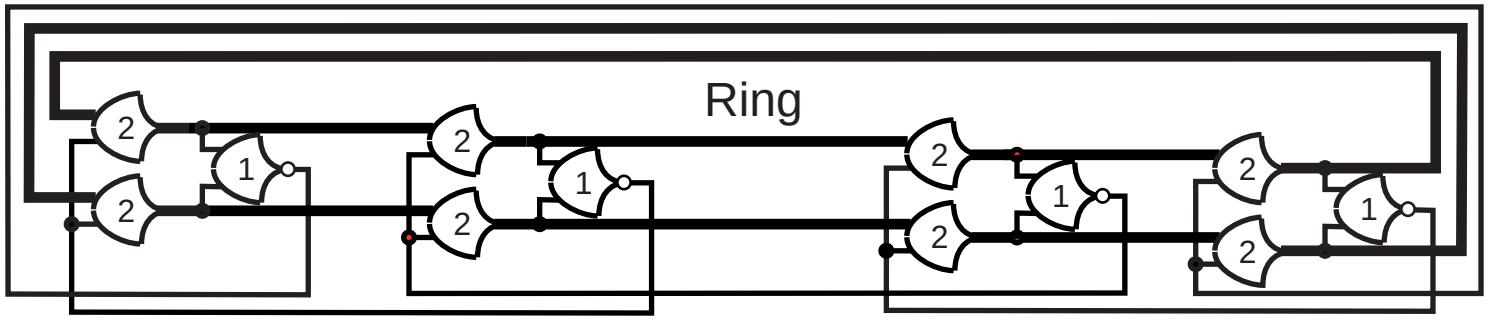
# QuickTime Ring Movies

This discussion accompanies a set of QuickTime movies that visualize the dynamic spatial relationships of wavefronts and bubbles flowing through a ring. The movie behavior is compared to the view in terms of signal behavior presented as a collection of correlated signal traces.

The juxtaposed views illuminate ring behavior more effectively than either view by itself.

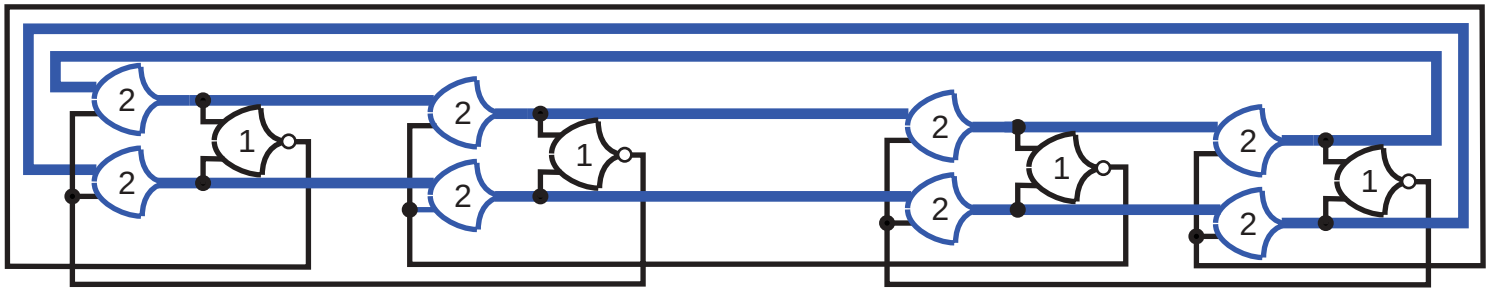
## The Pipeline Ring

The pipeline ring is a pipeline with its data path closed into a ring.



