Presentation Slides

Chapter 12

Ring Behavior

Logically Determined Design:
Clockless System Design With NULL Convention Logic

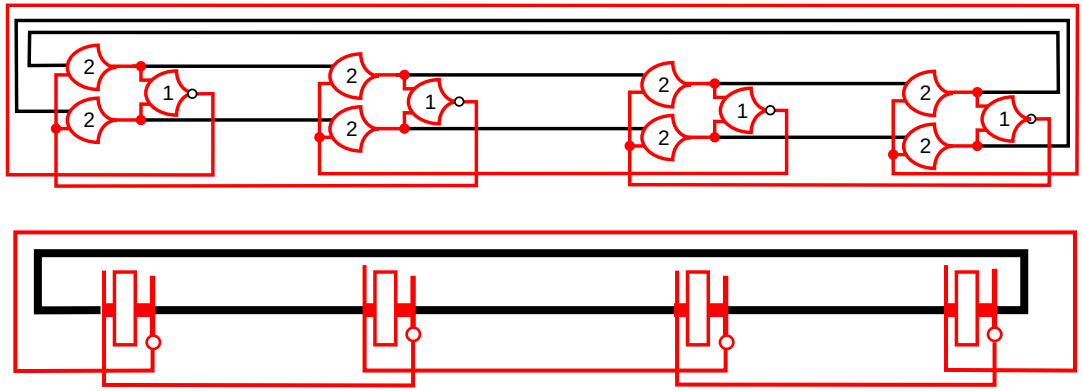
by Karl Fant

John Wiley & Sons, Inc.

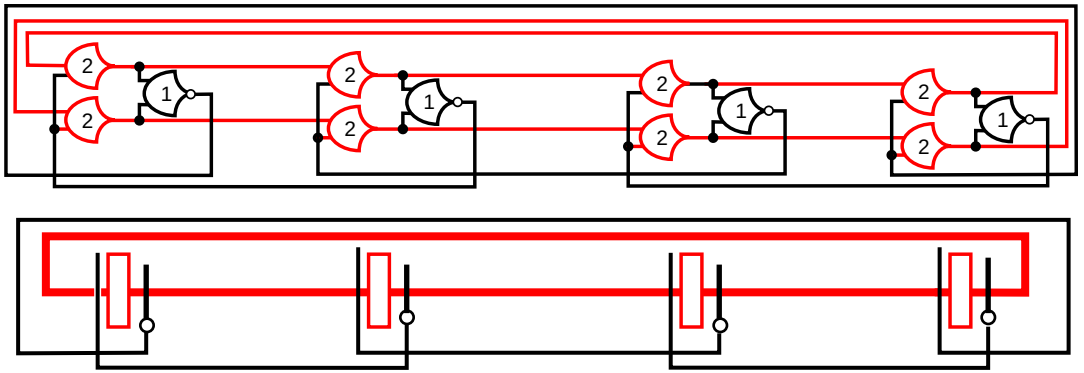
Introduces the modes of pipeline ring behavior

Ring structures

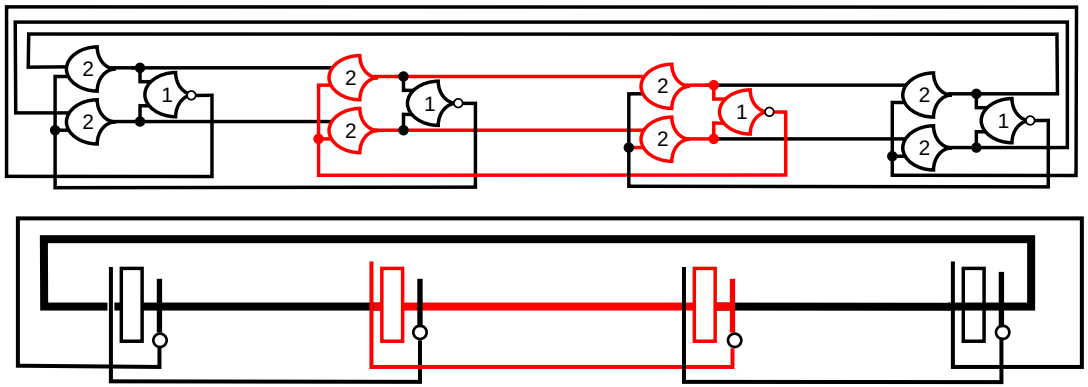
Bubble path
Acknowledge path,
reverse latency



Wavefront path
Data path,
forward latency



Cycle path



Behavior Rationale

The referents are:

the period of the slowest cycle in the ring (the total delay of the cycle path),

wavefront rejoin period (the total delay of the wavefront path),

bubble rejoin period (the total delay of the bubble path),

the wavefront population period of (number of wavefronts times slowest cycle period) and

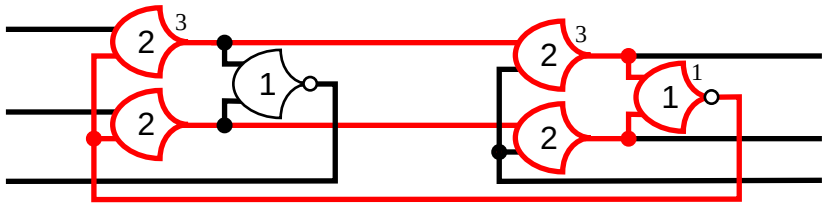
the bubble population period of (number of bubbles times slowest cycle period).

Each member of a population chases its population around the ring. The critical question is whether a member ever catches up with its population or not. This is determined by whether a population can propagate through the slowest cycle (population period) before a member can propagate around the ring and rejoin the population (rejoin period).

If a member does not catch up with its population it encounters no waits on its journey around the ring, therefore, its propagation time around the ring (rejoin period) is determined solely by the delays along its propagation path.

Example Behavior Periods

Cycle path. Period is 7 tics

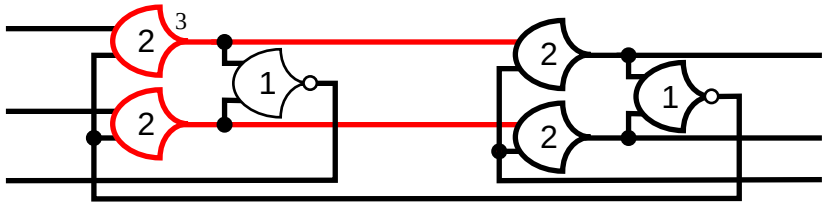


Wavefront population period
wavefronts X 7 tics

Bubble population period
bubbles X 7 tics

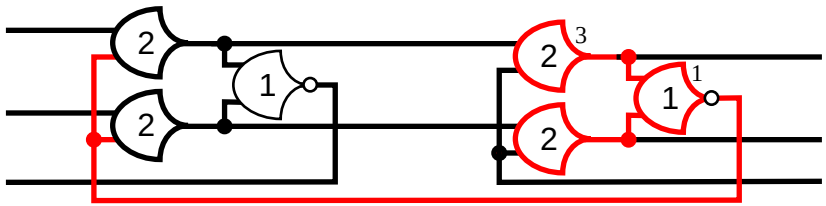
For a 24 cycle ring
wavefronts + bubbles = 24

Wavefront path segment. Delay per cycle is 3 tics



Wavefront rejoin period
for a 24 cycle ring is
24 X 3 tics = 72 tics

Bubble path segment. Delay per cycle is 4 tics



Bubble rejoin period
for a 24 cycle ring is
24 X 4 tics = 96 tics

Ring Behavior Modes

Bubble limited

If the bubble rejoin period is greater than the bubble population period then bubbles will not catch up with their population. The slowest cycle will have to wait on bubbles and the ring is bubble limited. Its throughput is the bubble population per bubble rejoin period.

Wavefront limited

If the wavefront rejoin period is greater than the wavefront population period then wavefronts will not catch up with their population. The slowest cycle will have to wait on wavefronts and the ring is wavefront limited. Its throughput is the wavefront population per wavefront rejoin period.

Delay limited

If there is a slow cycle then both population periods can be greater than their respective rejoin periods. Both wavefronts and bubbles will catch up with their populations. The throughput of the ring is neither wavefront limited nor bubble limited but it is limited by the delay of the slow cycle and the ring is delay limited. Its throughput is the throughput of the slow cycle.

A ring cannot be both wavefront limited and bubble limited. A cycle must contain either a wavefront or a bubble. It cannot be empty of both and waiting on both.

Wavefront and Bubble Limited Behavior

In wavefront limited behavior cycles have to wait on wavefronts. In bubble limited behavior cycles have to wait on bubbles.

In both cases the wait is the factor limiting the throughput of the ring.

wavefronts in ring	wavefront population period	wavefront rejoin period	bubbles in ring	bubble population period	bubble rejoin period	cycles/ wavefront	throughput waves/period	throughput waves/ 100 tics	limiting behavior Mode
2	14	72	22	154	96	12.00	2/72	2.78	Wavefront
4	28	72	20	140	96	6.00	4/72	5.56	Wavefront
6	42	72	18	126	96	4.00	6/72	8.33	Wavefront
8	56	72	16	112	96	3.00	8/72	11.11	Wavefront
10	70	72	14	98	96	2.40	10/72	13.89	Wavefront
12	84	72	12	84	96	2.00	12/96	12.50	Bubble
14	98	72	10	70	96	1.71	10/96	10.42	Bubble
16	112	72	8	56	96	1.50	8/96	8.33	Bubble
18	126	72	6	42	96	1.33	6/96	6.25	Bubble
20	140	72	4	28	96	1.20	4/96	4.16	Bubble
22	154	72	2	14	96	1.09	2/96	2.08	Bubble
24	168	72	0	0	96	1.00	deadlock	deadlock	deadlock

Delay Limited Behavior

A slow cycle in the ring the causes the population periods to increase much faster than the rejoin periods. When both population periods are greater than their rejoin periods the ring is neither wavefront limited nor bubble limited but is limited by the slow cycle that is increasing the population periods. The throughput of this slow cycle will determine the throughput of the ring.

The wait to get through the slow cycle is the factor limiting the throughput of the ring.

The table illustrates a ring with a 4 tic delay in its data path making one 11 tic cycle.

wavefronts in ring	wavefront population period	wavefront rejoin period	bubbles in ring	bubble population period	bubble rejoin period	cycles/ wavefront	throughput waves/period	throughput waves/ 100 tics	limiting behavior Mode
2	22	76	22	242	96	12.00	2/76	2.63	Wavefront
4	44	76	20	220	96	6.00	4/76	5.26	Wavefront
6	66	76	18	198	96	4.00	6/76	7.89	Wavefront
8	88	76	16	176	96	3.00	1/11	9.09	Delay
10	110	76	14	154	96	2.40	1/11	9.09	Delay
12	132	76	12	132	96	2.00	1/11	9.09	Delay
14	154	76	10	110	96	1.71	1/11	9.09	Delay
16	176	76	8	88	96	1.50	8/96	8.33	Bubble
18	198	76	6	66	96	1.33	6/96	6.25	Bubble
20	220	76	4	44	96	1.20	4/96	4.16	Bubble
22	242	76	2	22	96	1.09	2/96	2.08	Bubble
24	264	76	0	0	96	1.00	deadlock	deadlock	deadlock

Perfectly Balanced Behavior

In a perfectly balanced ring all cycle periods are identical and both the rejoin periods are identical. When the ring is exaclty half full of wavefronts the peak throughput occurs which is identical to the throughput of each cycle in the ring. **There are no waits anywhere in the ring**. This may all sound good but for this example, but a 1 tic delay was added to the data path to make the wavefront rejoin path equal to the bubble rejoin path making the cycle periods longer. Notice that the peak throughput of this ring (12.5) is less than the wavefront limited peak throughput of the unbalanced ring (13.89).

