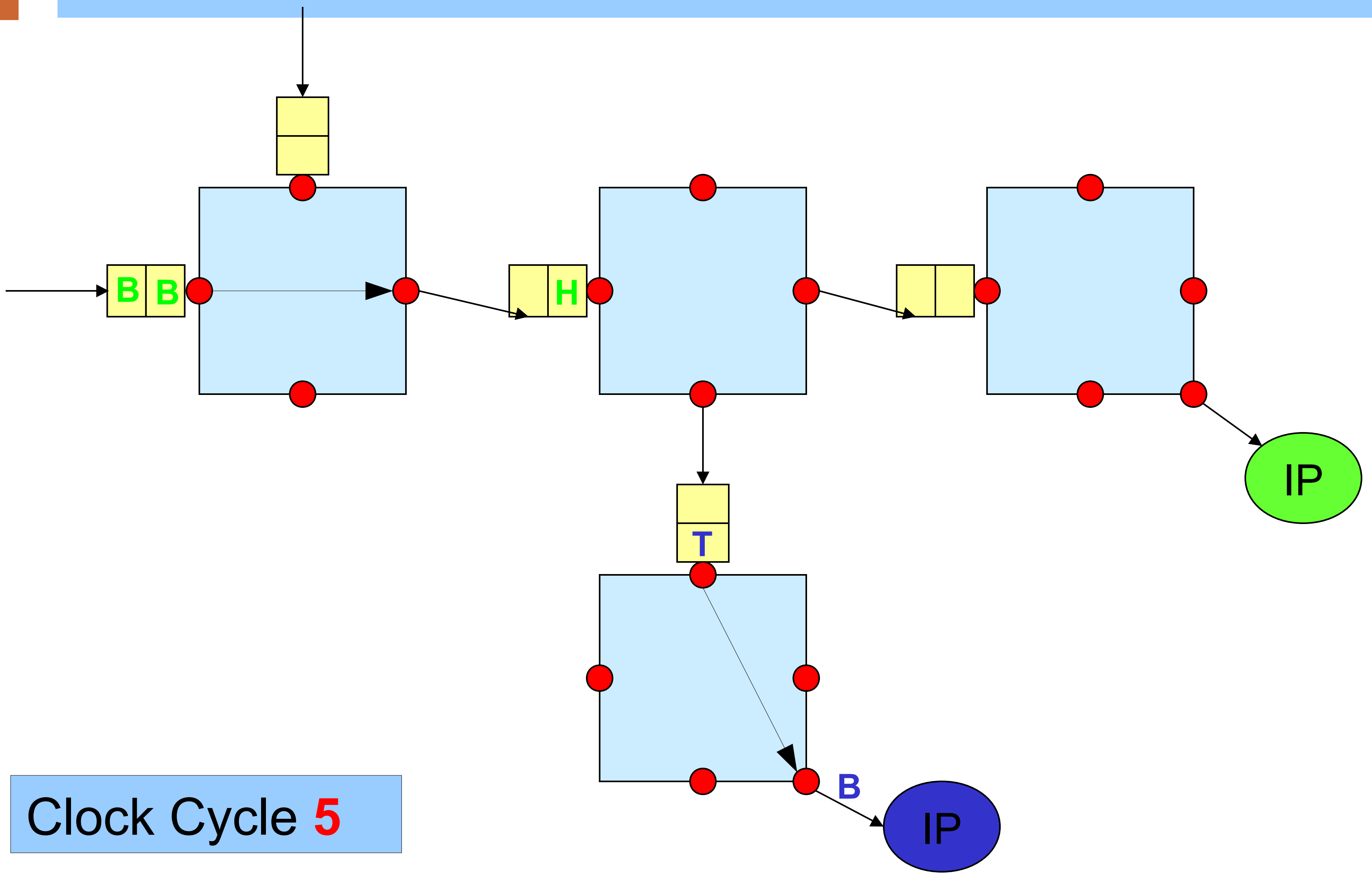
Clock Cycle **3**

Wormhole - Example



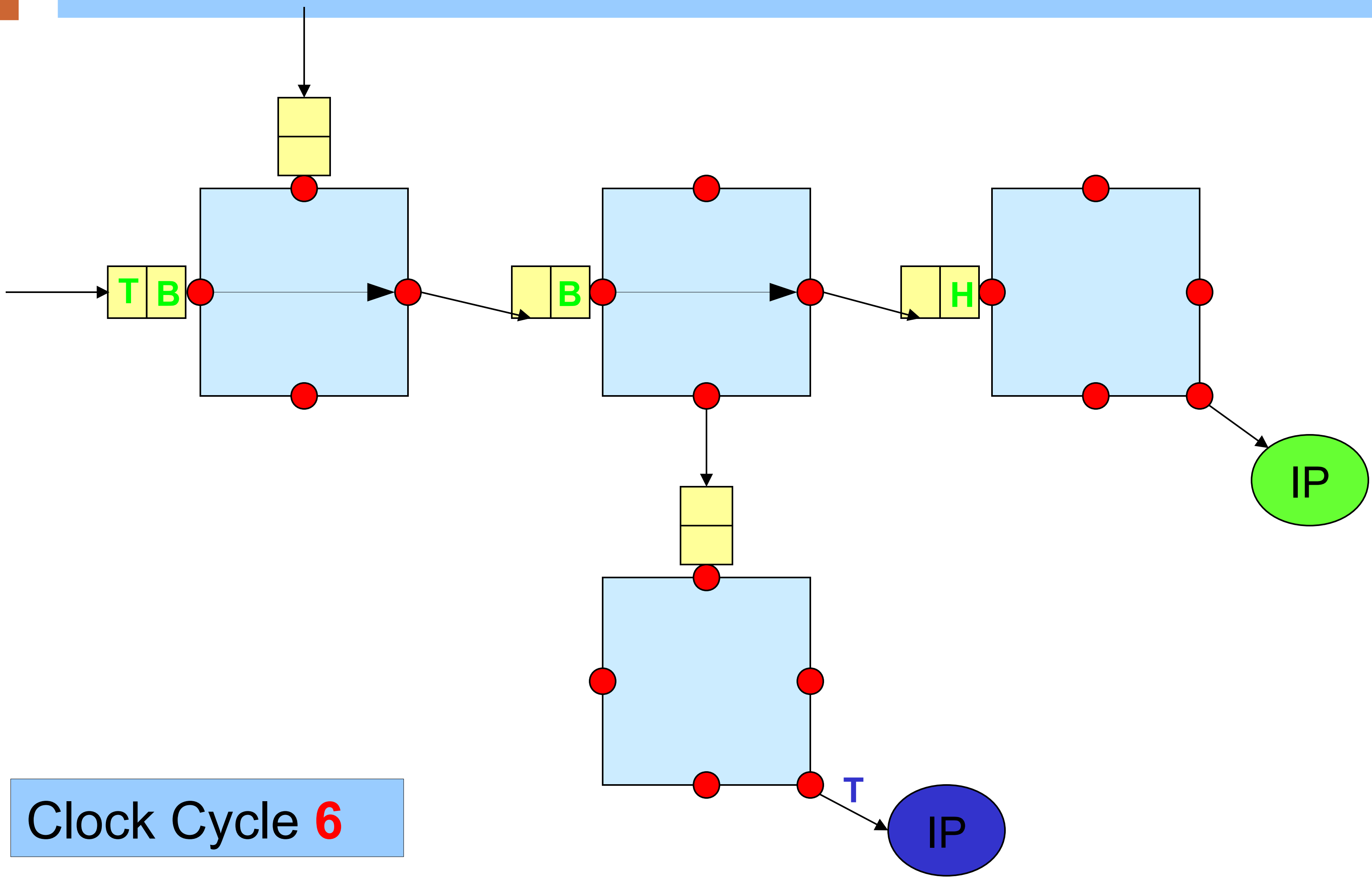
Clock Cycle **4**

Wormhole - Example



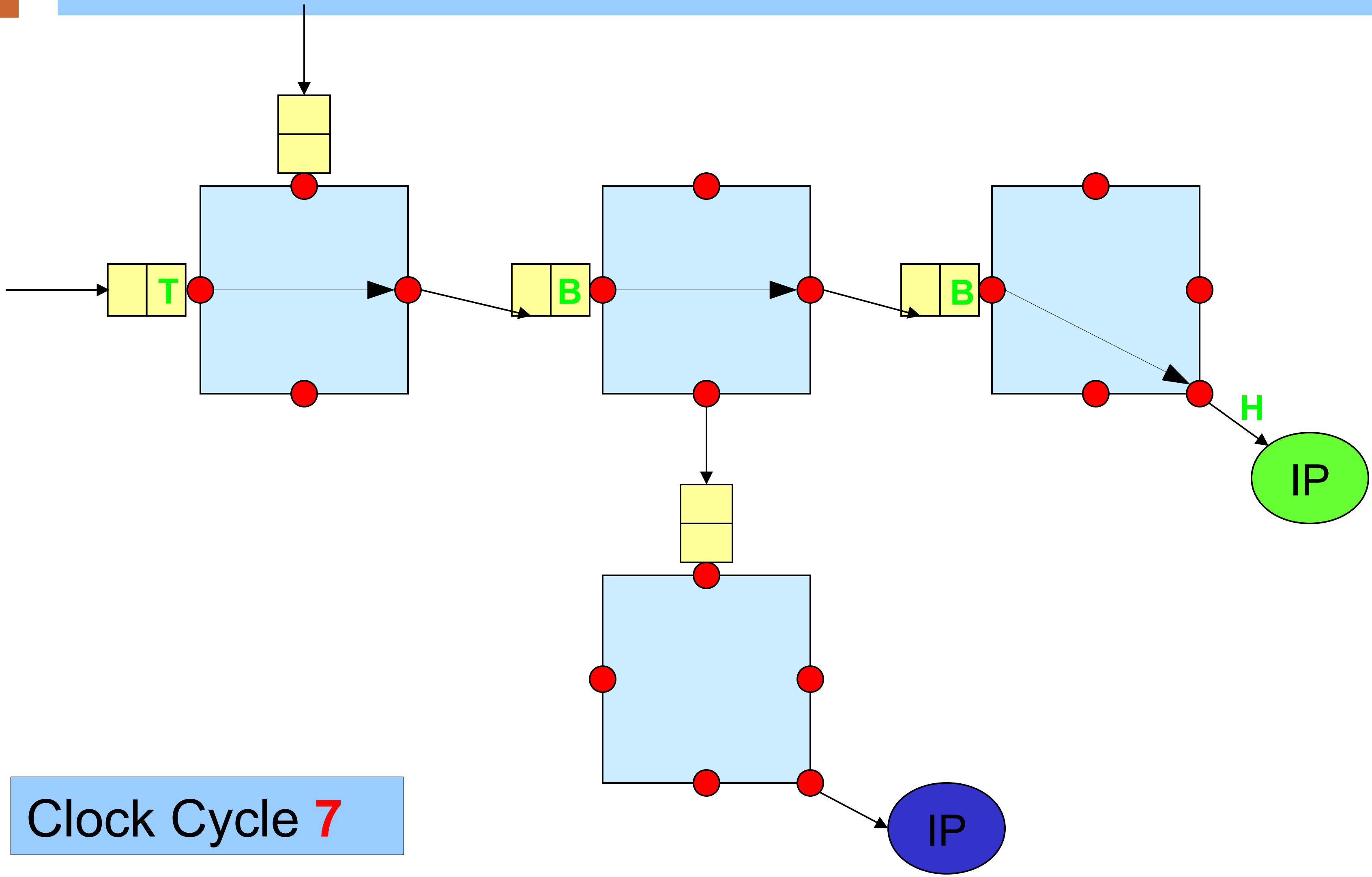
Clock Cycle **5**

Wormhole - Example



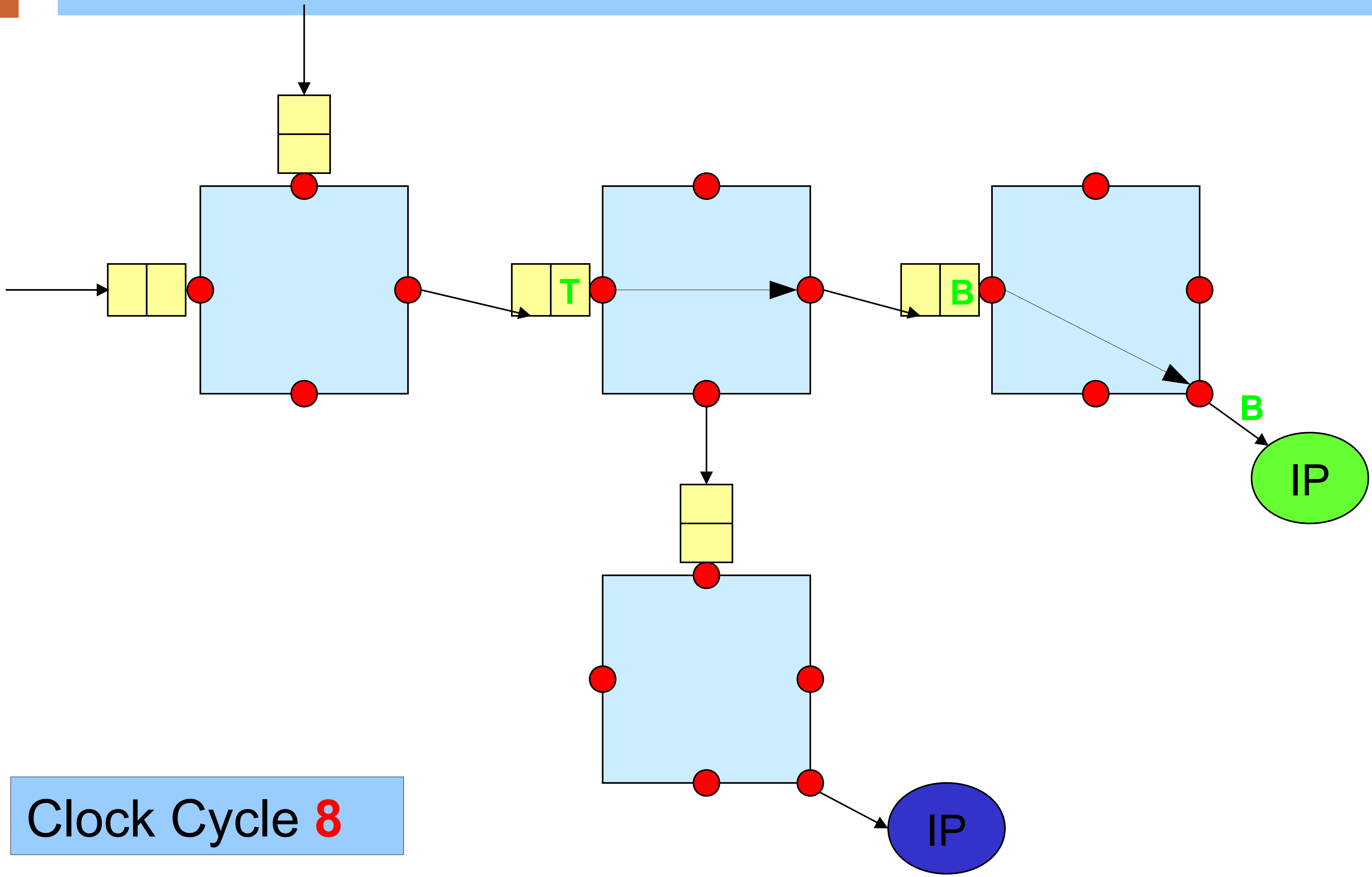
Clock Cycle 6

Wormhole - Example

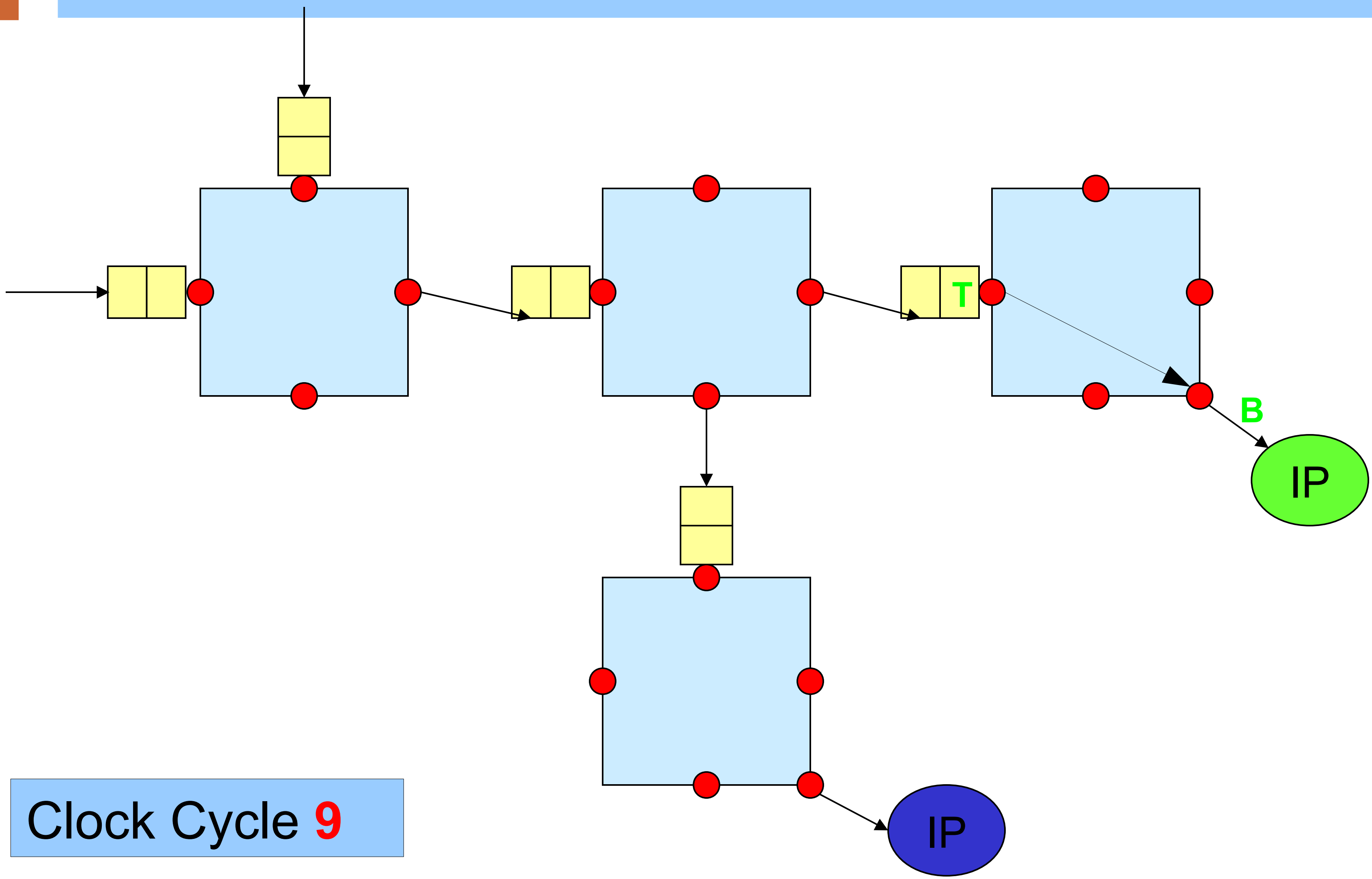


Clock Cycle 7

Wormhole - Example

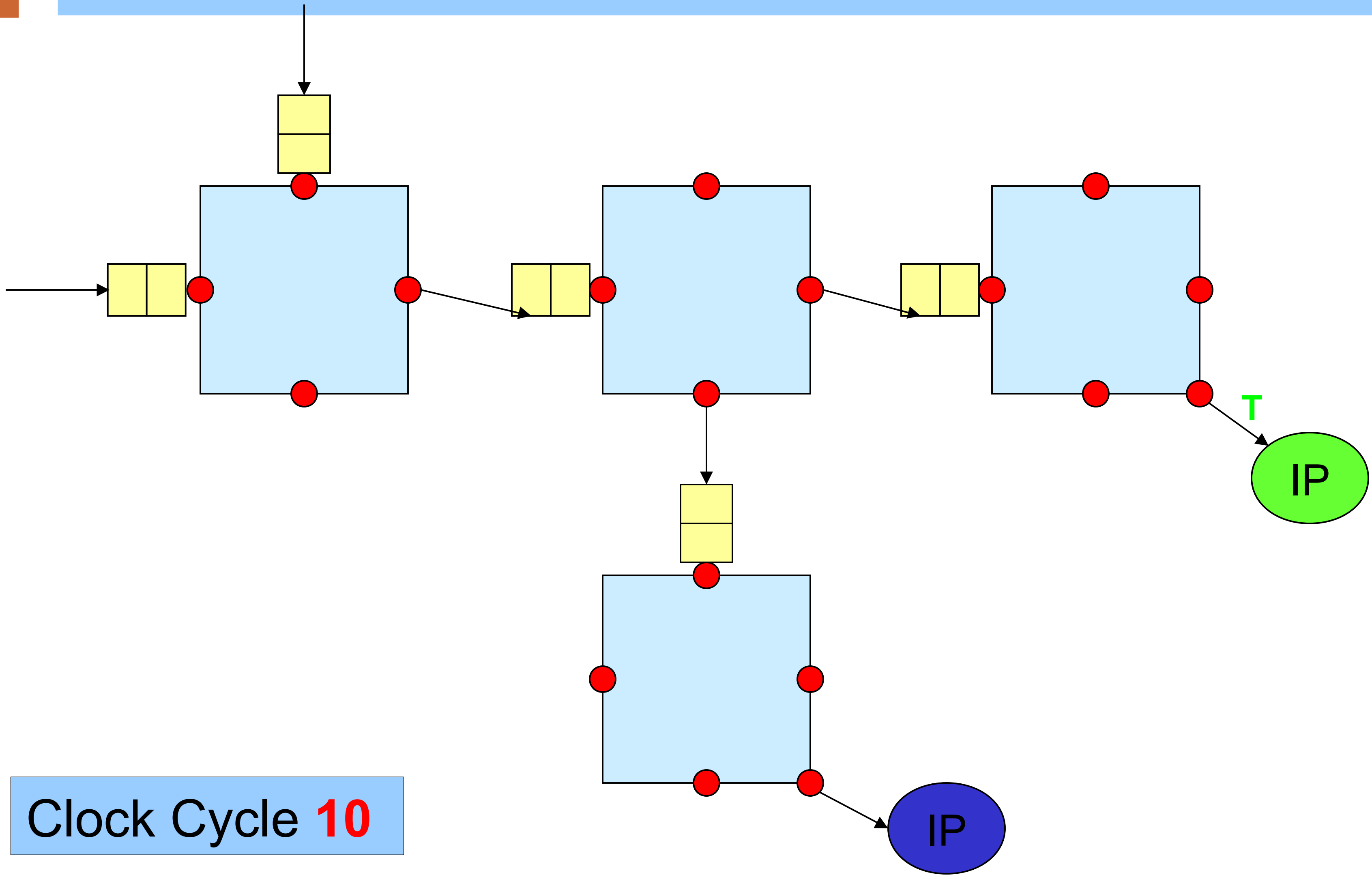