# The Wavefront Rejoin Period

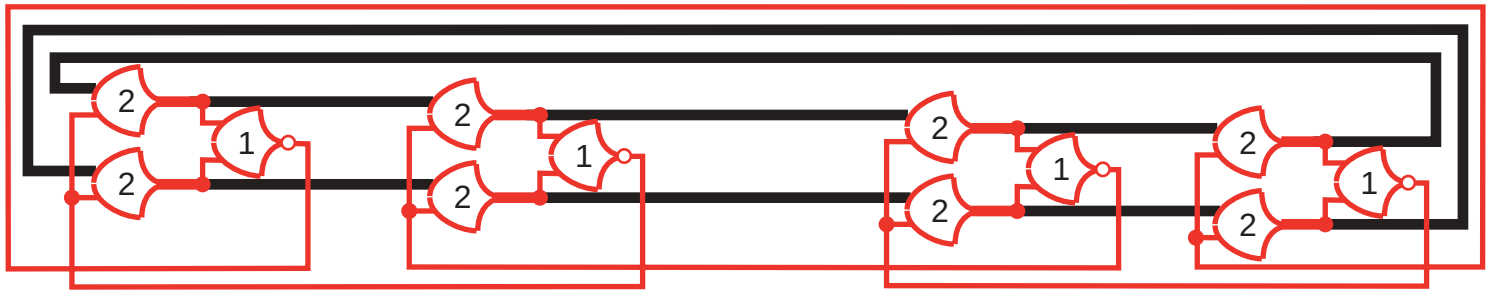
The wavefront rejoin path is the sum of the register delays and the data path delays of the wavefront path.




wavefront path

# The Bubble Rejoin Period

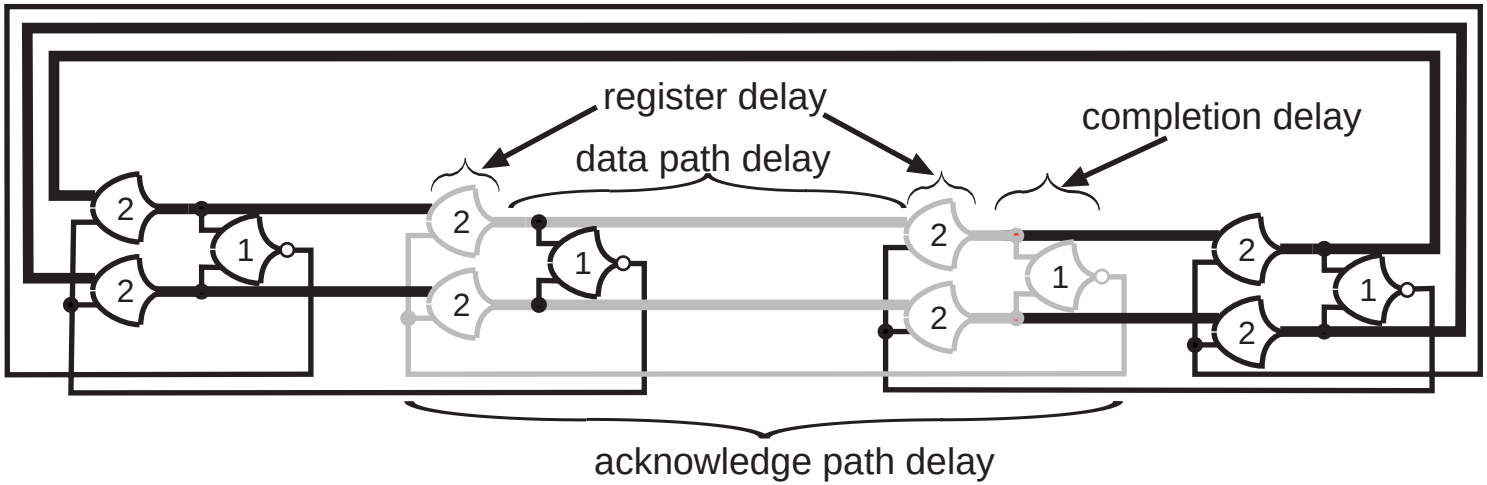
The bubble rejoin path is the sum of the register delays, the completion delays and the acknowledge path delays of the bubble path.




bubble path

# Cycle Period

The cycle period is the sum of the two register delays, the data path delay, the completion delay and the acknowledge path delay of a cycle path.




# The Wavefront Population Period

The wavefront population period is the time it takes for all the wavefronts in the ring to propagate through a slowest cycle in the ring which equals number of wavefronts in ring times slowest cycle period.

# The Bubble Population Period

The bubble population period is the time it takes for all the bubbles in the ring to propagate through a slowest cycle in the ring which equals  number of bubbles in the ring times the slowest cycle period.