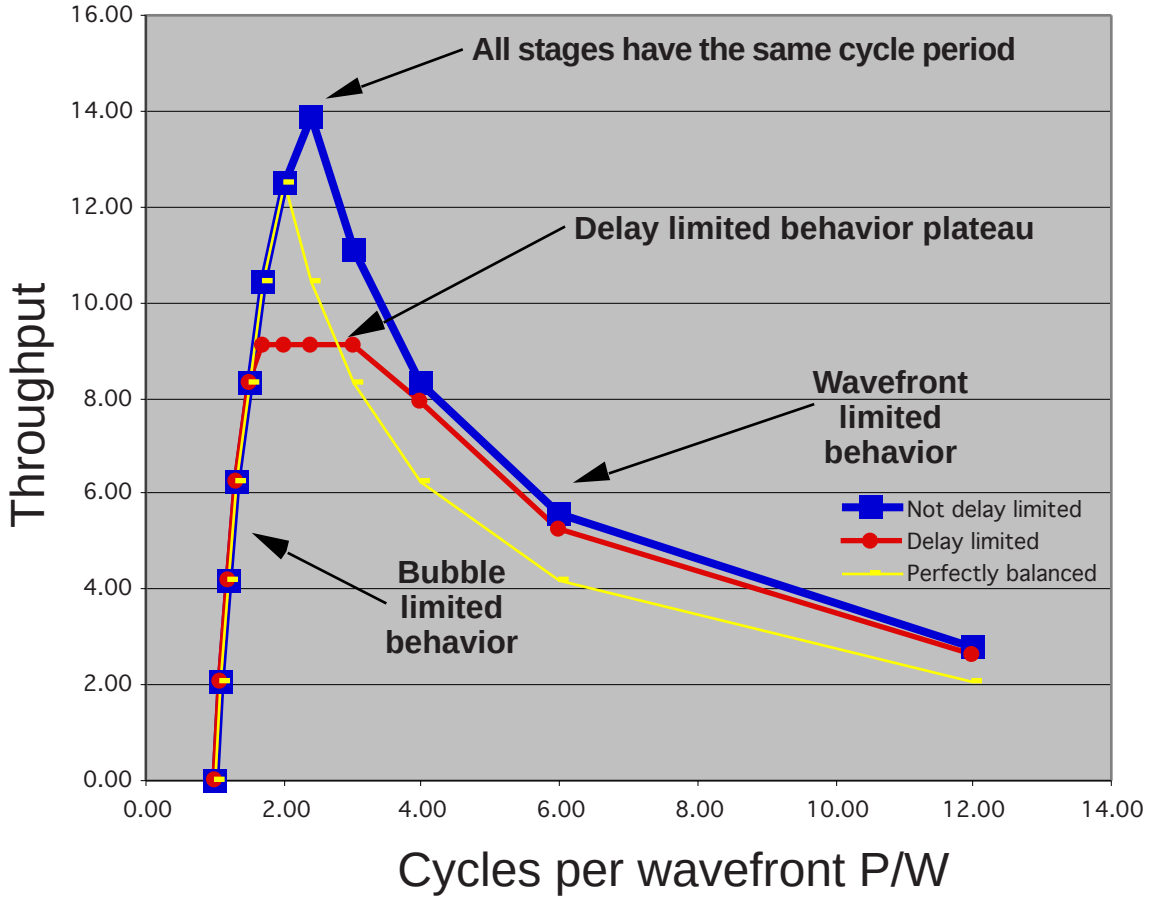
The important factors in ring behavior are the cycle periods and the cycles per wavefront ratio, not balancing delays

wavefronts in ring	wavefront population period	wavefront rejoin period	bubbles in ring	bubble population period	bubble rejoin period	cycles/ wavefront	throughput waves/period	throughput waves/ 100 tics	limiting behavior Mode
2	16	96	22	176	96	12.00	2/96	2.08	Wavefront
4	32	96	20	160	96	6.00	4/96	4.16	Wavefront
6	48	96	18	144	96	4.00	6/96	6.25	Wavefront
8	64	96	16	128	96	3.00	8/96	8.33	Wavefront
10	80	96	14	112	96	2.40	10/96	10.42	Wavefront
12	96	96	12	96	96	2.00	12/96	12.5	Balanced
14	112	96	10	80	96	1.71	10/96	10.42	Bubble
16	128	96	8	64	96	1.50	8/96	8.33	Bubble
18	144	96	6	48	96	1.33	6/96	6.25	Bubble
20	160	96	4	32	96	1.20	4/96	4.16	Bubble
22	176	96	2	16	96	1.09	2/96	2.08	Bubble
24	192	96	0	0	96	1.00	deadlock	deadlock	deadlock

Quantized Ring Behavior

Ring behavior occurs in discrete steps. A ring is a closed structure composed of elements that occur only as whole quantities. There cannot be a partial wavefront or a partial cycle. On the graph below even though there are lines connecting the behavior points to show relationships, there is no behavior on the lines between the points. There is ring behavior only at the points.

Cycle per Wavefront Ratio P/W

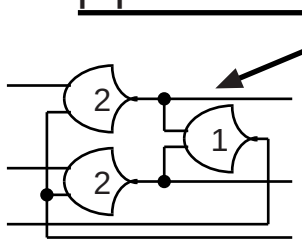


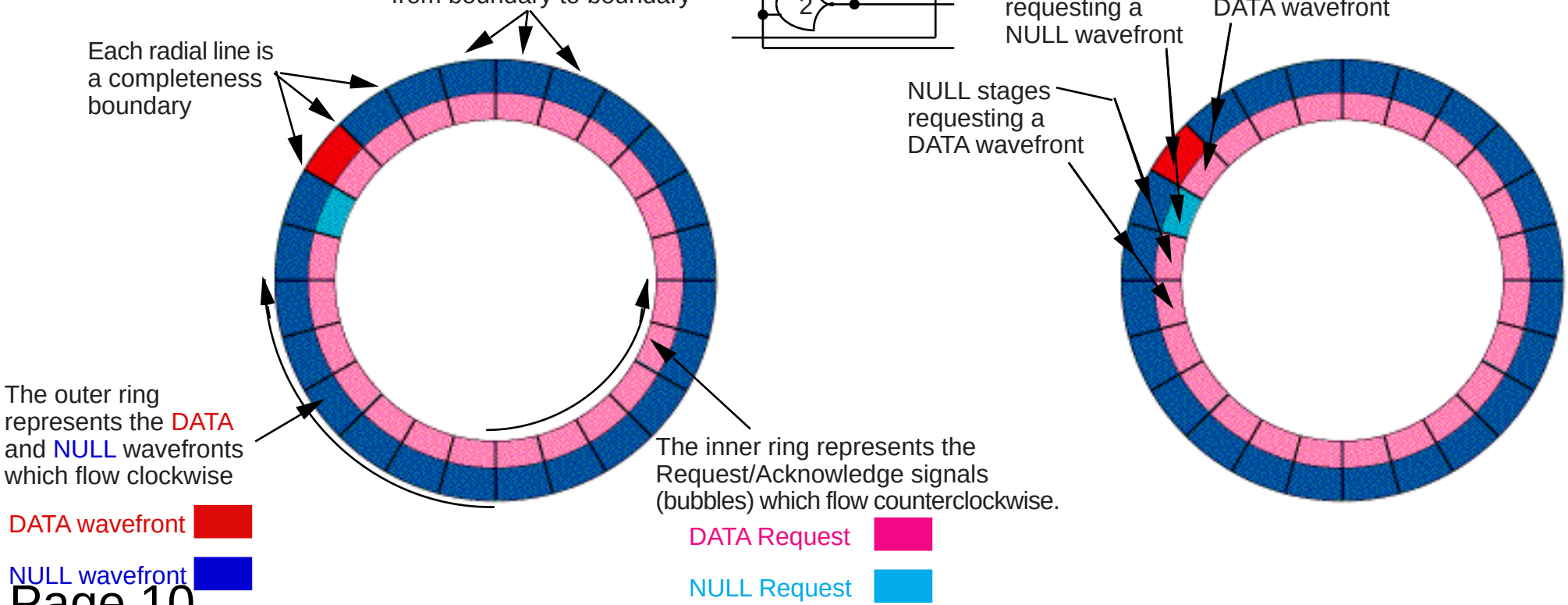
Optimal throughput occurs when the ring is approximately half full of wavefronts(the cycles per wavefront ratio is 2.0) when there is a bubble for every wavefront to flow into and a wavefront for every bubble to flow into. For a perfectly balanced ring the peak throughput occurs at exactly 2.0. For a delay limited ring the peak performance plateau will bracket 2.0. For the bubble/wavefront limited example, because it is not balanced and because of the quantized ring behavior its peak throughput occurs at 2.4.

Pipeline Ring Movie basics

These movies provide a visual experience of pipeline ring behavior. They can be stopped and single stepped in either direction

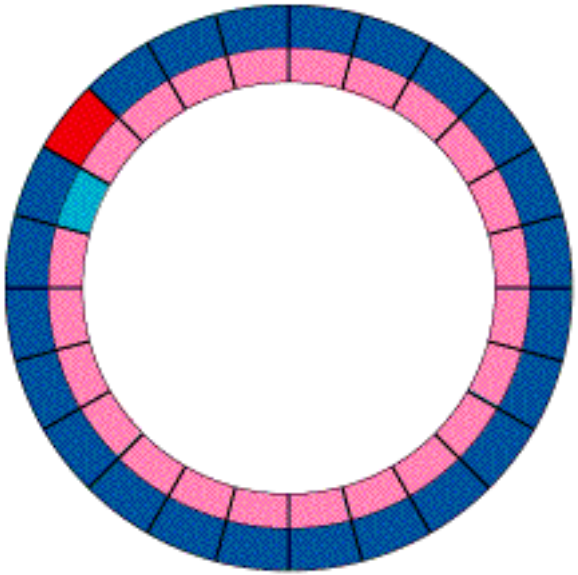
The movies show explicitly the wavefront flow in conjunction with the Acknowledge/Request flow. The outer ring represents the DATA/NULL wavefronts. DATA is red and NULL is BLUE. The inner ring represents the Acknowledge/Request signals. Request for DATA is pink and Request for NULL is light blue. Each radial line is a completeness boundary between pipeline stages. There are 24 lines and there are 24 pipeline stages in the ring.



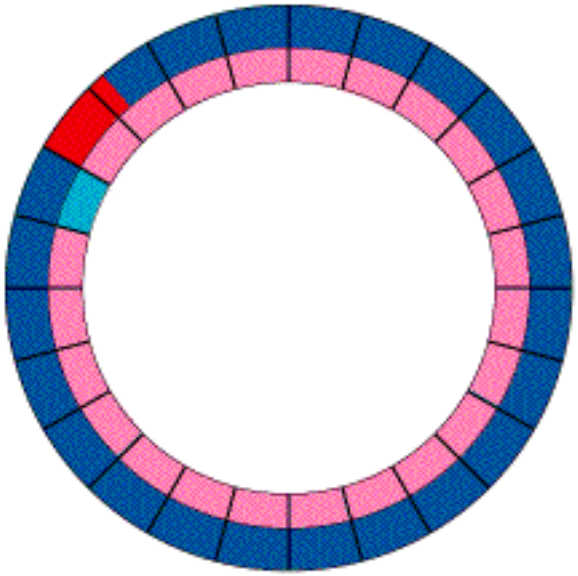


Pipeline Ring Movie Dynamics 1

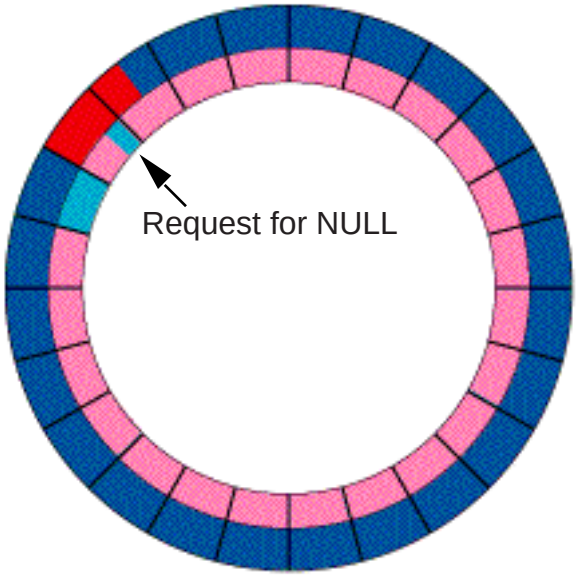
1 Initial state with one DATA wavefront



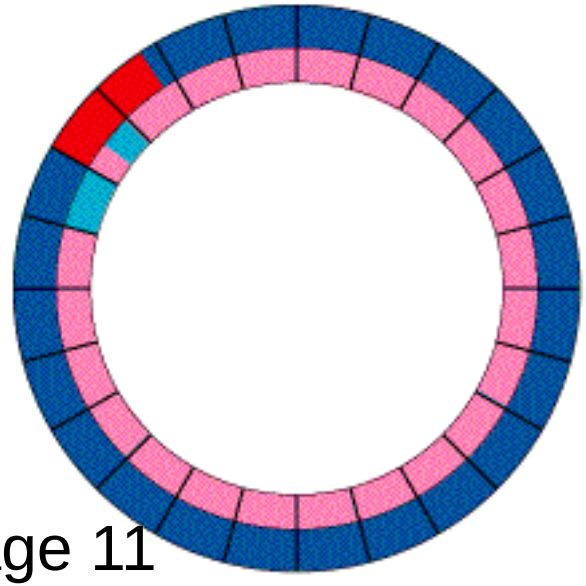
2 Init is released and DATA wavefront begins to propagate through NULL bubble



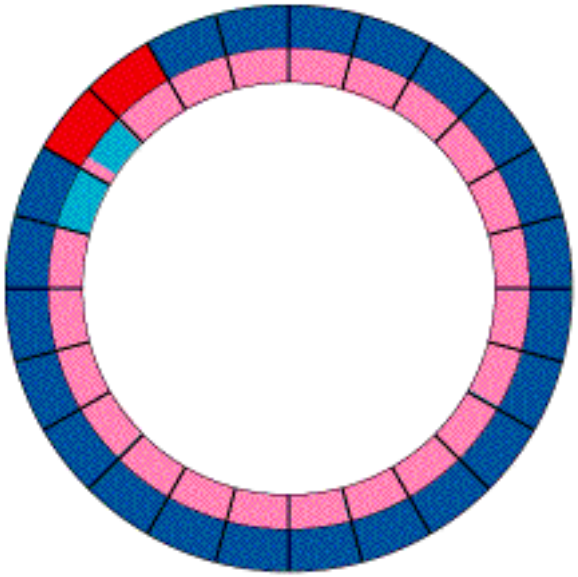
3 Boundary detects DATA completion and begins propagating request for NULL