Wormhole - Example



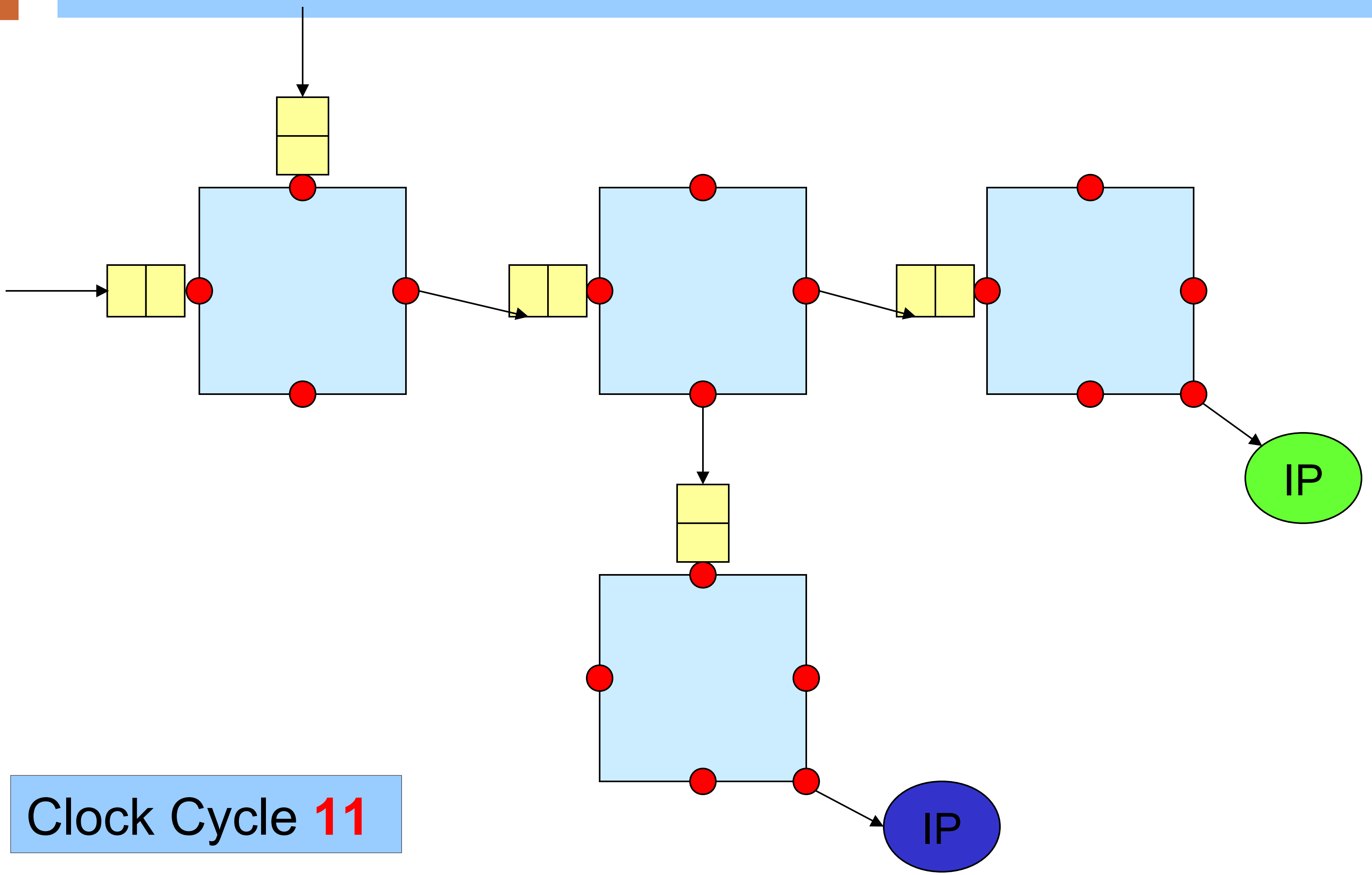
Clock Cycle **9**

Wormhole - Example



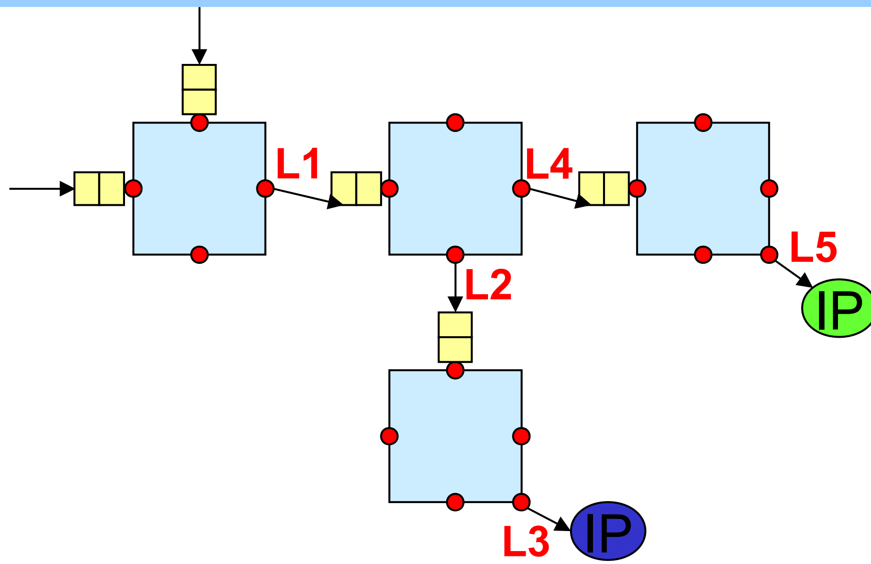
Clock Cycle 10

Wormhole - Example



Clock Cycle 11

Wormhole - Example



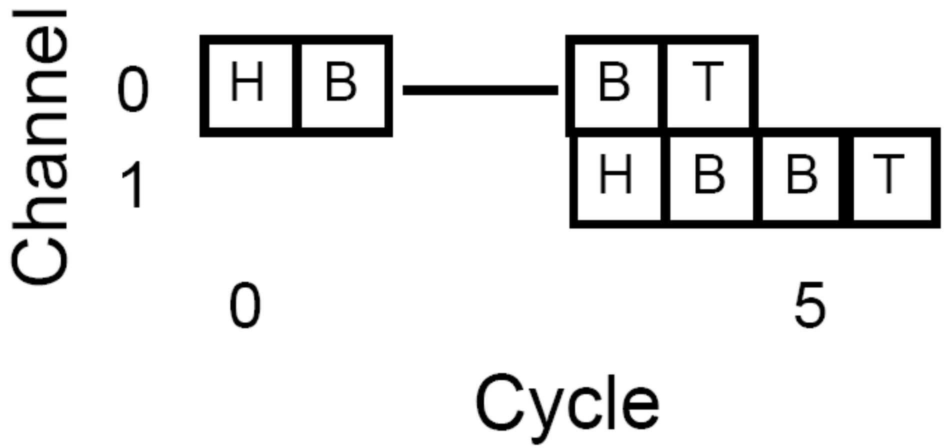
CC	0	1	2	3	4	5	6	7	8	9	10	11
Blue	Injected	L1	L1, L2	L1, L2, L3	L1, L2, L3	L2, L3	L3	Drained				
Green		Injected				L1	L1, L4	L1, L4, L5	L1, L4, L5	L4, L5	L5	Drained

- **Blue packet**
  - Injected at CC 0
  - Delivered at CC 7
  - **Latency 7 clock cycles**
- **Green packet**
  - Injected at CC 1
  - Delivered at CC 11
  - **Latency 10 clock cycles**

Wormhole Flow Control

- Comparison to cut-through
  - ➔ Wormhole flow control makes far more efficient use of buffer space
  - ➔ Throughput maybe less, since wormhole flow control may block a channels mid-packets