# Ring Behavior in a Nutshell

## Wavefront limited behavior

If the population of wavefronts can propagate through each cycle (wavefront population period) faster than they can propagate around the ring (wavefront rejoin period), then cycles will be idled waiting on wavefronts to propagate around the ring and the throughput of the ring is limited by how long it takes wavefronts to propagate around the ring. The throughput of the ring will be the number of wavefronts in the ring per wavefront rejoin period

## Bubble limited behavior

If the population of bubbles can propagate through each cycle (bubble population period) faster than they can propagate around the ring (bubble rejoin period), then cycles will be idled waiting on bubbles to propagate around the ring and the throughput of the ring is limited by how long it takes bubbles to propagate around the ring. The throughput of the ring will be the number of bubbles in the ring per bubble rejoin period

## Delay limited behavior

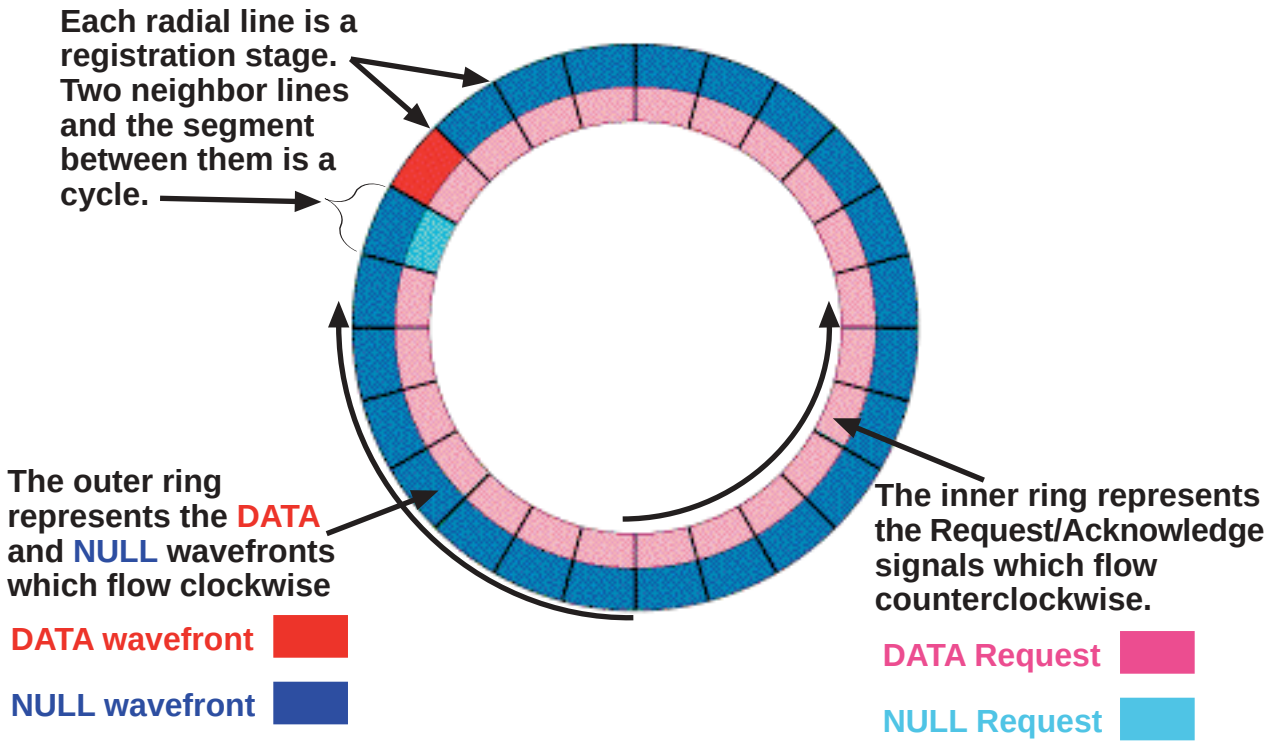
If one cycle of the ring has a long period such that both wavefronts and bubbles propagate around the ring faster than their populations can propagate through the slow cycle then, wavefronts and bubbles will always wait on this slow cycle. This cycle delay casts a shadow that dominates the throughput of the ring. The throughput of the ring will be one wavefront per slowest cycle period.

A ring cannot be both wavefront limited and bubble limited. Every cycle in a ring contains either a wavefront or a bubble. No cycle can be empty of both and waiting on both.

# Basics of the QuickTime Ring Movies

The outer ring represents the DATA/NULL data path 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 registration stage. Two neighboring radial lines and the segment between them is a cycle. There are 24 cycles in the ring.

The movies can be stopped and single stepped in either direction with the controls or the space bar and the arrow keys.