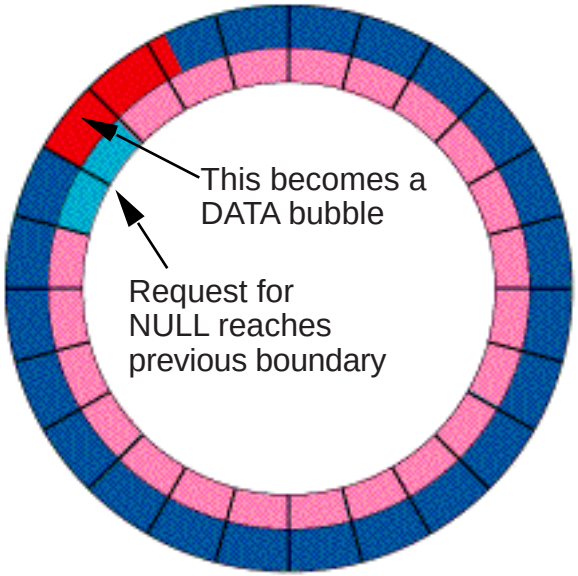
4 Propagation continues



5 Propagation continues

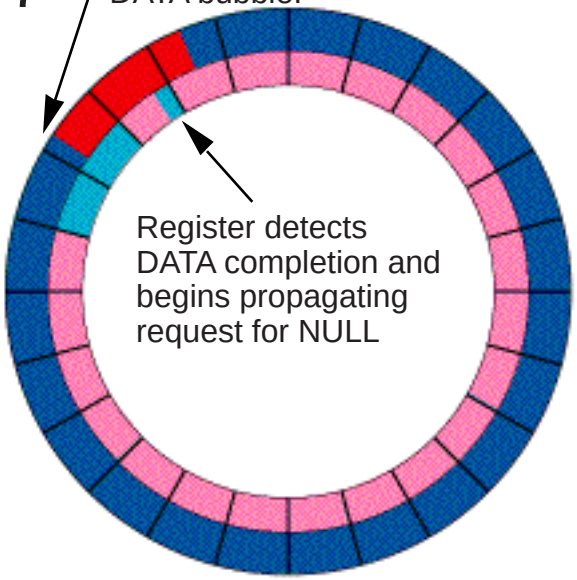


6 Request for NULL reaches previous boundary and DATA bubble forms.

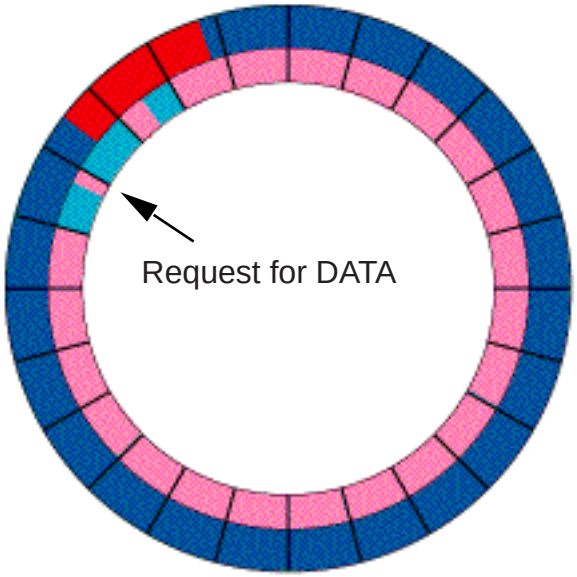


Pipeline Ring Movie Dynamics 2

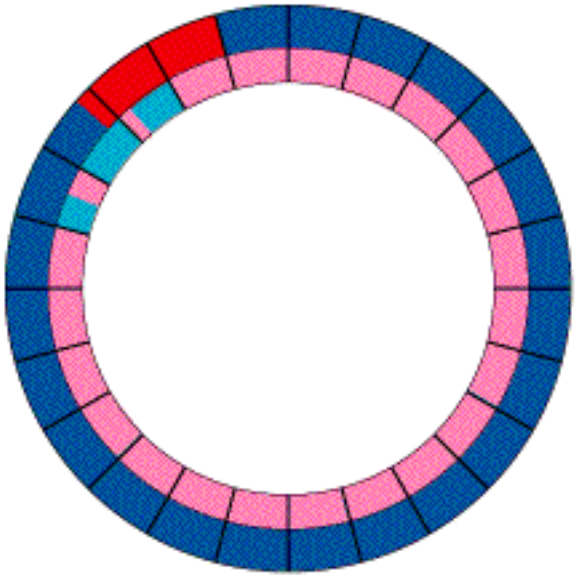
7 NULL wavefront begins to propagate through DATA bubble.



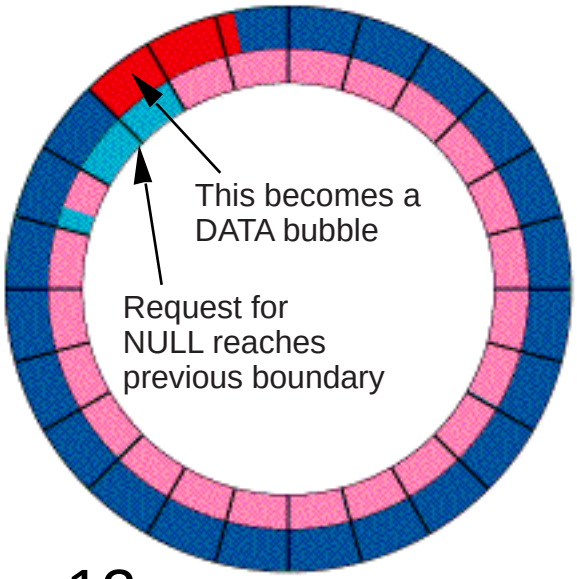
8 Boundary detects NULL completion and begins propagating request for DATA



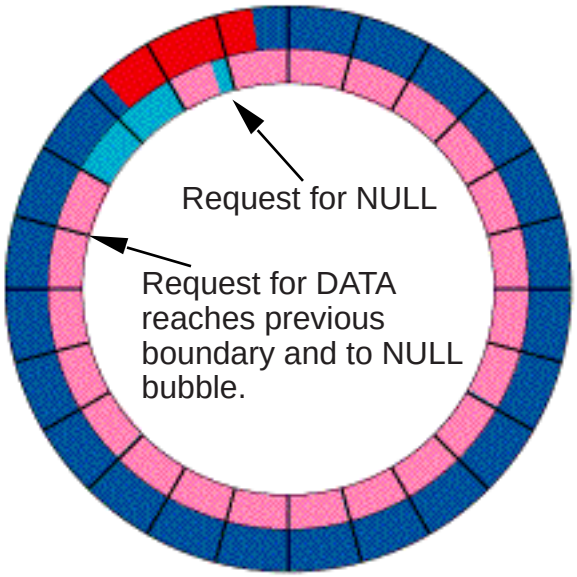
9 Propagation continues



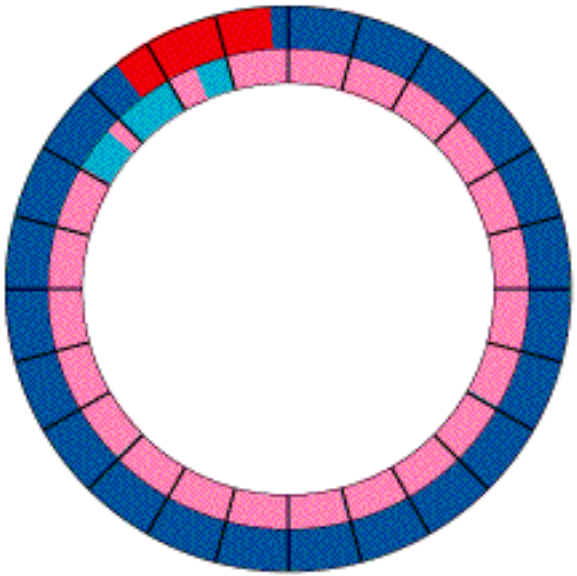
10 Request for NULL reaches previous boundary and DATA bubble forms.



11 Register detects DATA completion and begins propagating request for NULL



12 And so on.....

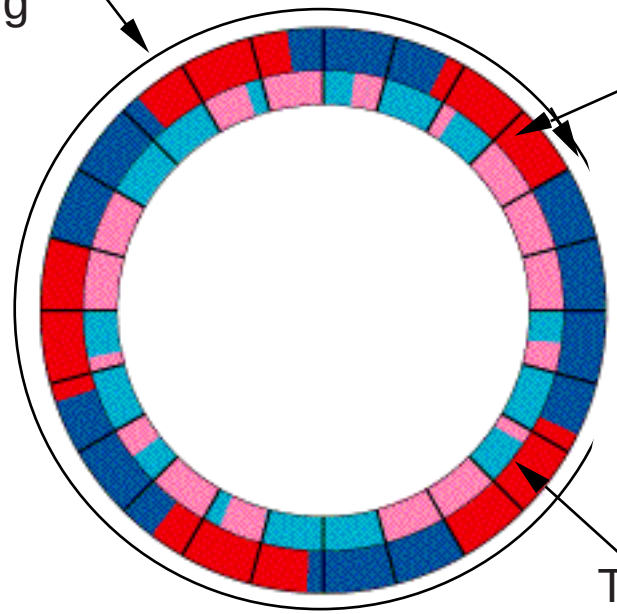


Wavefront Limited Behavior

If the data wave population period is less than the wavefront rejoin period of the ring the lead data wavefront does not get around the ring before the end wavefront moves and generates a bubble. There is always sufficient bubble for all wavefronts to flow freely. The bubbles are waiting for wavefronts.

The throughput of the ring depends on how many data wavefronts there are and how long it takes the data wavefronts to flow around the ring (wavefront rejoin period of the ring).

The wave population period is less than the wavefront rejoin period of the ring



Lead data wavefront

Movie
10 wavefronts.mov

The bubble population period is greater than the bubble rejoin period of the ring so the bubbles generated by the tail bump into each other and jam up waiting for wavefronts.

The end wavefront stays ahead of the lead wavefront continually generating bubble for the lead wavefront to flow through

Bubble Limited Behavior

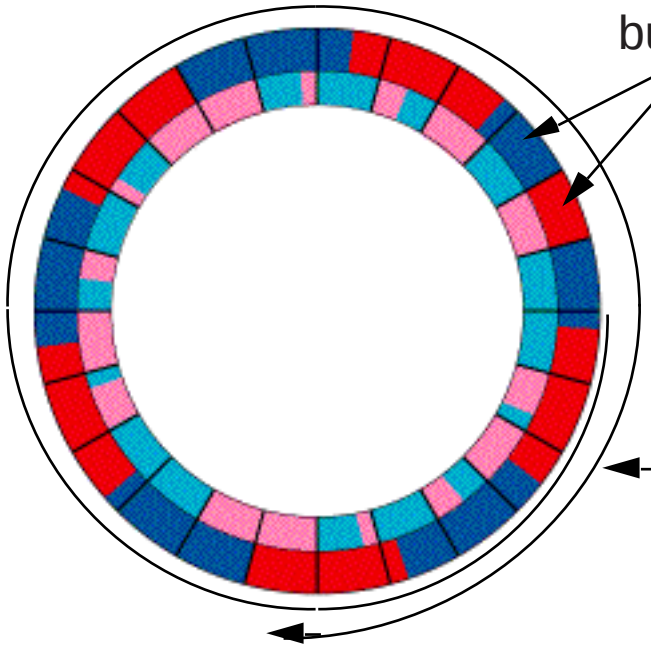
If the wavefront population period exceeds the wavefront rejoin period of the ring the lead data wavefront gets around the ring before the end wavefront moves. It bumps into the end and has to wait for a bubble to flow through the end wavefront. There is not sufficient bubble for all wavefronts to flow freely. The wavefronts must wait for bubbles to flow into them.

The throughput of the ring depends on how many bubbles there are and how long it takes the bubbles to flow around the ring (bubble rejoin period of the ring).

Movie
12 wavefronts.mov

Bubble population period is less than the bubble rejoin period of the ring so the bubbles will free flow through the wavefronts.

The wavefronts bump into each other and jam up waiting for bubbles to arrive.

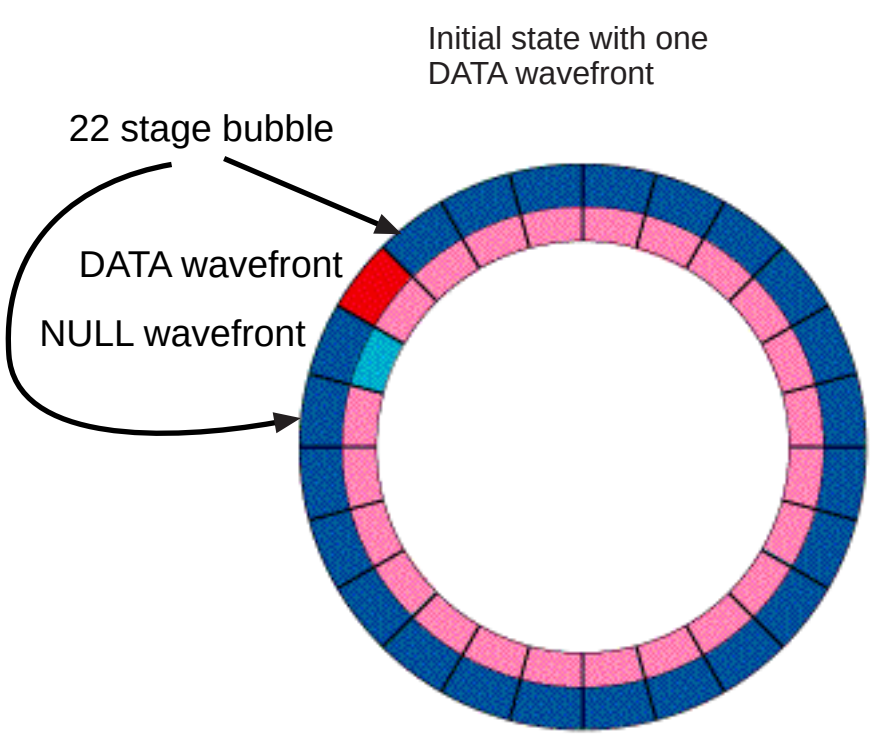


The wave population period exceeds the bubble rejoin period of the ring.