Wormhole Flow Control

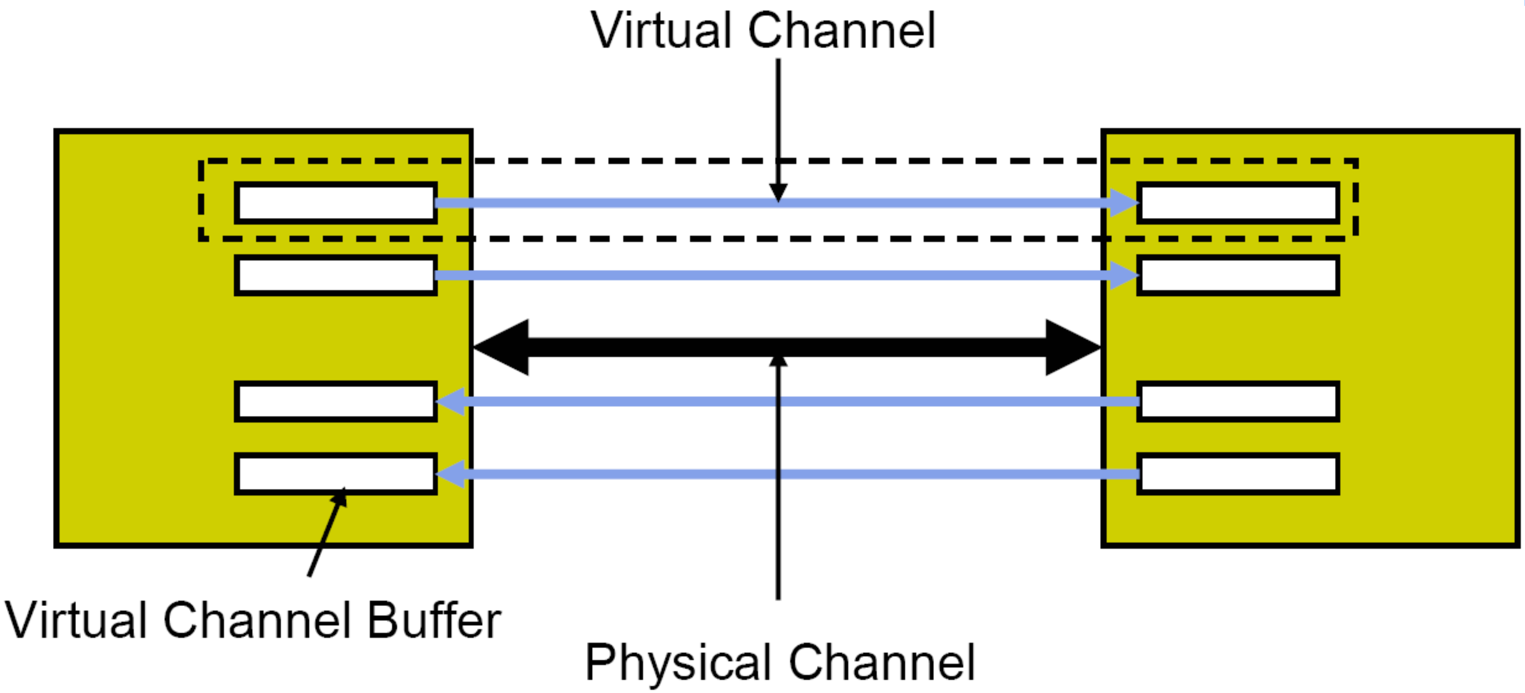


- The main advantage of wormhole to cut-through is that buffers in the routers do not need to be able to hold full packets, but only need to store a number of flits
- This allows to use smaller and faster routers

Virtual Channel Flow Control

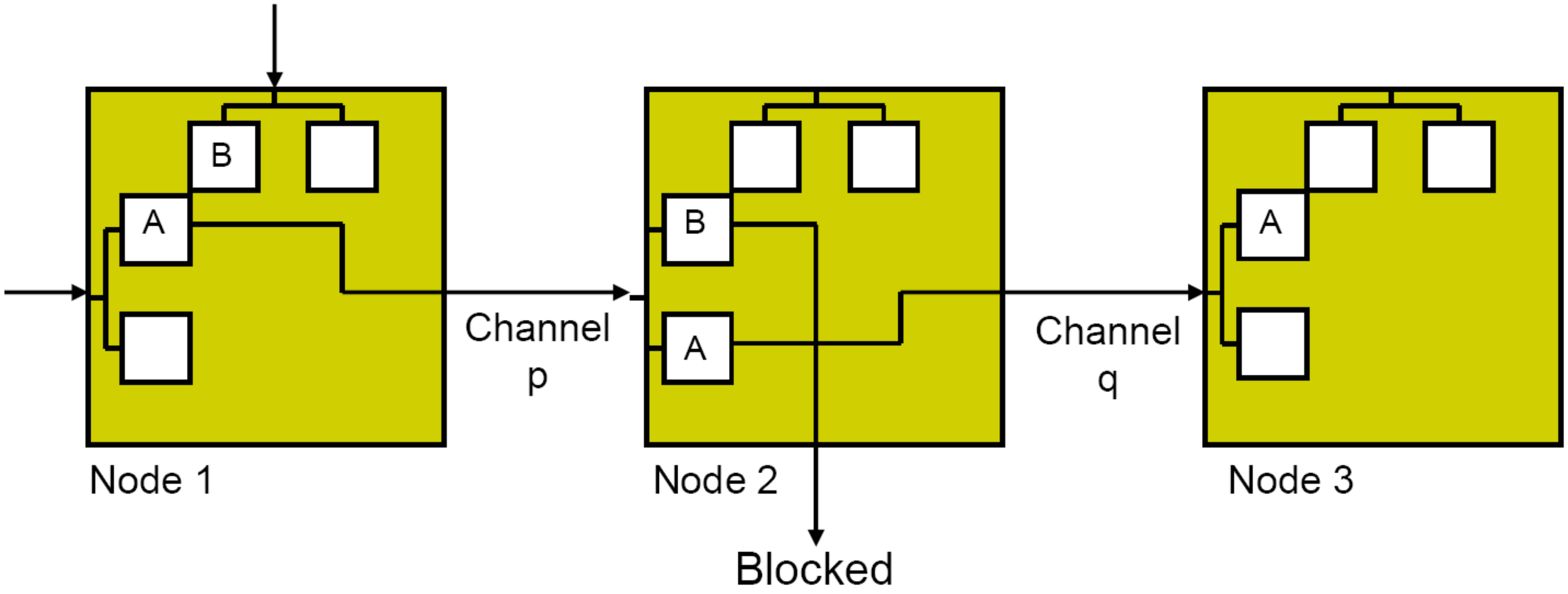
- In virtual channel flow-control several channels are associated with a single physical channel
- This allows to use the bandwidth that otherwise is left idle when a packet blocks the channel
- Unlike wormhole flow control subsequent flits are not guaranteed bandwidth, since they have to compete for bandwidth with other flits

Concept of Virtual Channels



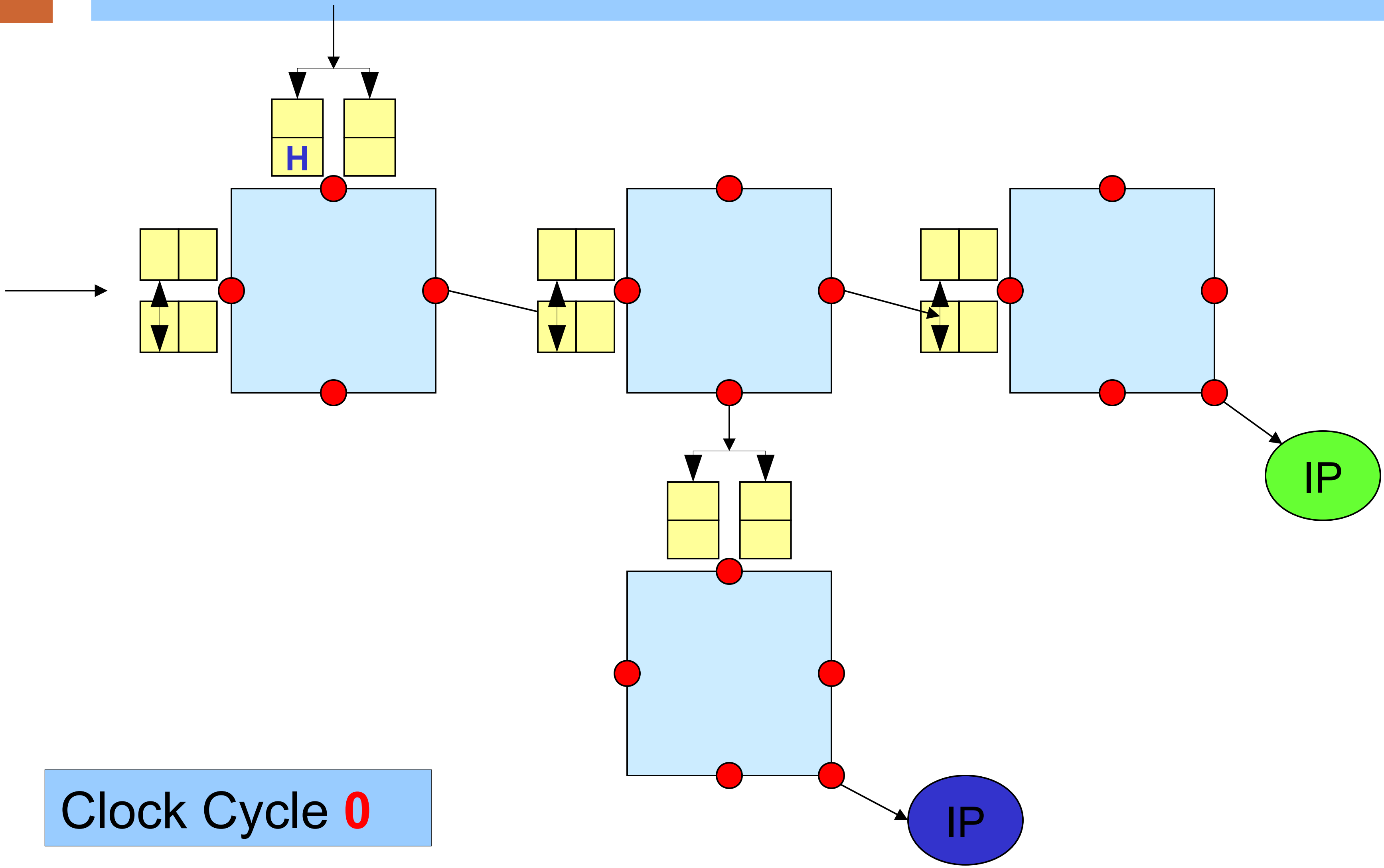
- A physical channel is shared by several virtual channels
- Naturally the speed of each virtual channel connection is reduced