# Vital parameters for the ring movies

For each cycle:
Wavefront propagation delay = 4 steps
Completion delay = 1 step
Acknowledge propagation delay = 4 steps
Register propagation delay = 0 steps
Cycle period = 4 + 0 + 1 + 4 + 0 = 9 steps

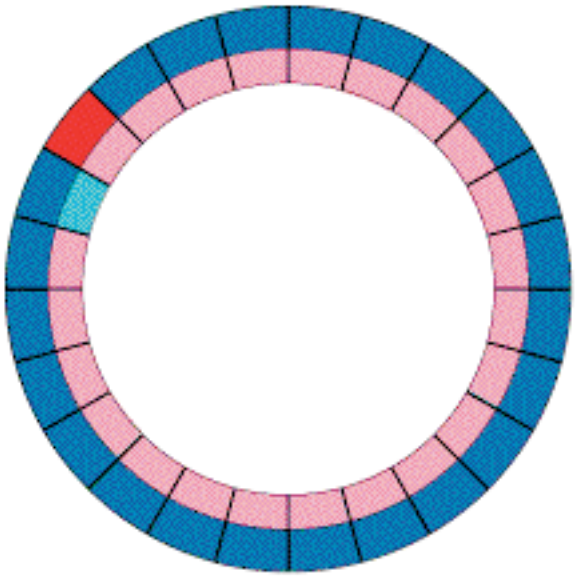
Number of cycles = 24
Number of bubbles = 24 - number of wavefronts

Wavefront population period = number of wavefronts * 9 steps
Wavefront renew period = (24 * 4) + (24 * 0) = 96 steps

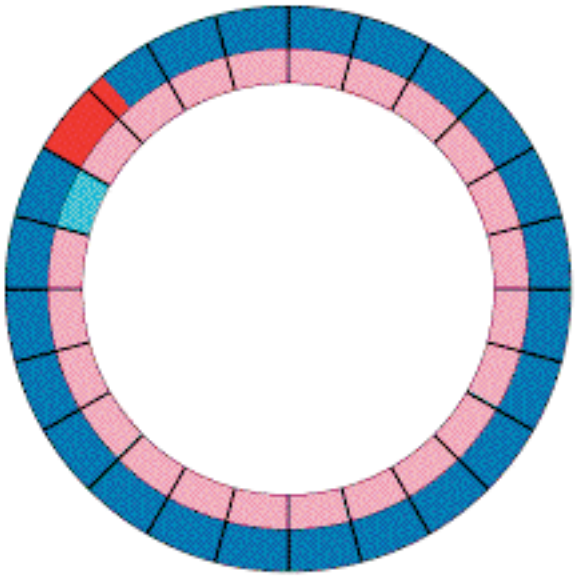
Bubble population period = number of bubbles * 9 steps
Bubble renew period = (24 * 4) + (24 * 1) + (24 * 0) = 120 steps

# Pipeline Ring Movie Dynamics 1

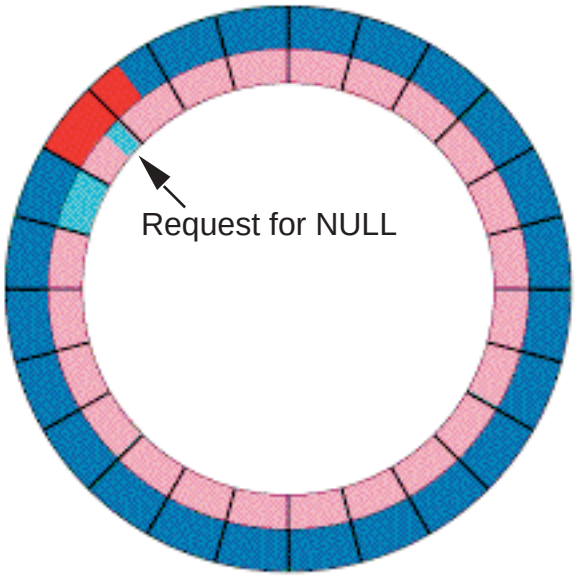
1 Initial state with one DATA wavefront, one NULL wavefront and a long NULL bubble train