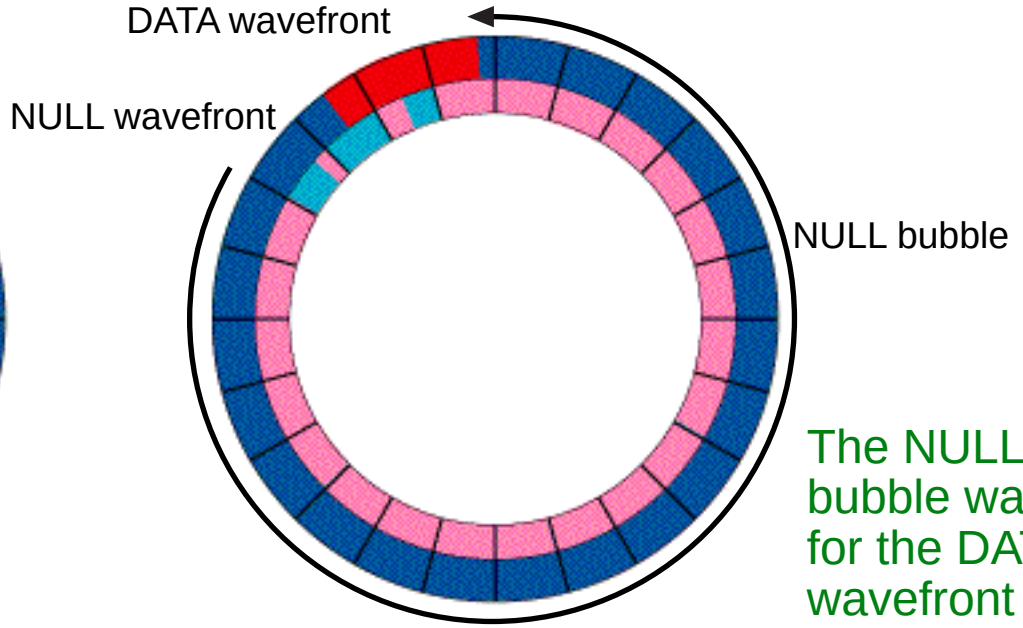
Wavefront Limited Ring Movie

At the one extreme is a large ring with a single data wavefront. The lone DATA wavefront propagates around the ring through an always sufficient NULL bubble. It is followed by a lone NULL wavefront trailing the long NULL bubble. There is always sufficient bubble for the DATA wavefront to flow into so it never waits, but the throughput of the ring is one DATA wavefront for each trip of the wavefront around the ring.

If there are 2 wavefronts the throughput doubles. If there are 3 wavefronts the throughput triples and so on until the lead wavefront starts bumping into the end wavefront and has to wait on a bubble. (the wavefront population period exceeds the wavefront rejoin period of the ring)



Movie
2 wavefronts.mov



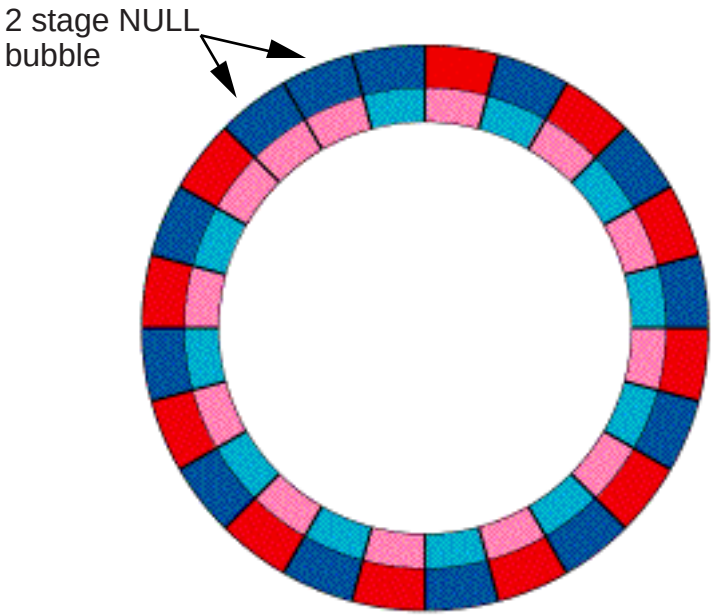
The NULL bubble waits for the DATA wavefront

Bubble Limited Ring Movie

At the other extreme is a large ring filled with DATA wavefronts such that there are only two bubble stages. The DATA and NULL wavefronts are all blocked until they are presented with a bubble. Bubbles travel around the ring in the opposite direction to the DATA/NULL wavefronts sort of tunneling through the wavefronts. A DATA wavefront flows into a NULL bubble and a DATA bubble forms behind the DATA wavefront. A NULL wavefront flows into a DATA bubble and a NULL bubble forms behind the NULL wavefront.

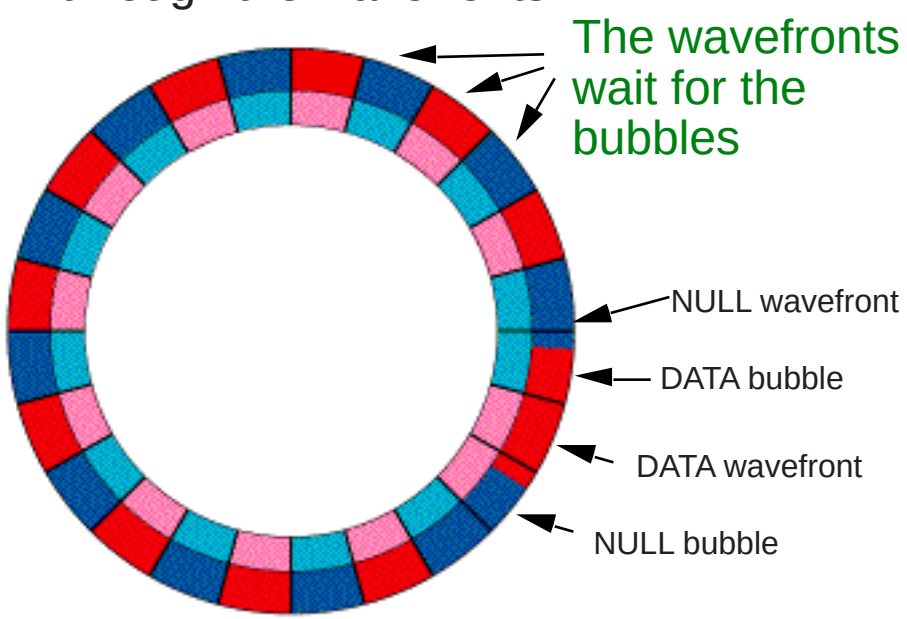
In the bubble limited ring there are always sufficient wavefronts for the bubbles to flow through so the throughput will be 1 wavefront per bubble per trip around the ring, increasing as bubbles increase (DATA wavefronts decrease) until the DATA wavefronts no longer have to wait. (the bubble population period exceeds the bubble rejoin period of the ring)

Initial state of 24 stage ring with 11 DATA wavefronts



The two bubbles flowing through the wavefronts

Movie 22 wavefronts.mov



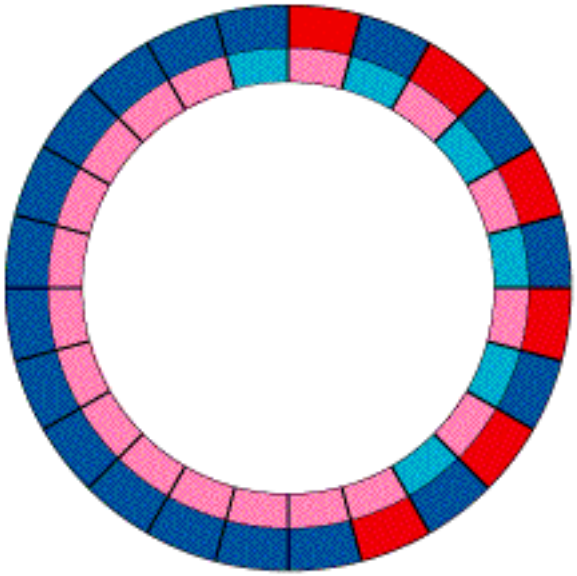
Slightly Bubble Limited Ring Movie

The bubble population period is slightly less than the bubble rejoin period of the ring. The wavefront population period is slightly greater than the wavefront rejoin period of the ring.

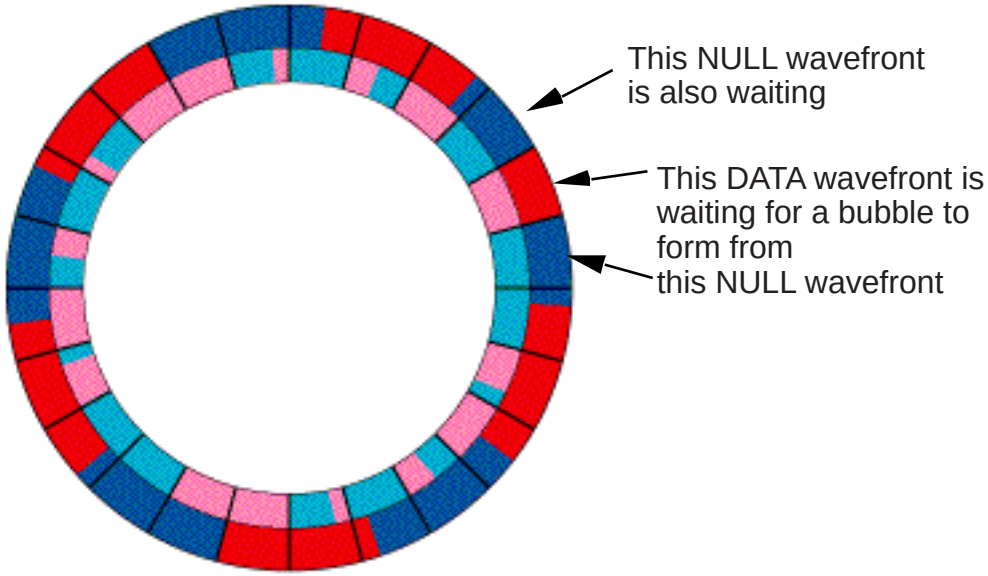
The ring approaches but does not quite reach a balance where wavefronts and bubbles freely flow through each other. Because of the integral nature of the ring this balance is almost never achieved for a ring with equal delay pipeline stages. So it will be either slightly wavefront limited or slightly bubble limited. This case is slightly bubble limited so wavefronts have to wait a bit on bubbles.

Movie
12 wavefronts.mov

Initial state of 24 stage ring with 6 DATA wavefronts



The flowing wavefronts distribute themselves around the ring



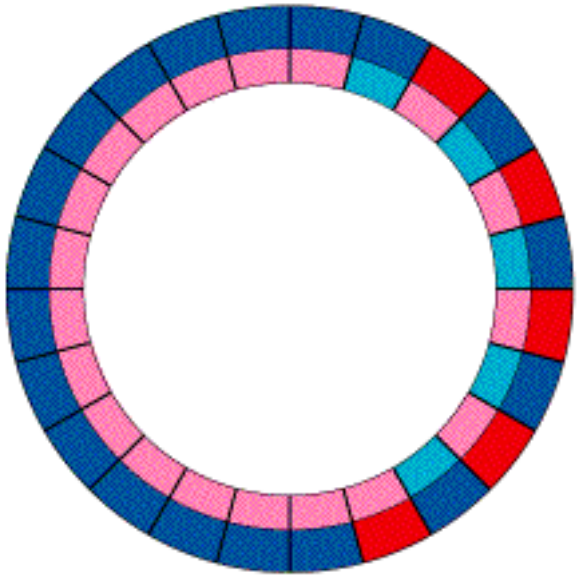
Slightly Wavefront Limited Ring Movie

The wavefront population period is slightly less than the wavefront rejoin period of the ring The bubble population period is slightly greater than the reverse latency of the ring.

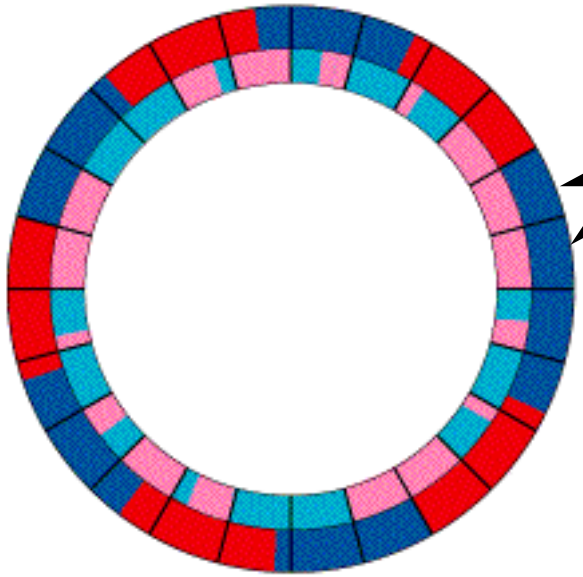
Again, the ring approaches but does not quite reach a balance where wavefronts and bubbles freely flow through each other. This case is slightly wavefront limited so bubbles have to wait a bit on wavefronts.

The integral nature of the ring with equal delay pipeline stages is illustrated here. To achieve the balanced free flow of wavefronts and bubbles with the given delays would require either a fractional wavefront or a fractional stage, neither of which is possible. With the given wavefronts and buble it would require precisely tuned delays. This is not a practical goal.