Virtual Channel Flow Control



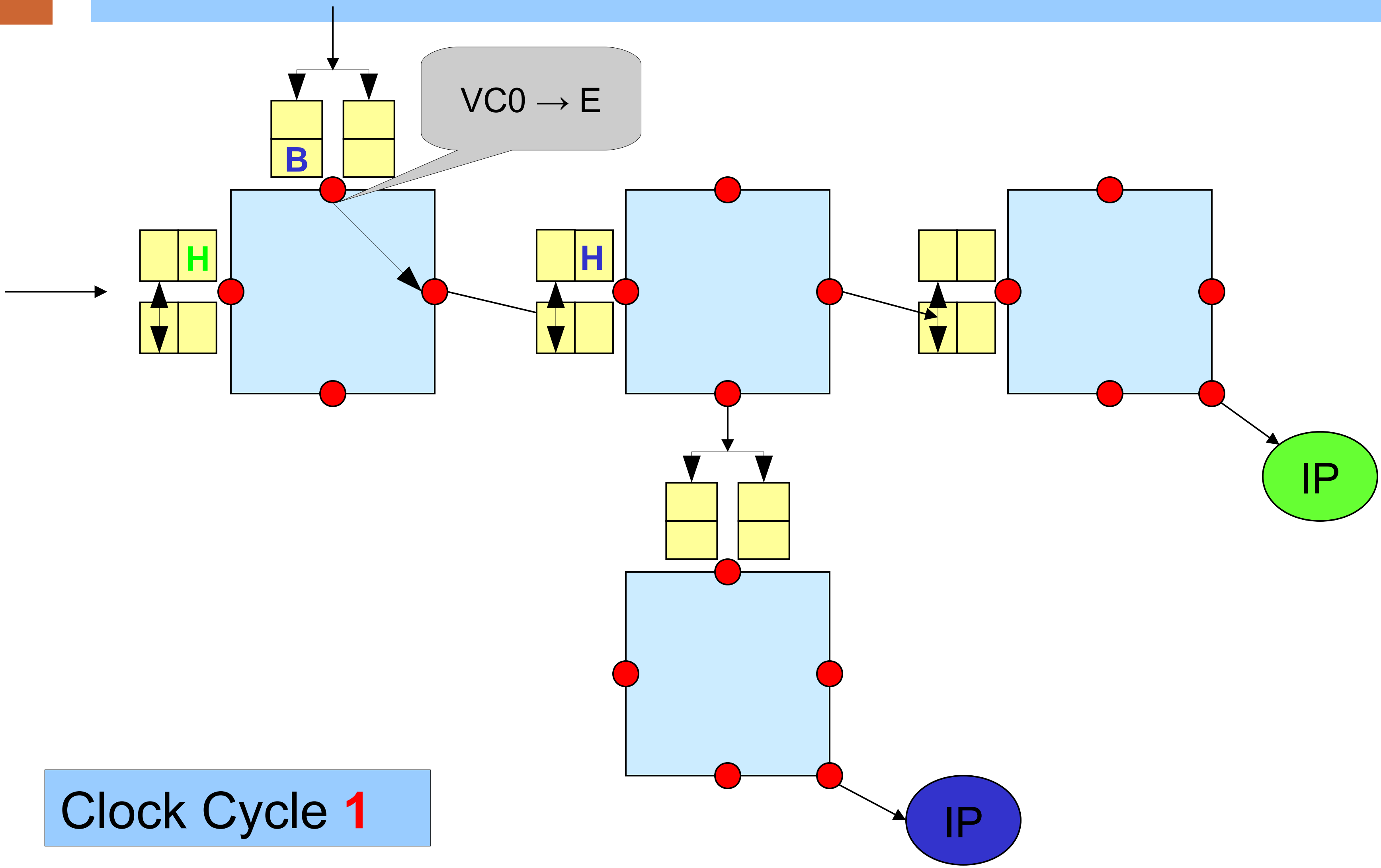
- There are several virtual channels for each physical channel
- Packet *A* can use a second virtual channel and thus proceed over channel *p* and *q*

Virtual Channels - Example



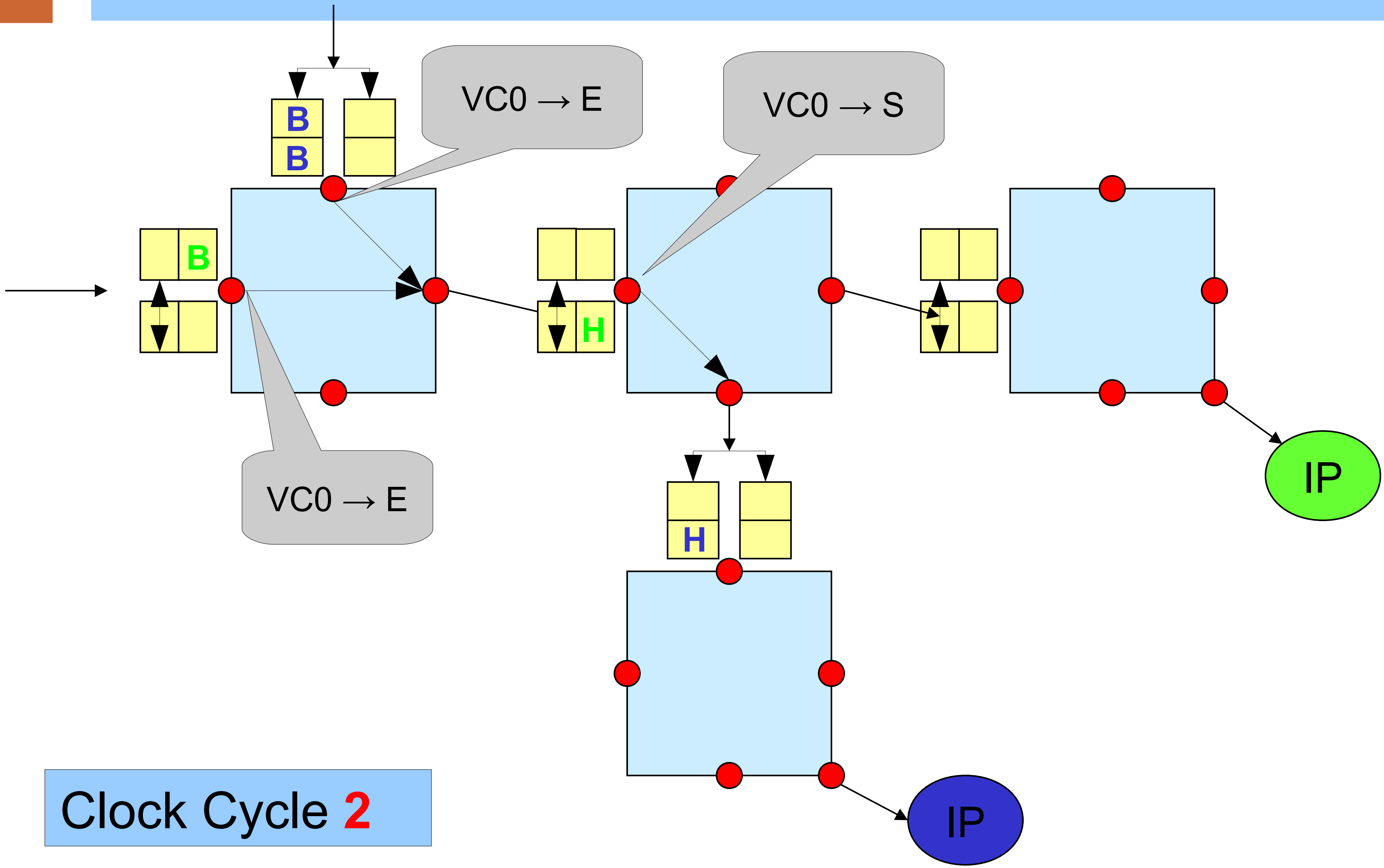
Clock Cycle 0

Virtual Channels - Example



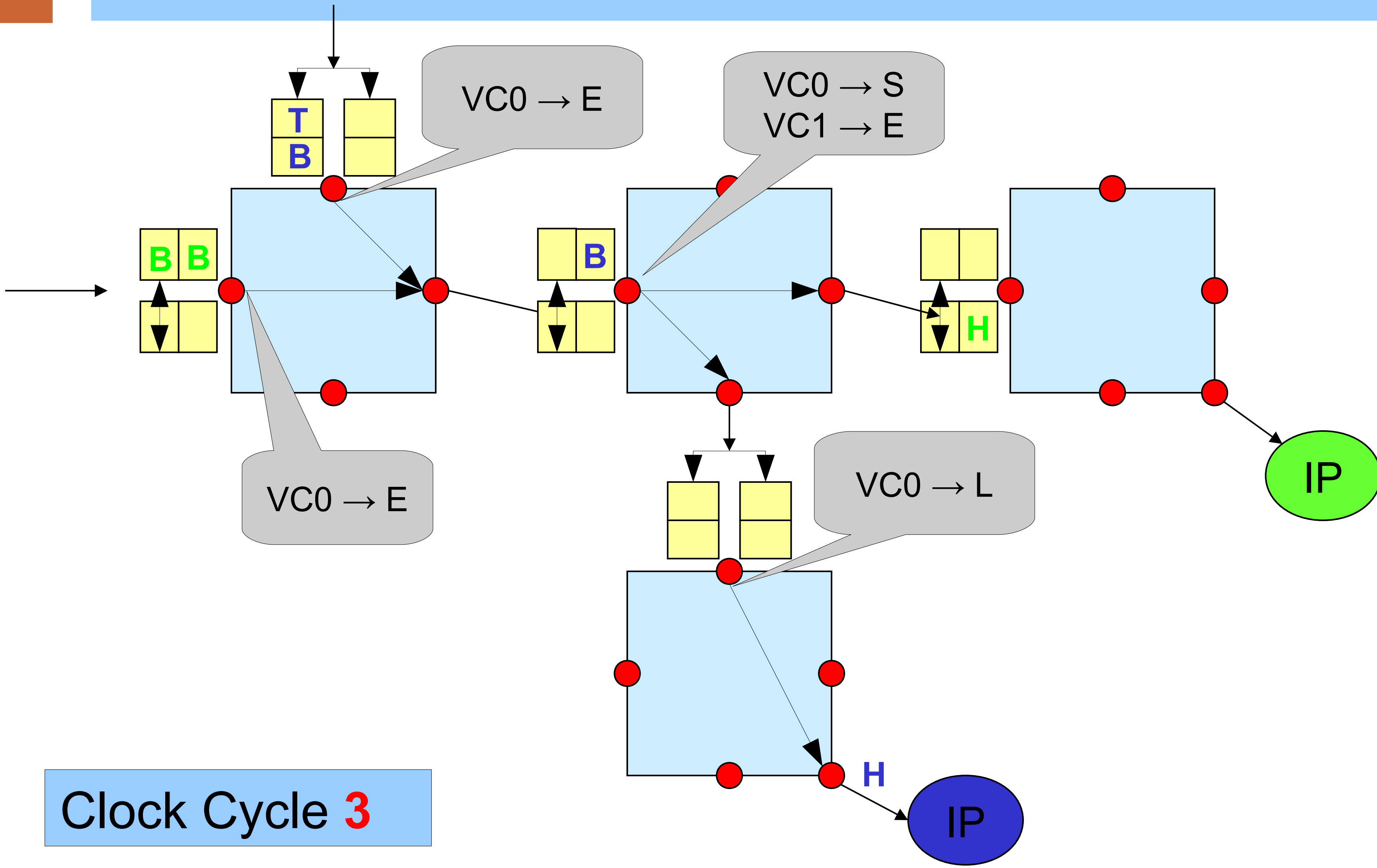
Clock Cycle 1

Virtual Channels - Example



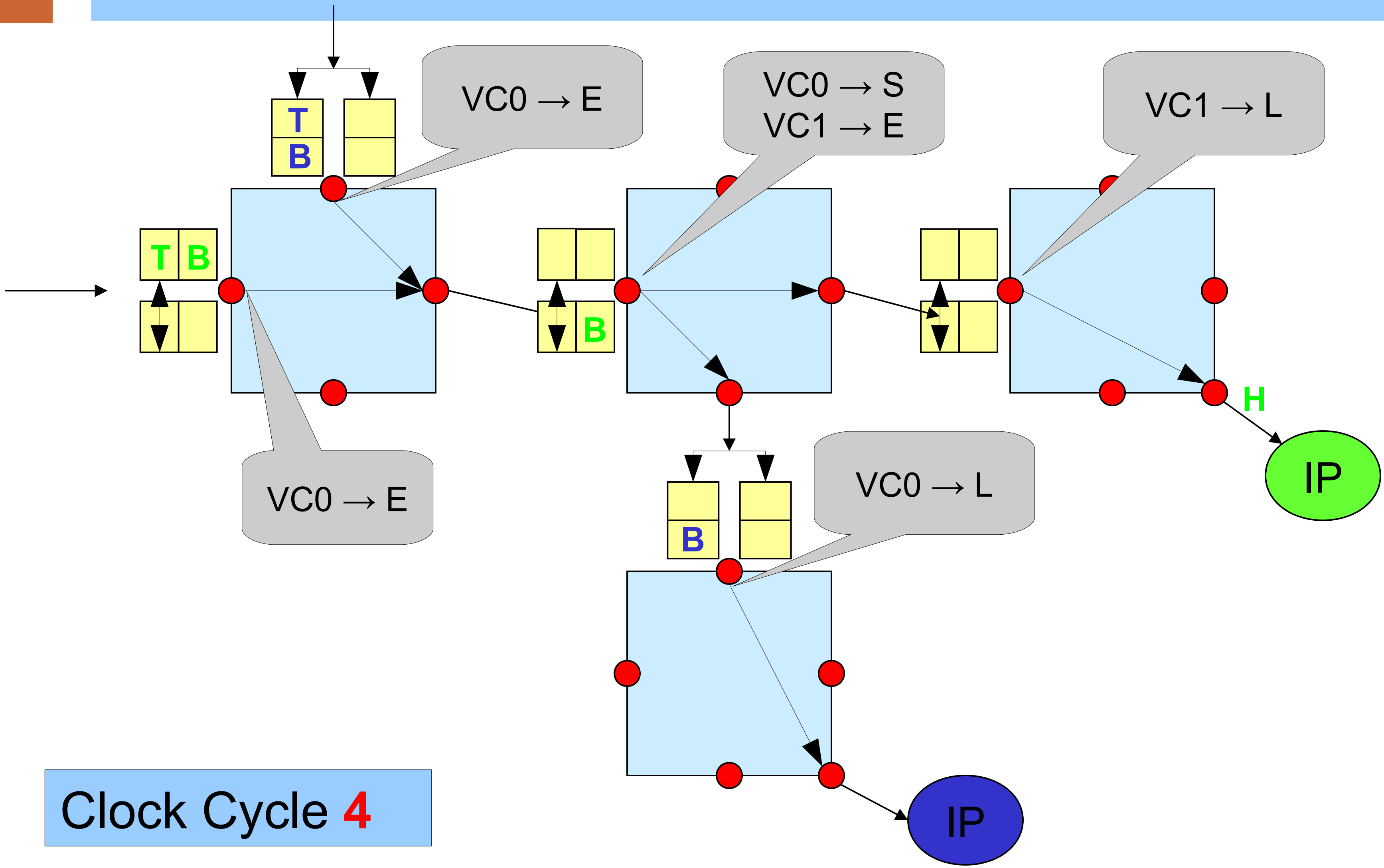
Clock Cycle 2

Virtual Channels - Example



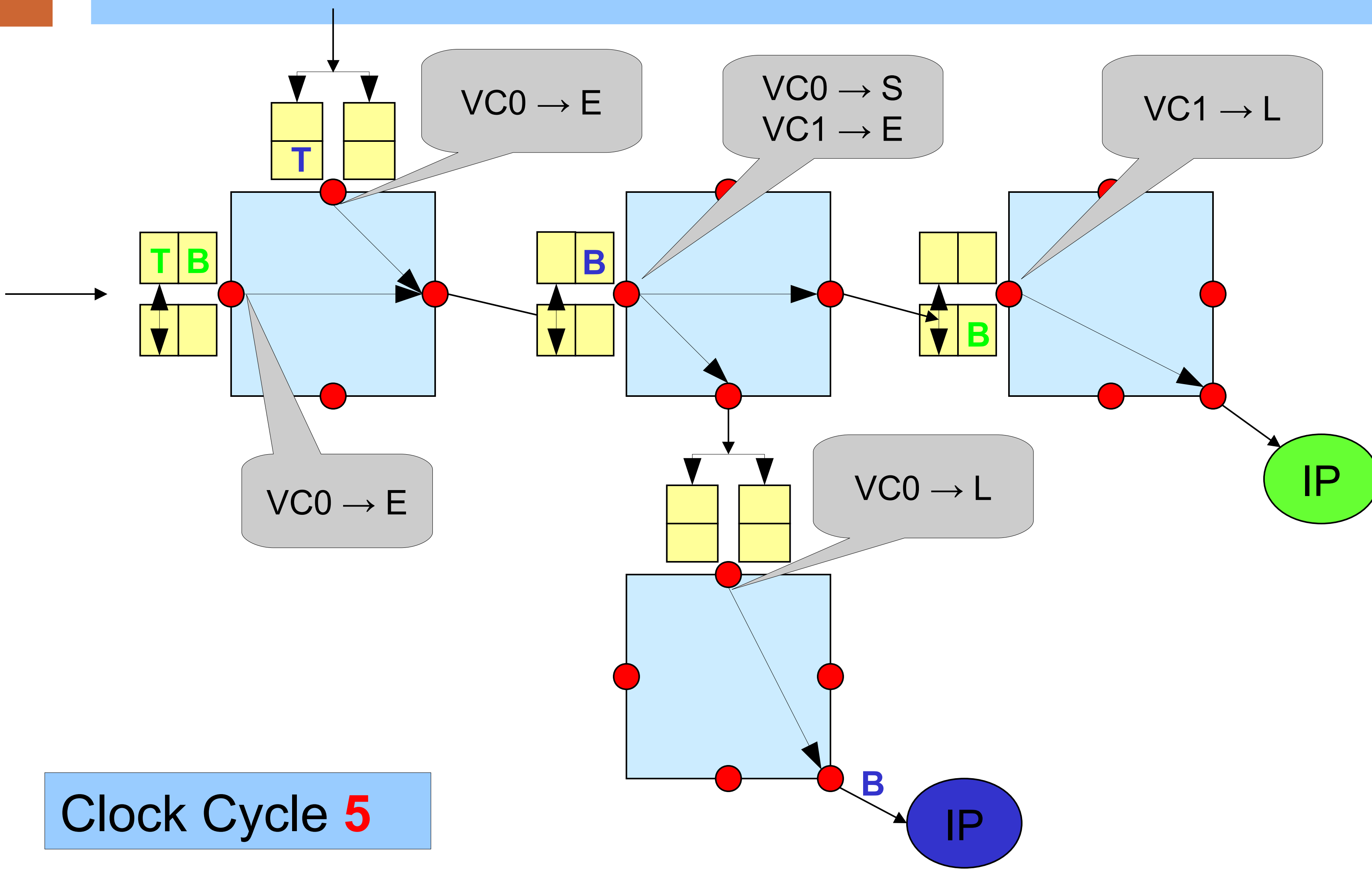
Clock Cycle 3

Virtual Channels - Example



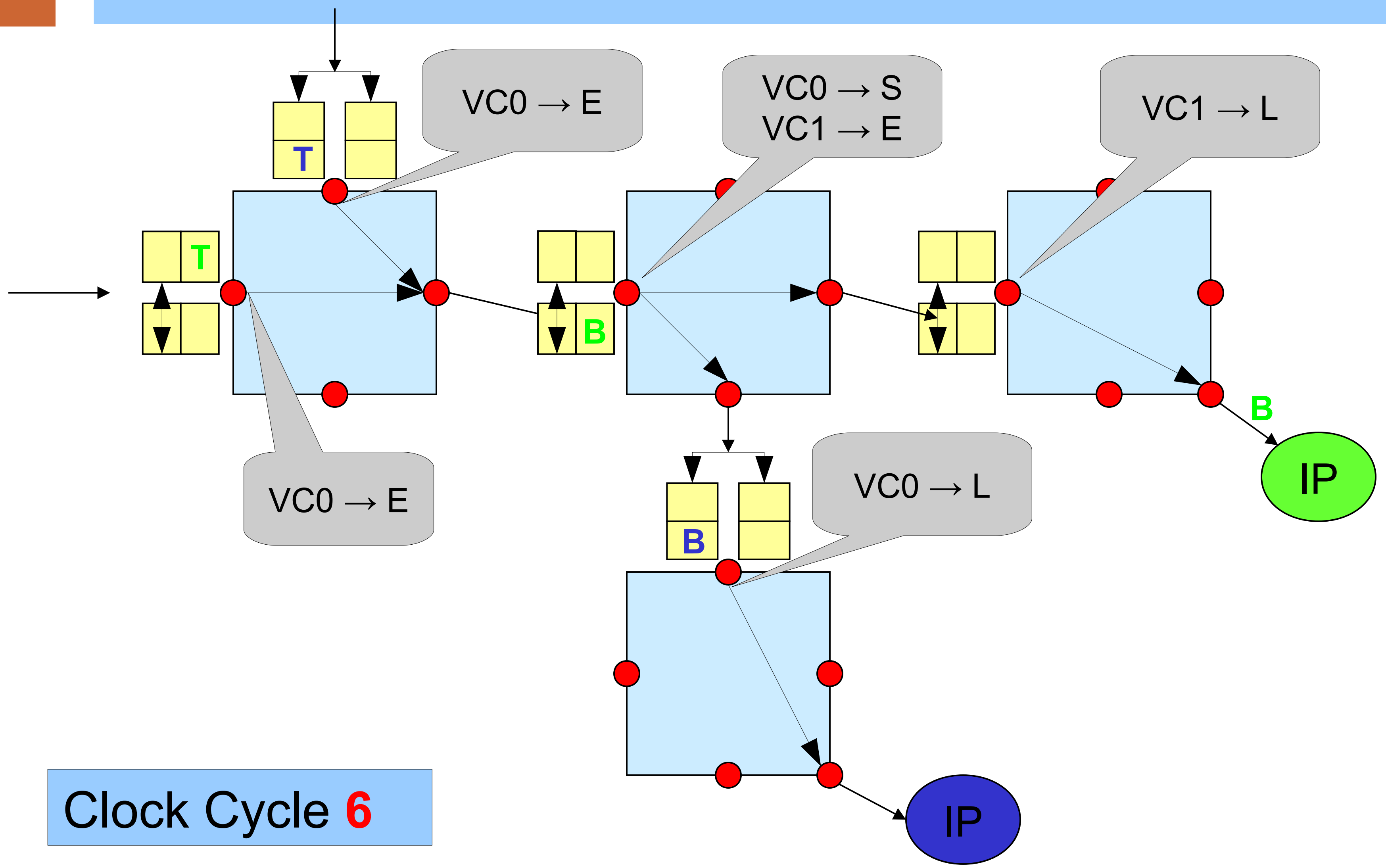
Clock Cycle 4

Virtual Channels - Example