Initial state of 24 stage ring with 5 DATA wavefronts



The flowing wavefronts distribute themselves around the ring



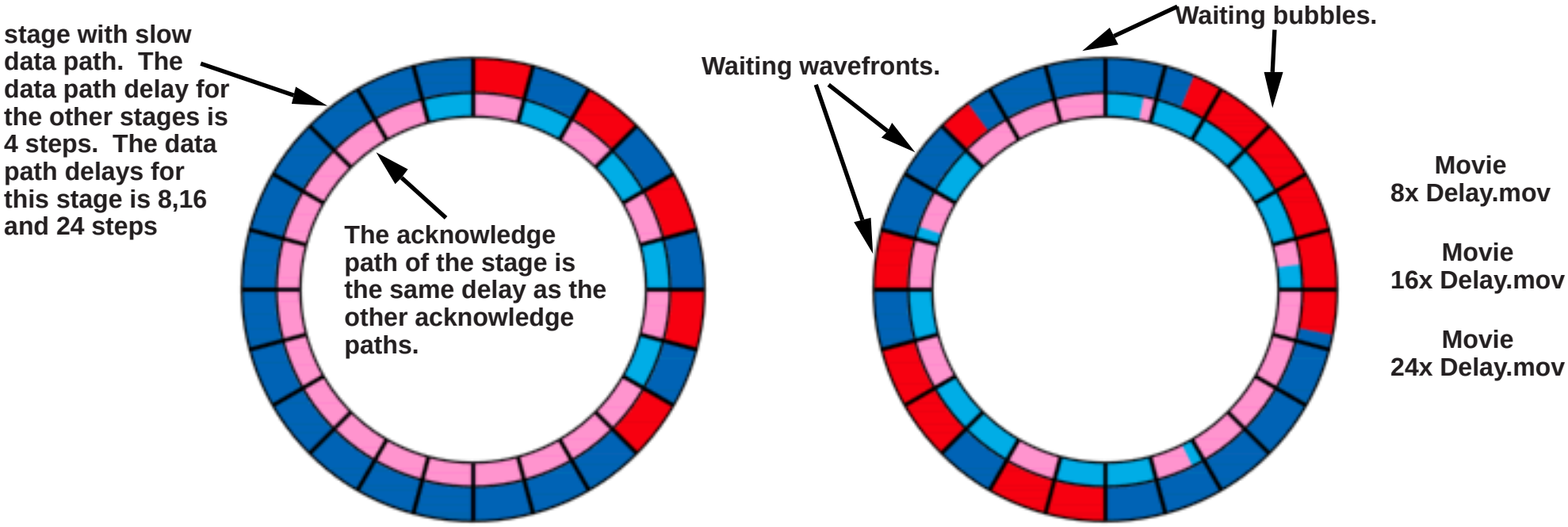
Movie
10 wavefronts.mov

This is a NULL bubble waiting for the DATA wavefront

Delay Limited Ring Movies

These rings contain one slow stage. The wavefront population period is greater than the wavefront rejoin period of the ring and the bubble population period is less than the bubble rejoin period of the ring. This means that both wavefronts and bubbles are always waiting on the slow stage and the ring is delay limited.

In the delay limited mode of operation the throughput of the ring is determined by this slowest stage. The ring is operating at maximum possible throughput and is not limited by the closed integral nature of the ring. An open pipeline with the same delay configuration would deliver the same throughput.



Ring Signal Behavior

Each of the following slides shows how the wavefront behavior in a ring would appear as the signal traces viewed at each cycle of the ring.

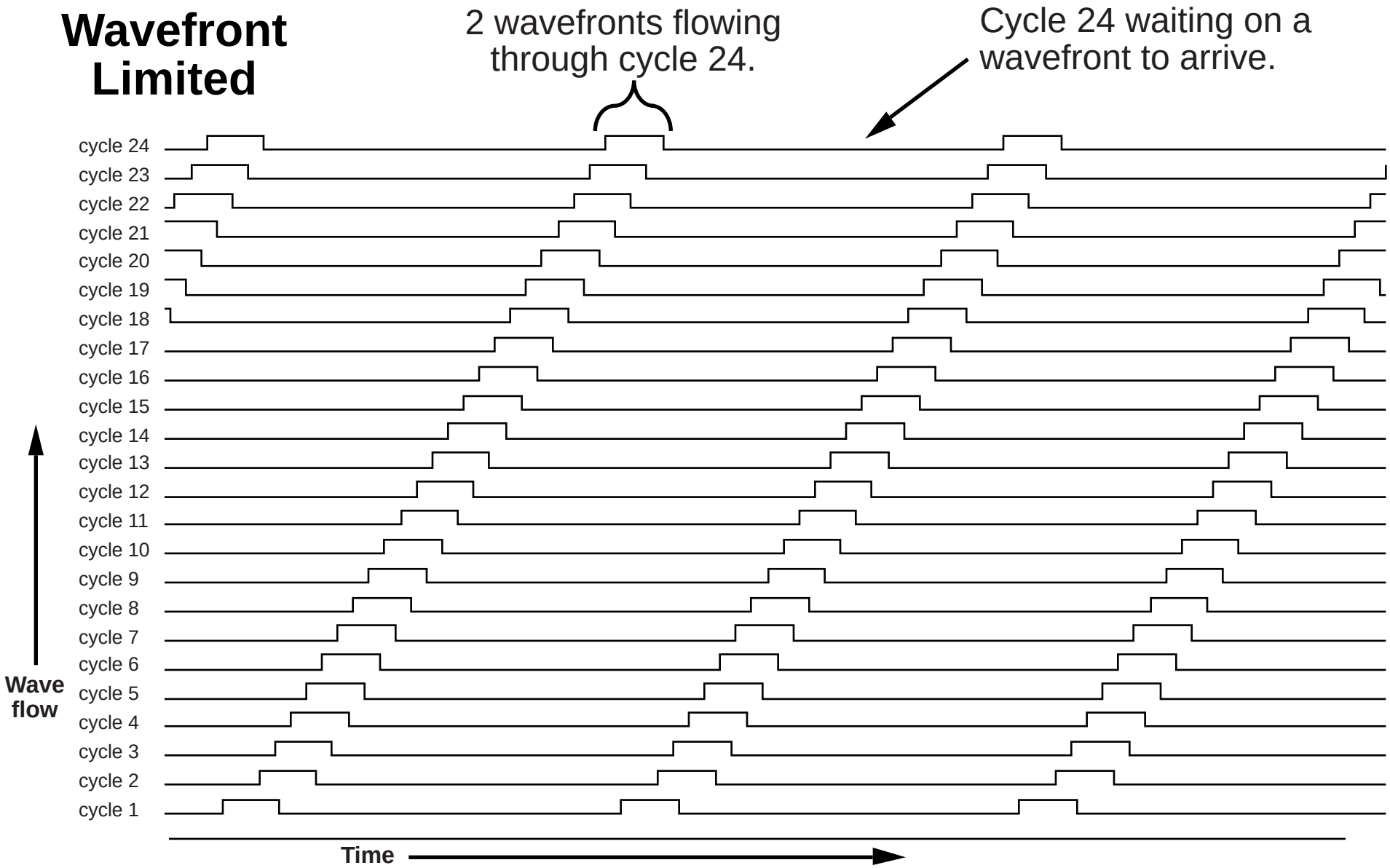
The simulation is of example 2 with a single 4 tic delay in one stage.

The signals are captured after the startup transient when the ring behavior has stabilized.

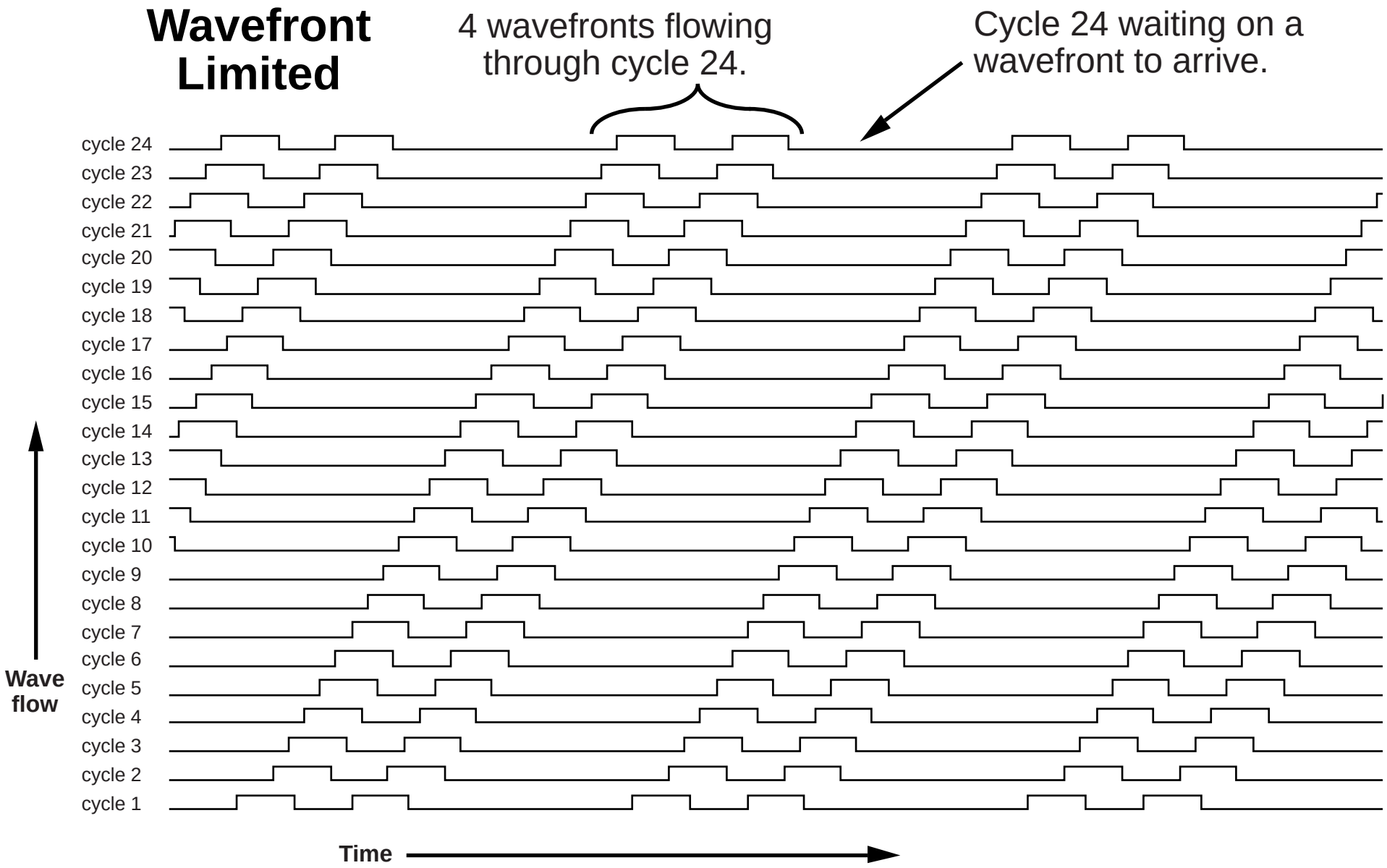
Notice that in delay limited behavior with eight to fourteen wavefronts the signal behavior of the cycles and the throughput of the ring are identical and constant.

Notice also that in wavefront limited behavior every cycle waits in the same state while in bubble limited behavior alternate cycles wait in alternating states.

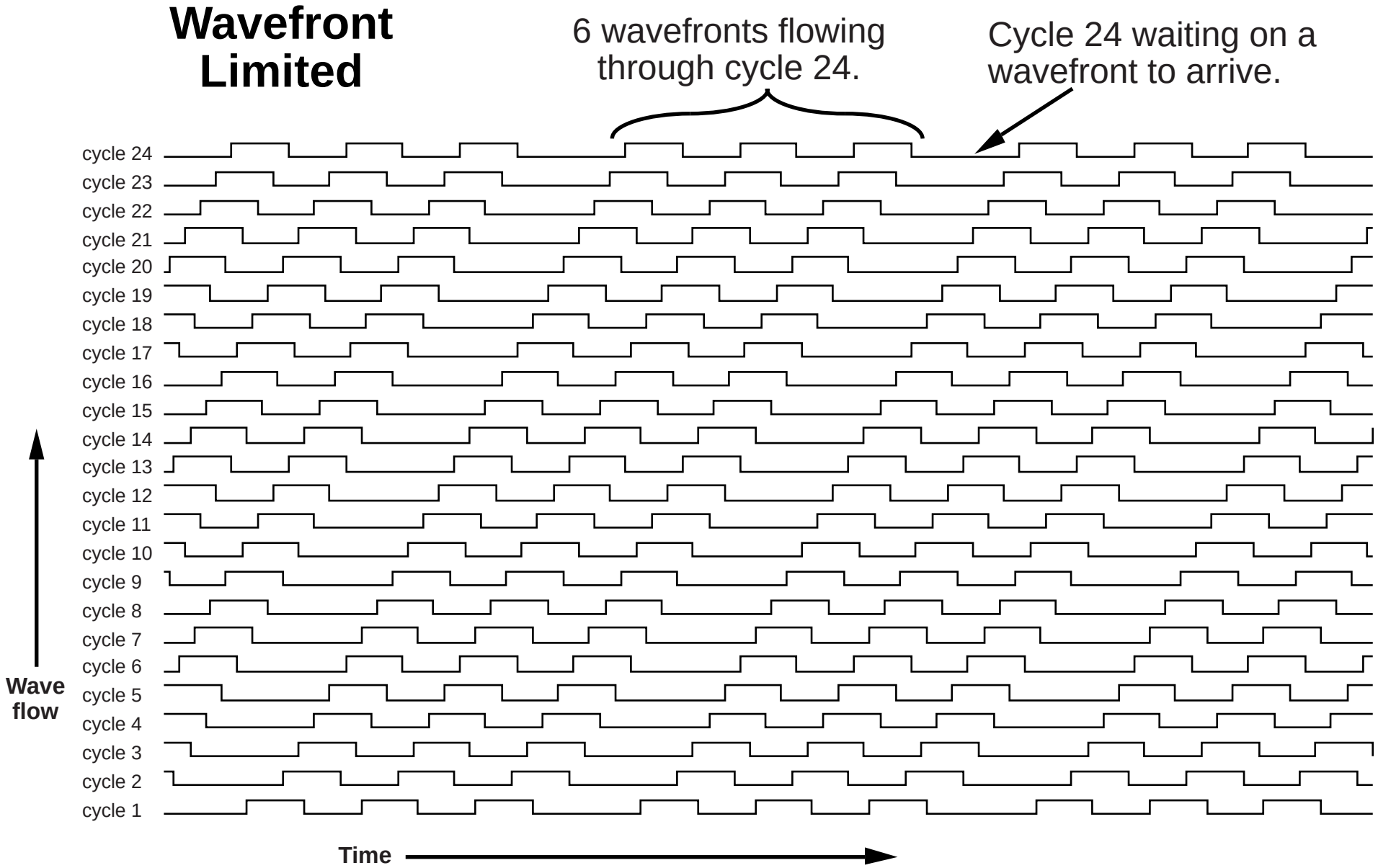
24 Stage Ring, one slow stage
1 data wavefront