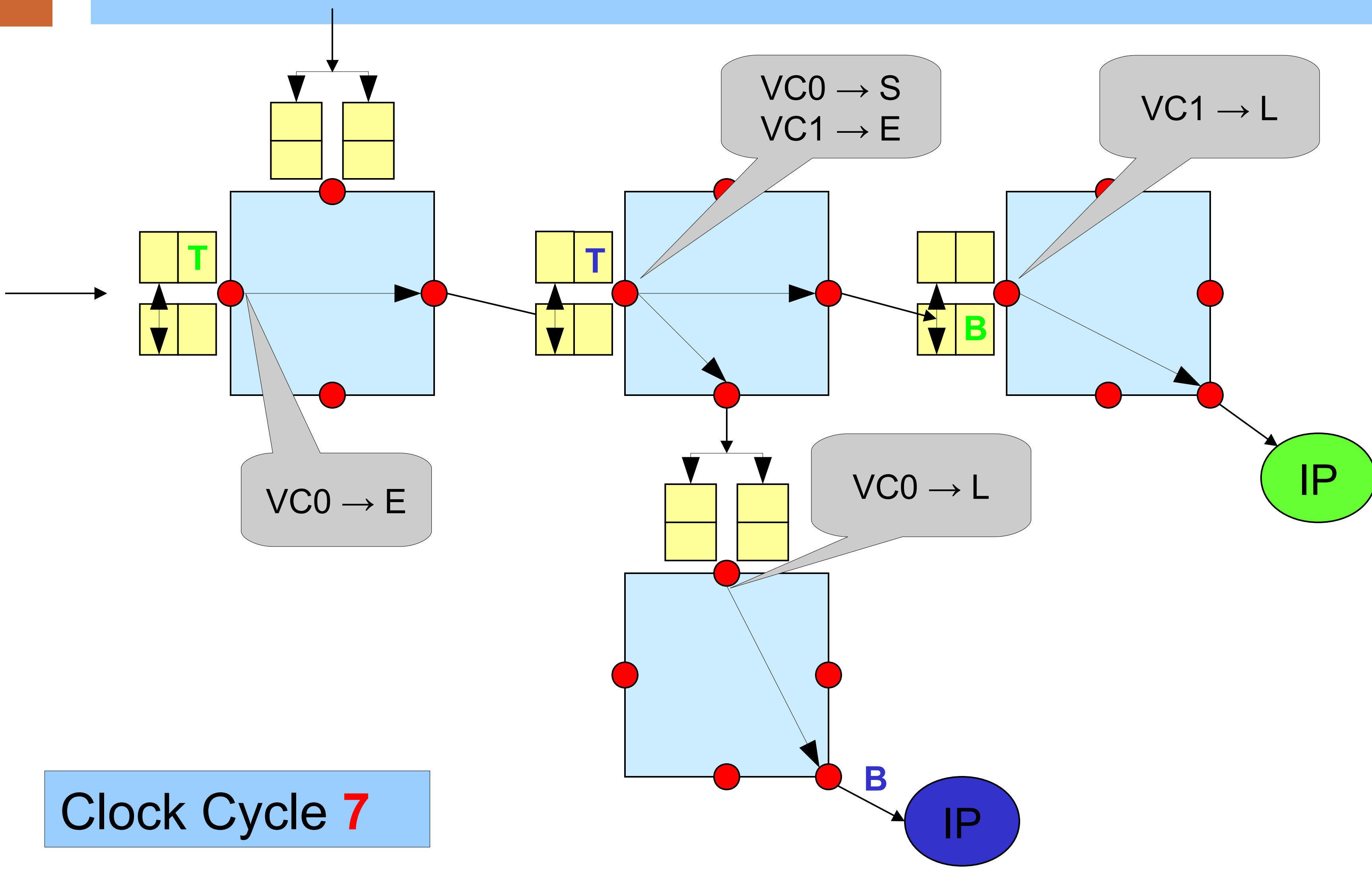
Clock Cycle 5

Virtual Channels - Example



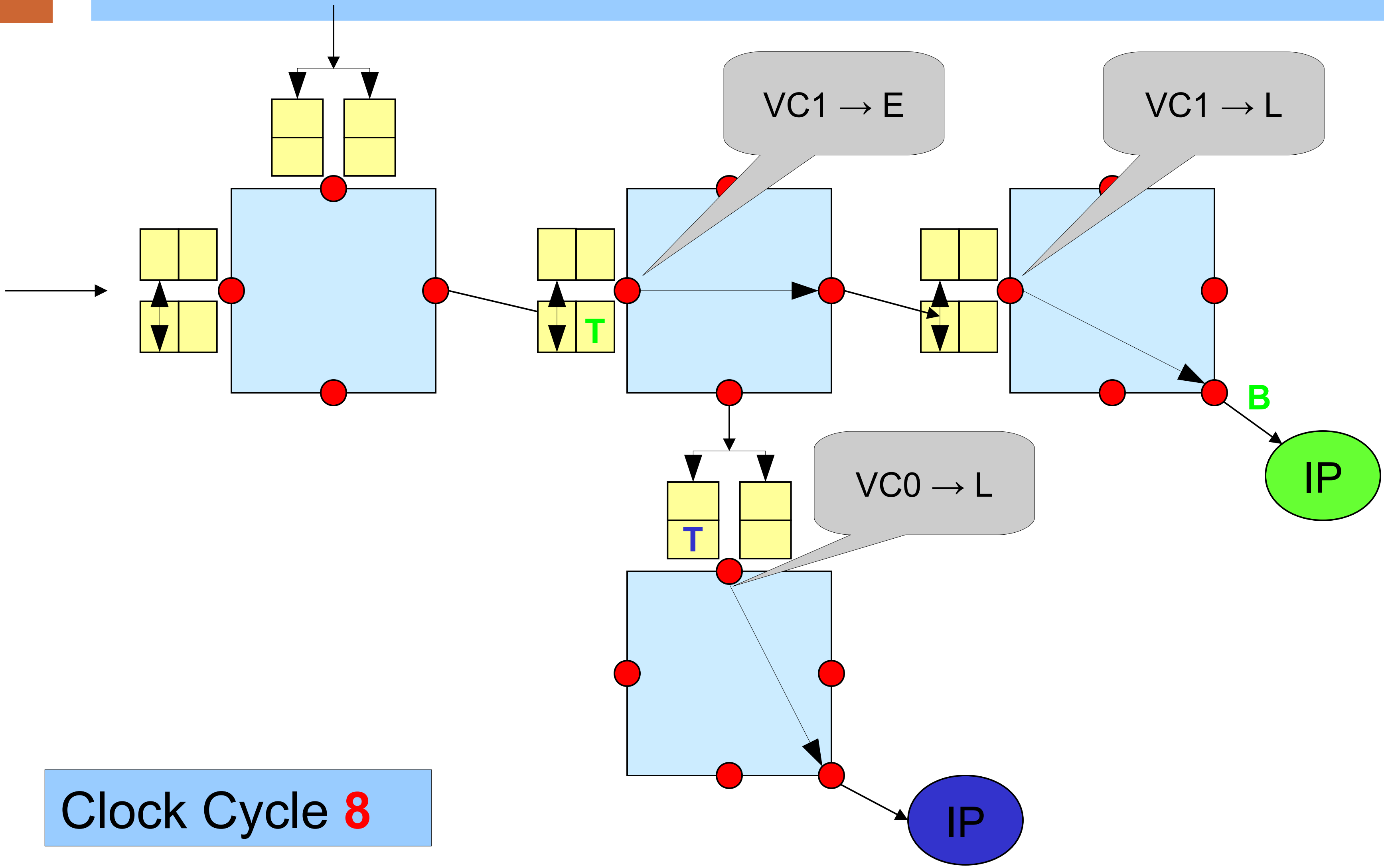
Clock Cycle 6

Virtual Channels - Example



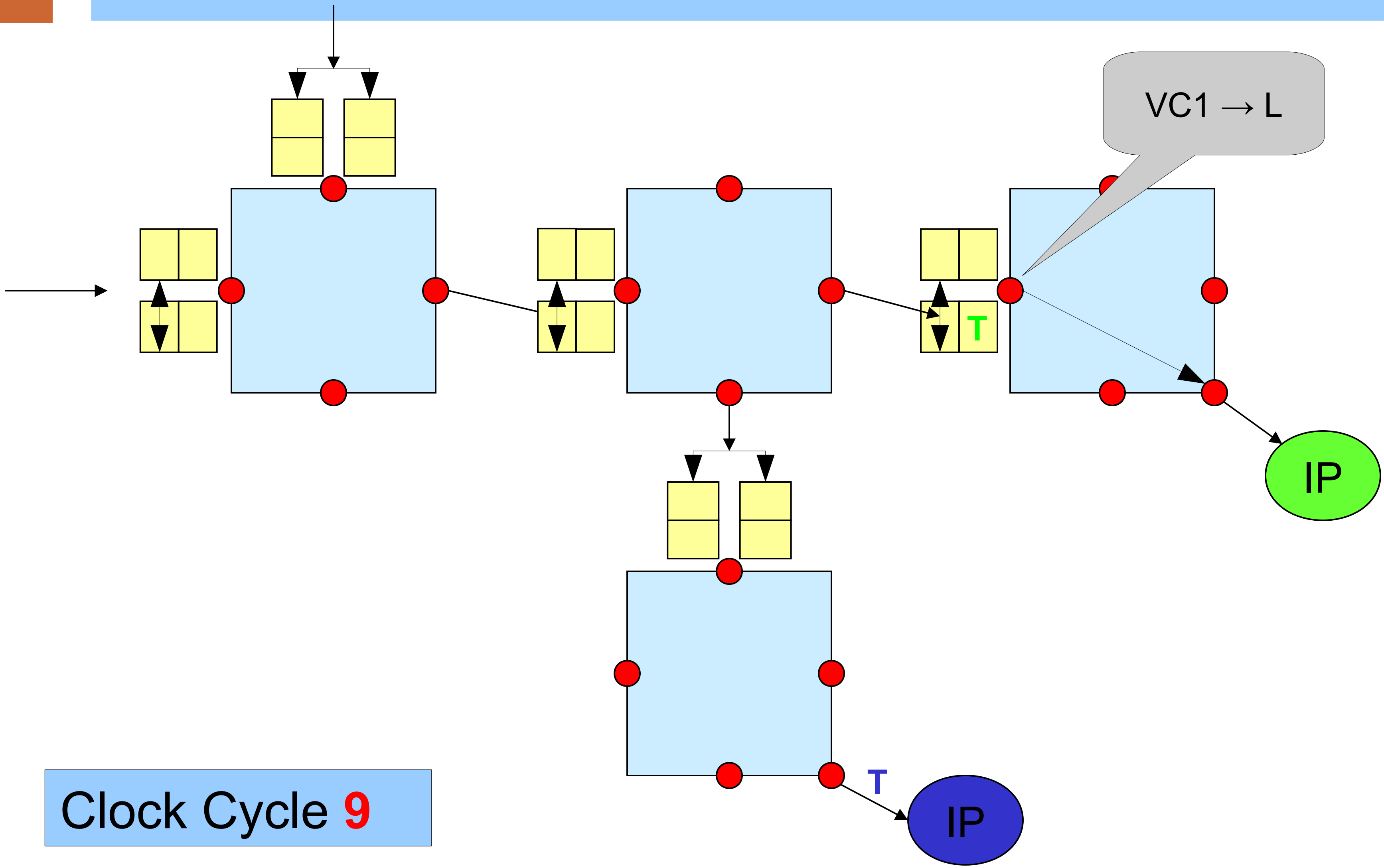
Clock Cycle 7

Virtual Channels - Example



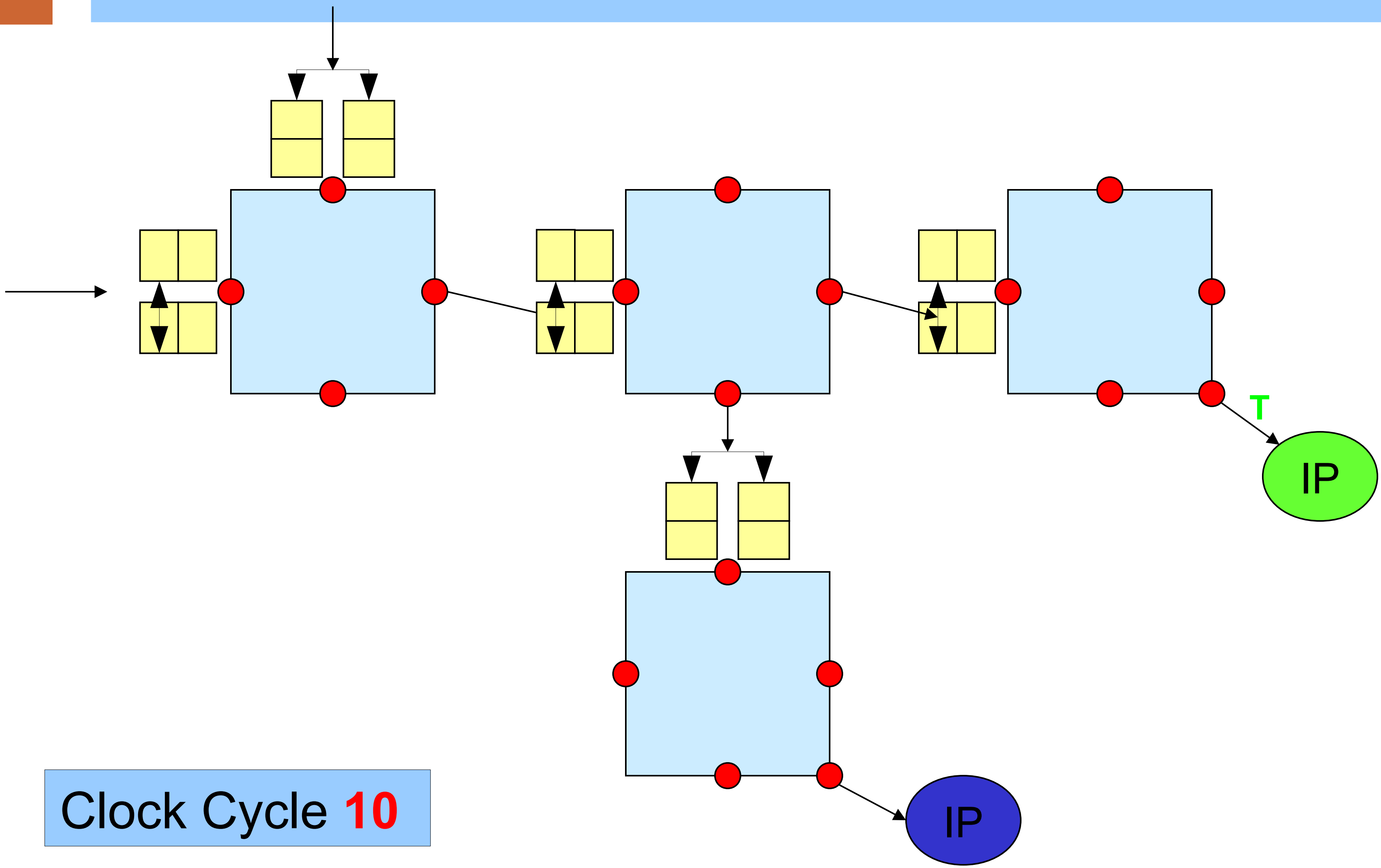
Clock Cycle **8**

Virtual Channels - Example



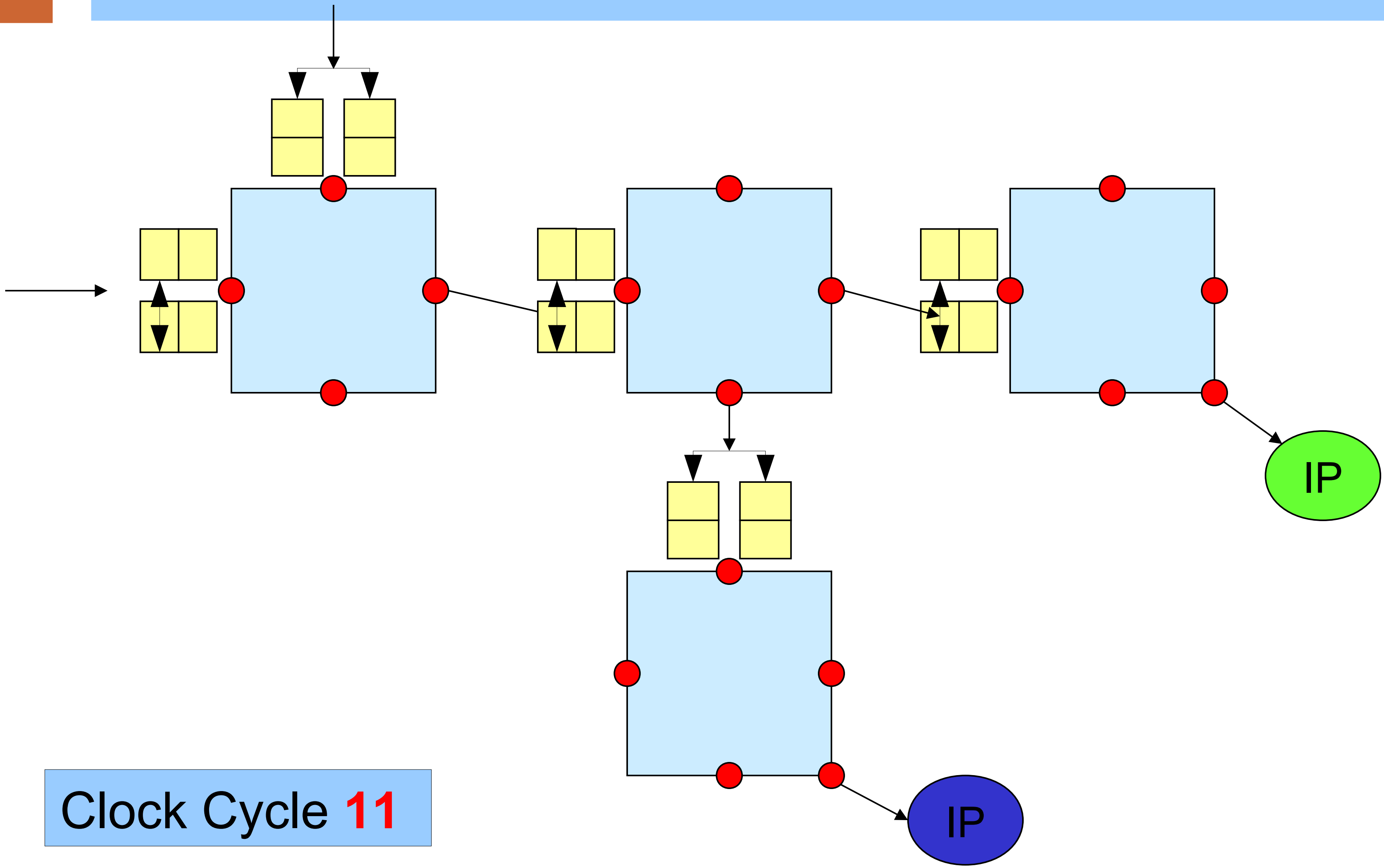
Clock Cycle 9

Virtual Channels - Example



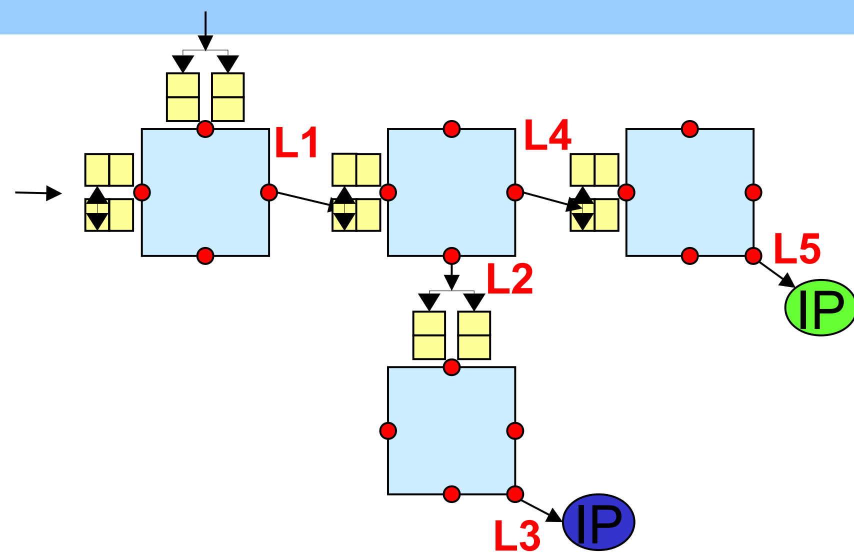
Clock Cycle **10**

Virtual Channels - Example



Clock Cycle 11

Virtual Channels - Example



CC	0	1	2	3	4	5	6	7	8	9	10	11
Blue	Injected	L1	L2	L1, L3	L2	L1, L3	L2	L1, L3	L2	L3	Drained	
Green		Injected	L1	L4	L1, L5	L4	L1, L5	L4	L1, L5	L4	L5	Drained

- **Blue packet**
  - Injected at CC 0
  - Delivered at CC 10
  - **Latency 10 clock cycles**
- **Green packet**
  - Injected at CC 1
  - Delivered at CC 11
  - **Latency 10 clock cycles**