24 Stage Ring, one slow stage
2 data wavefronts



24 Stage Ring, one slow stage
3 data wavefronts

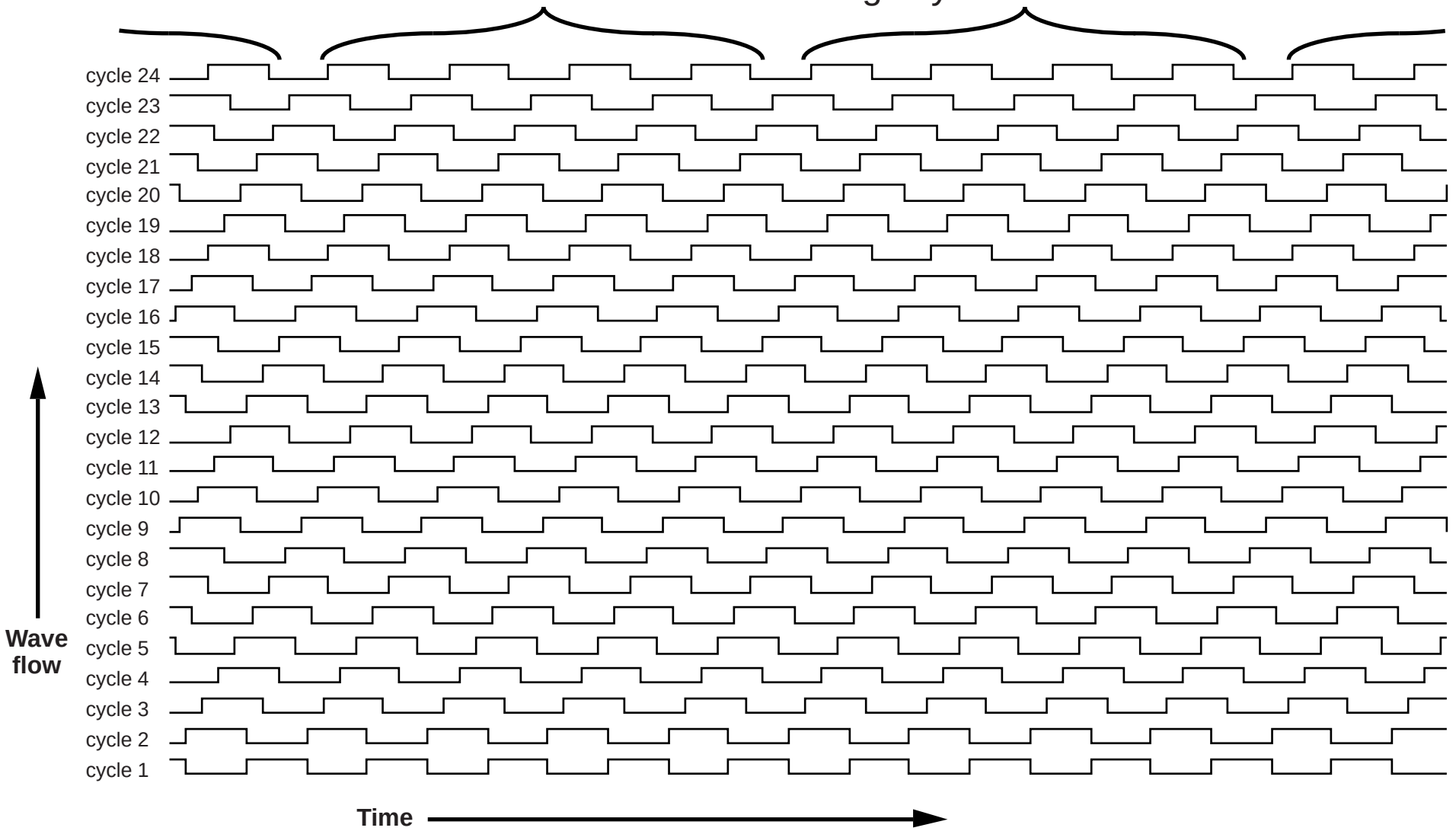


24 Stage Ring, one slow stage
4 data wavefronts

Delay Limited

There is no waiting for the wavefronts or bubbles to arrive.

8 wavefronts flow through cycle 24.

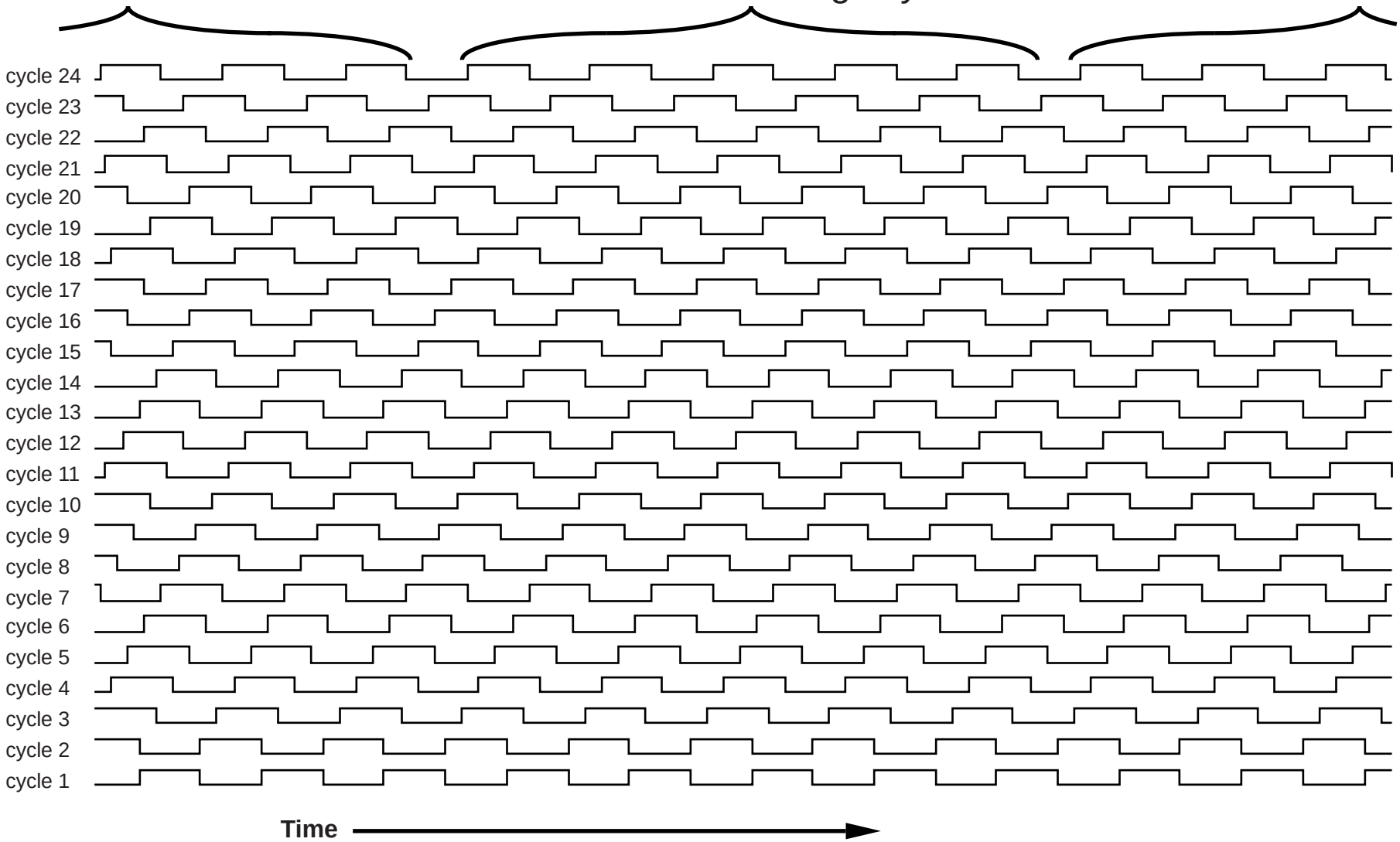


24 Stage Ring, one slow stage
5 data wavefronts

Delay Limited

There is no waiting for the wavefronts or bubbles to arrive.

10 wavefronts flow through cycle 24.

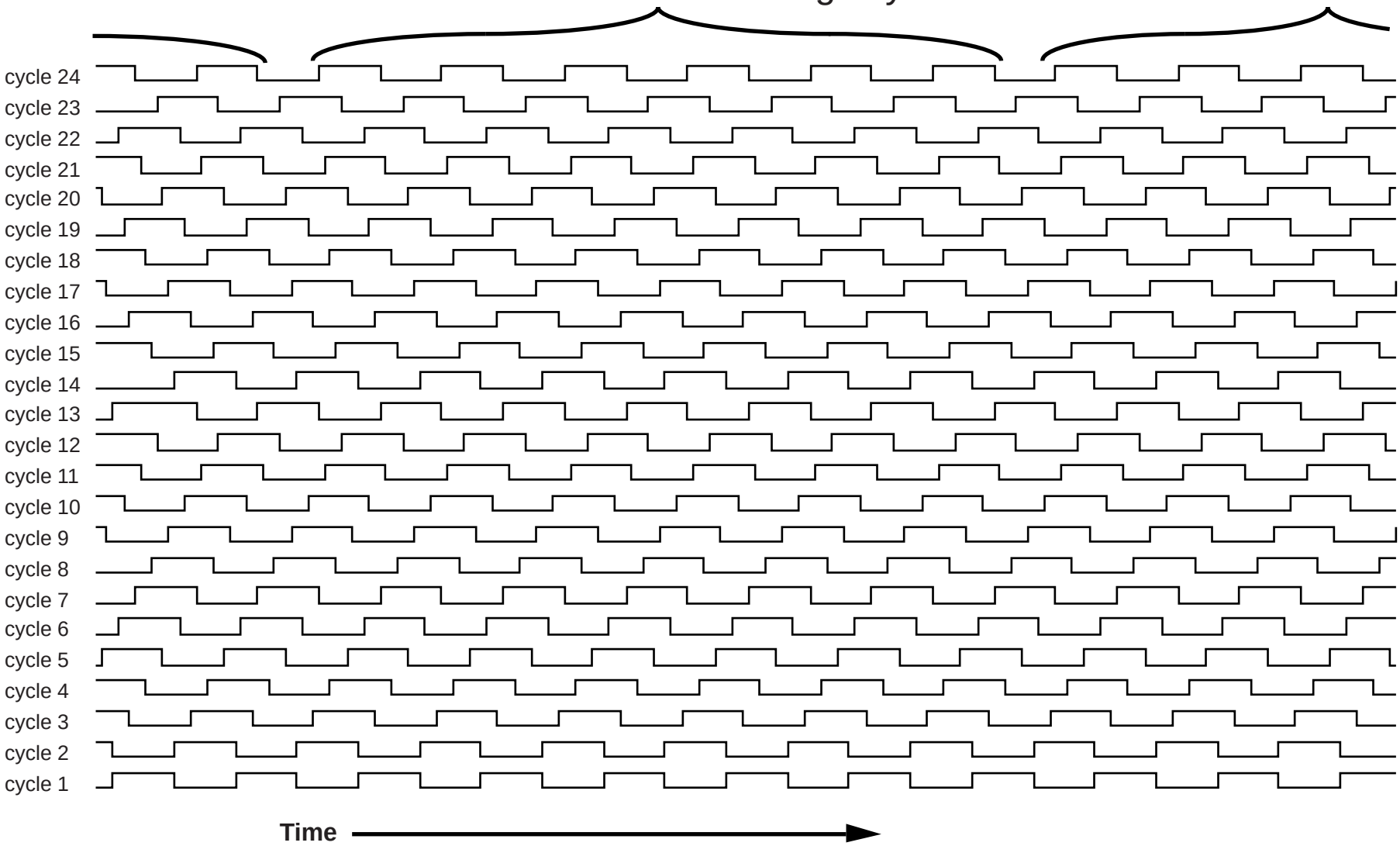


24 Stage Ring, one slow stage
6 data wavefronts

Delay Limited

There is no waiting for the wavefronts or bubbles to arrive.

12 wavefronts flow through cycle 24.

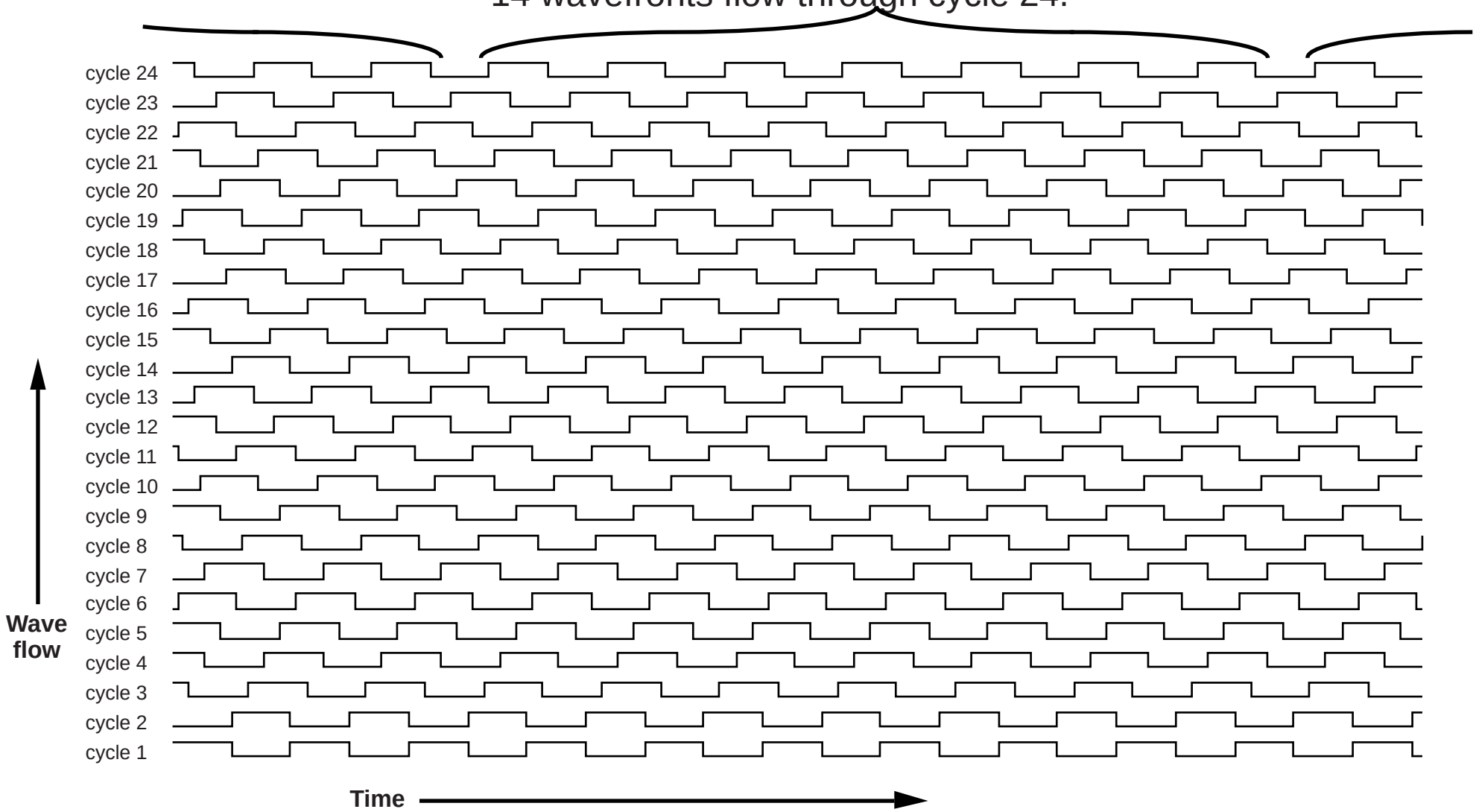


24 Stage Ring, one slow stage
7 data wavefronts

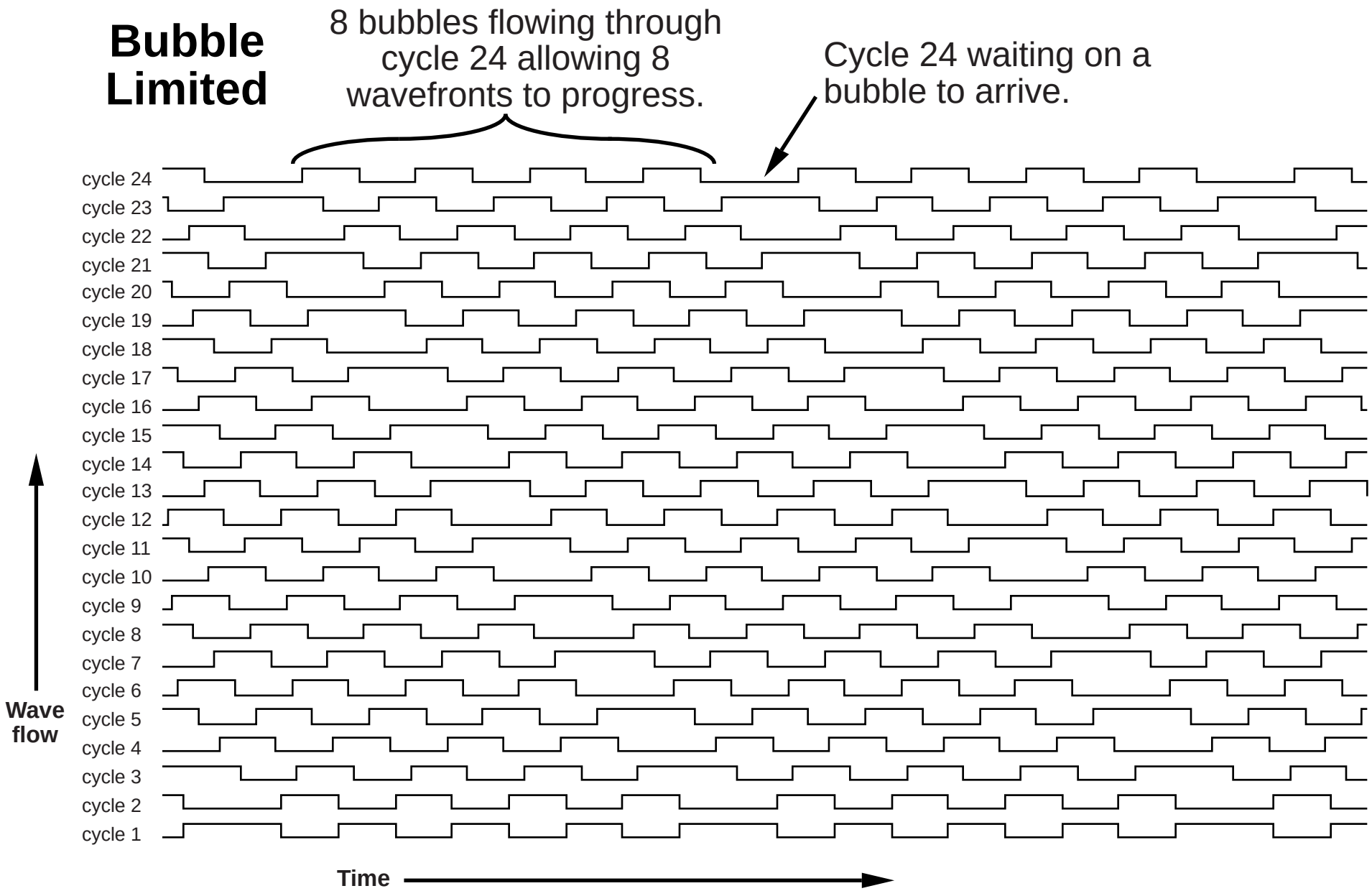
Delay Limited

There is no waiting for the wavefronts or bubbles to arrive.

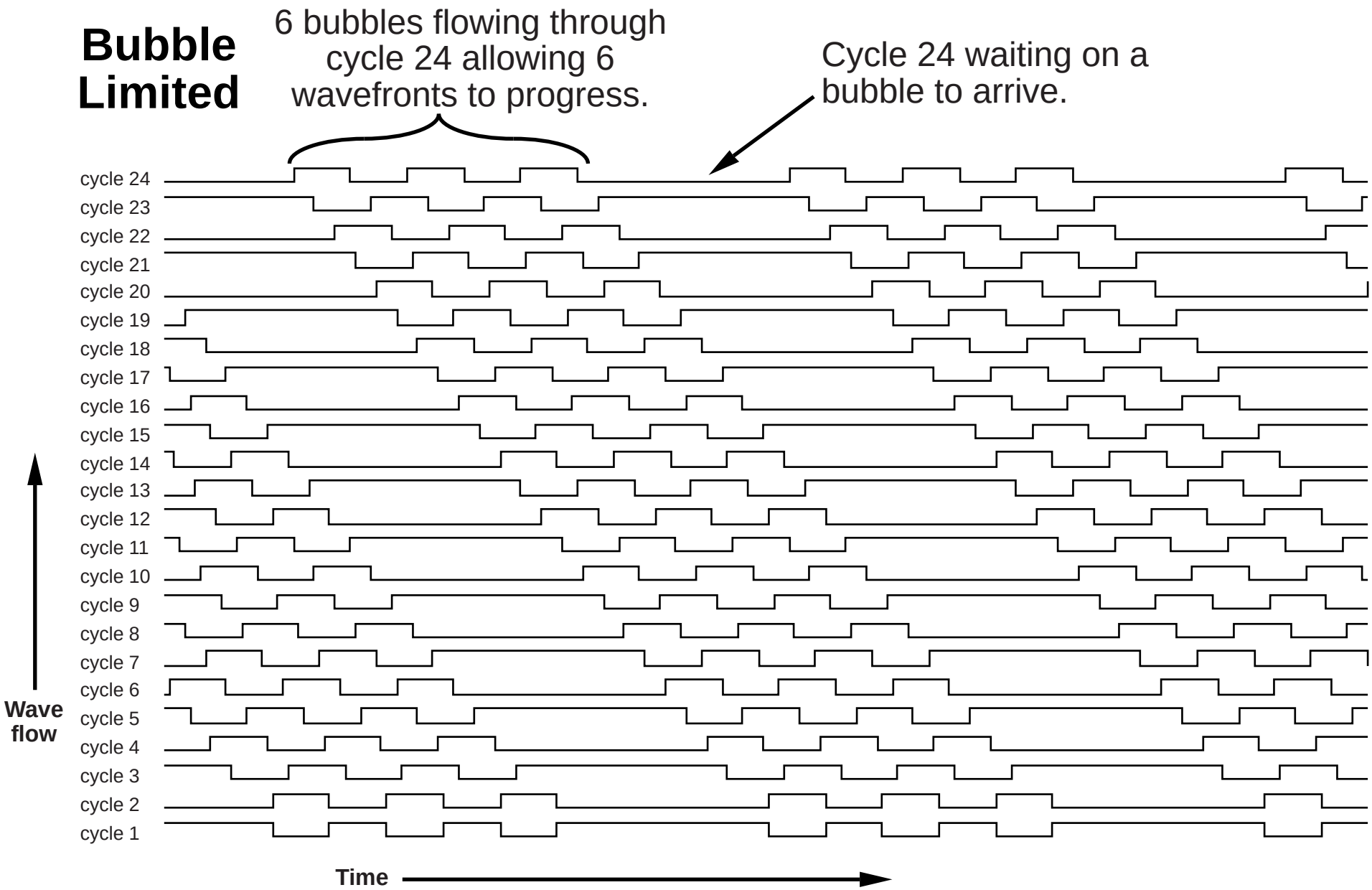
14 wavefronts flow through cycle 24.



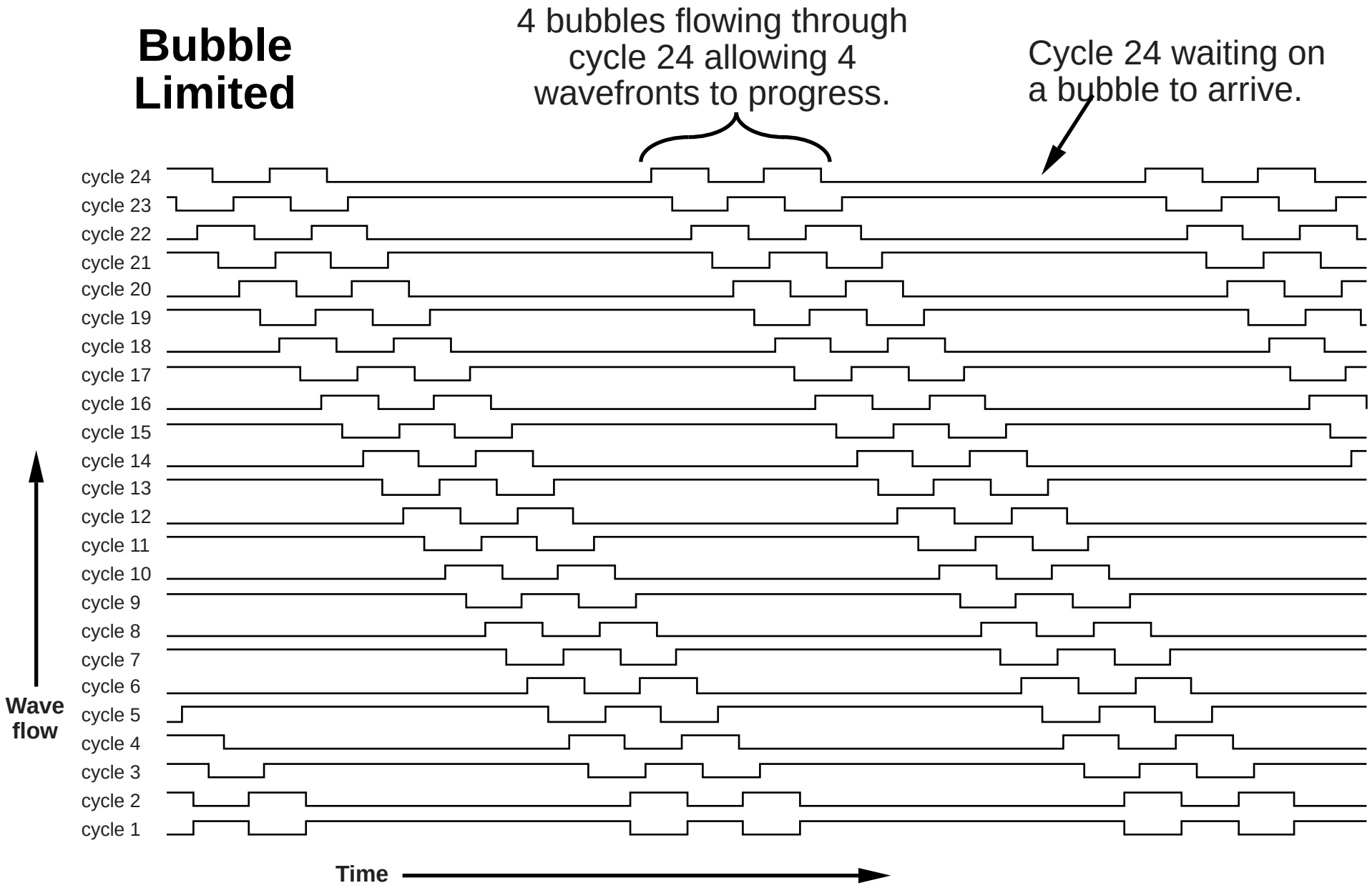
24 Stage Ring, one slow stage
8 data wavefronts



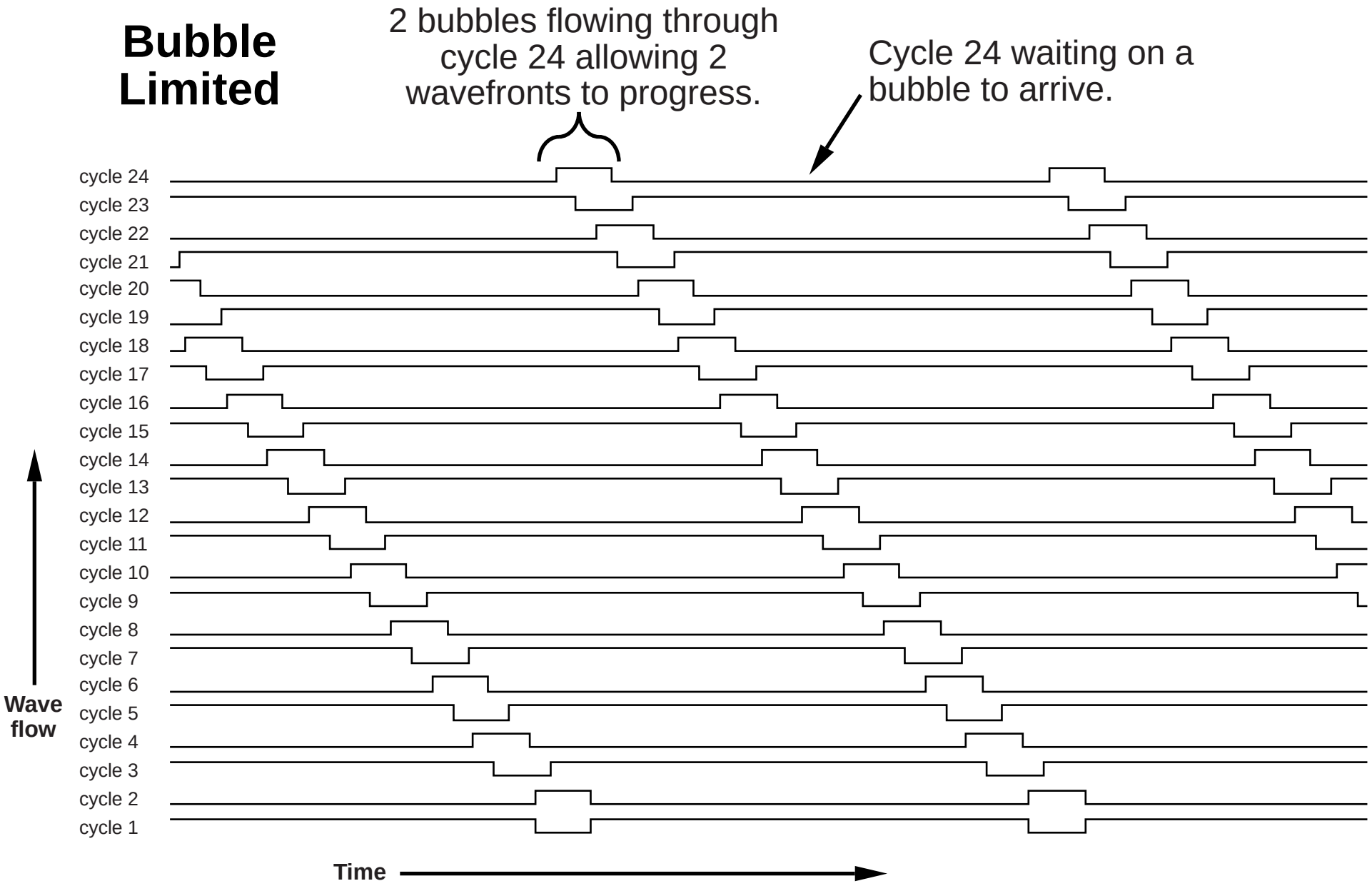
24 Stage Ring, one slow stage
9 data wavefronts



24 Stage Ring, one slow stage
10 data wavefronts



24 Stage Ring, one slow stage
11 data wavefronts

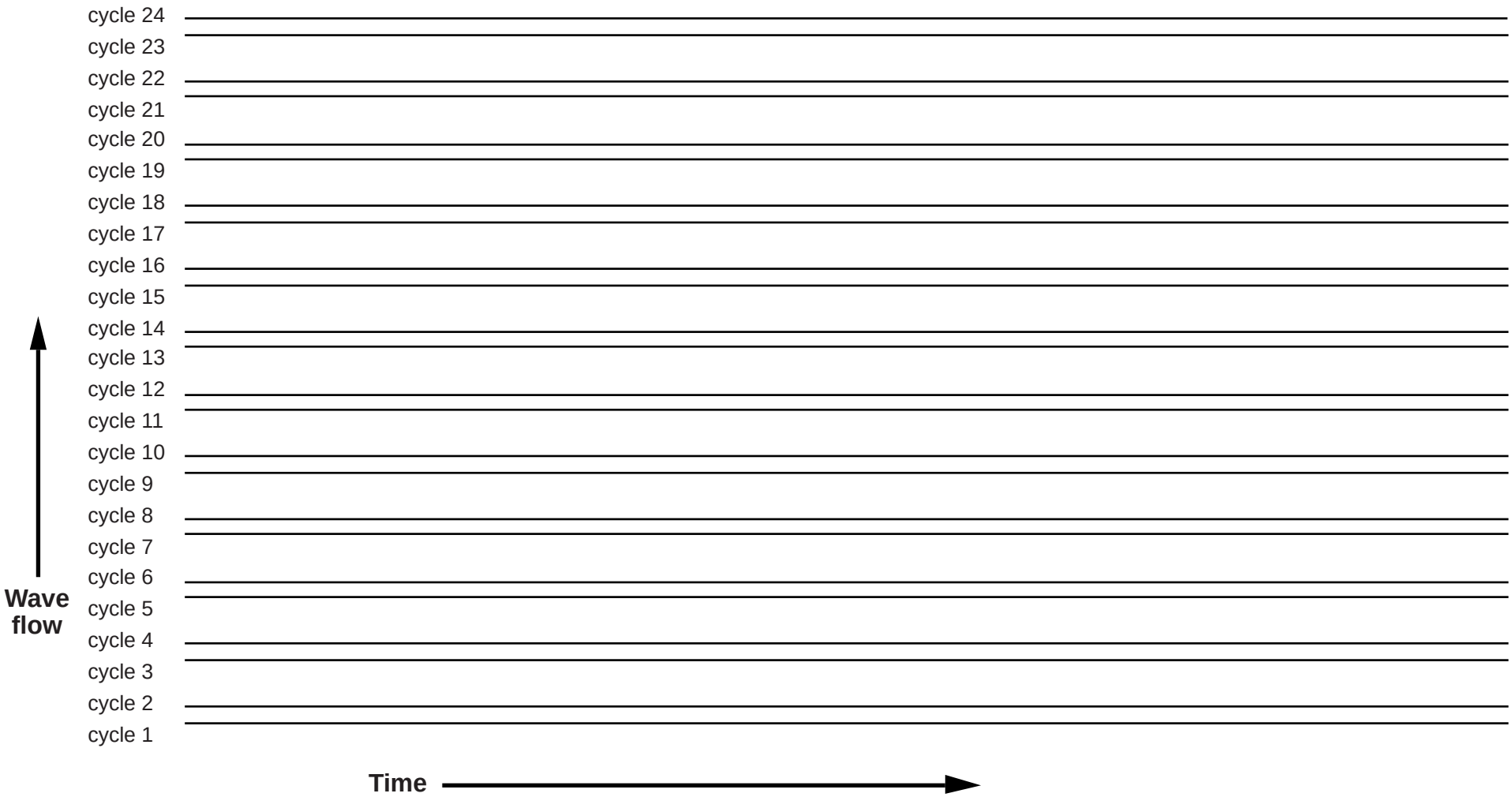


24 Stage Ring, one slow stage
12 data wavefronts

Deadlocked

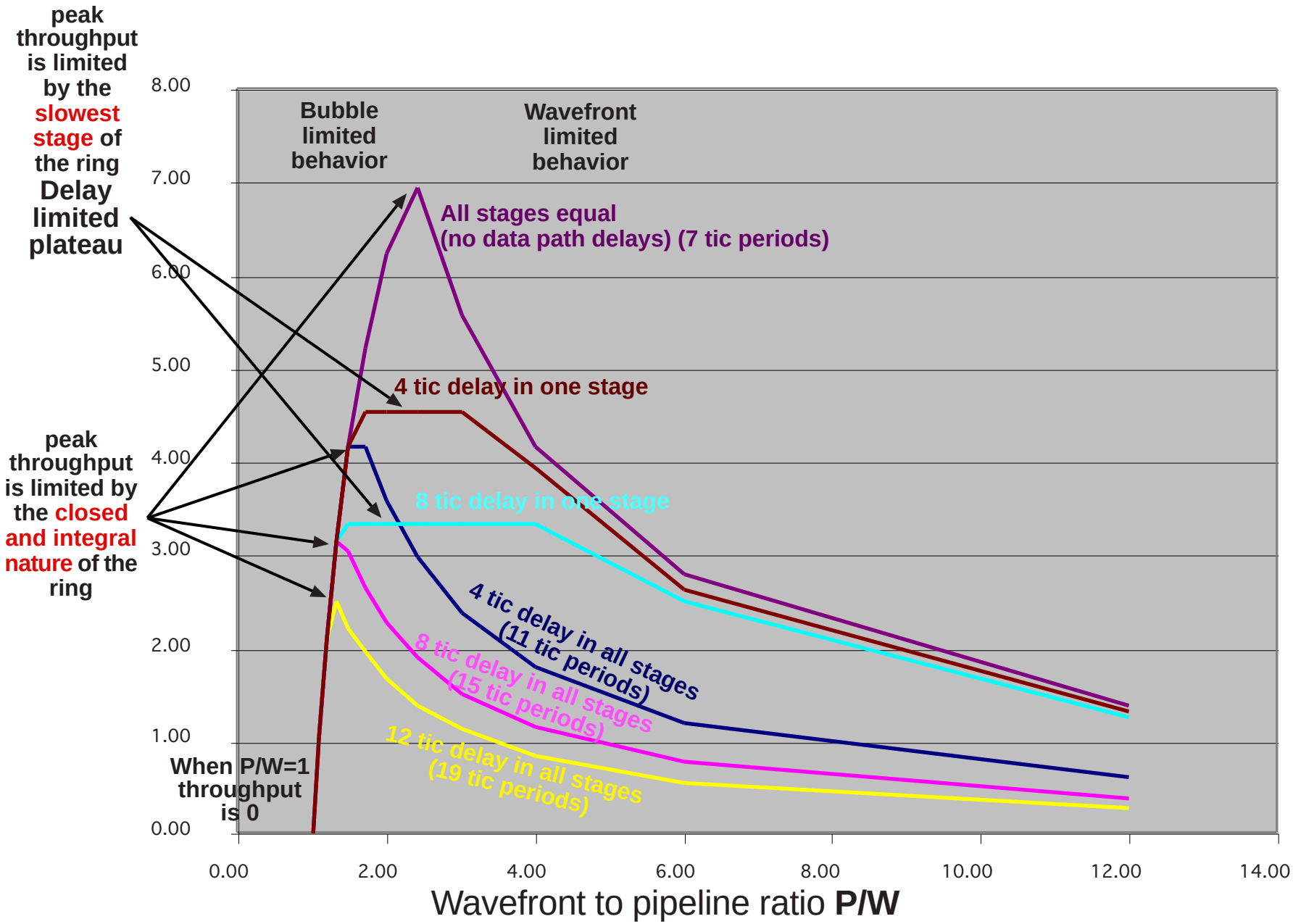
0 bubbles flowing through cycle 24 allowing 0 wavefronts to progress.

Pipeline is deadlocked.



Overall View of Ring Behavior

All cases are 24 stage rings with varying wavefront populations



As the data path delay grows maximum throughput is achieved with smaller P/W

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