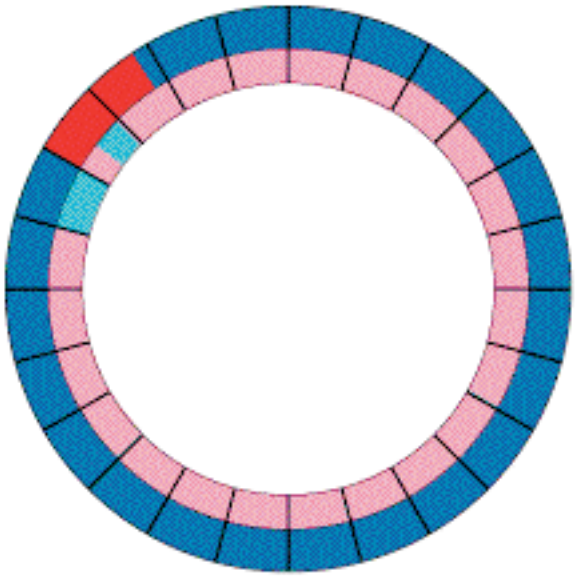
2 Init is released and the DATA wavefront begins to propagate through a NULL bubble



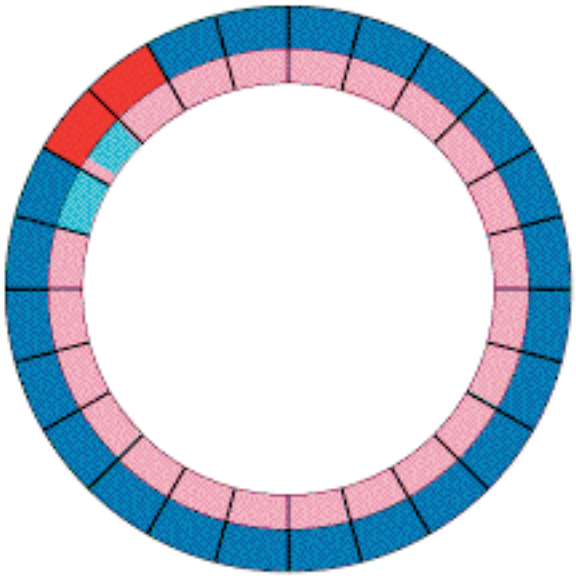
3 DATA completion is detected and request for NULL begins propagating



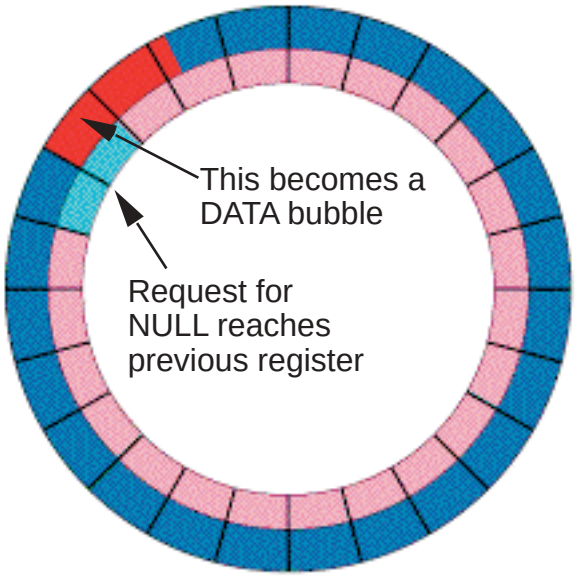

4 Propagations continue



5 Propagations continue

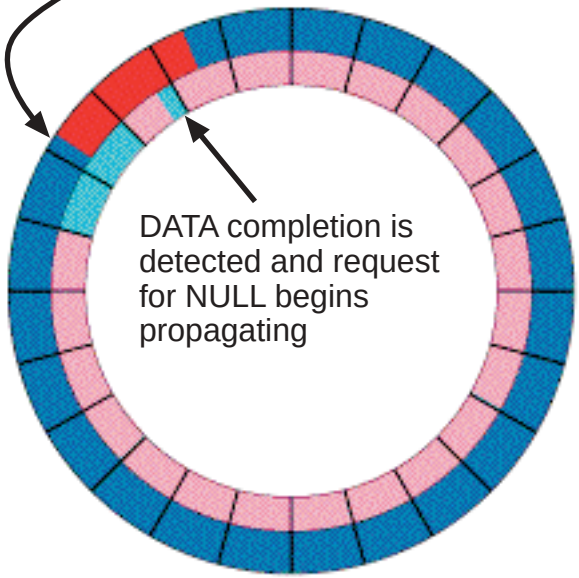


6 Request for NULL reaches previous register forming a DATA bubble

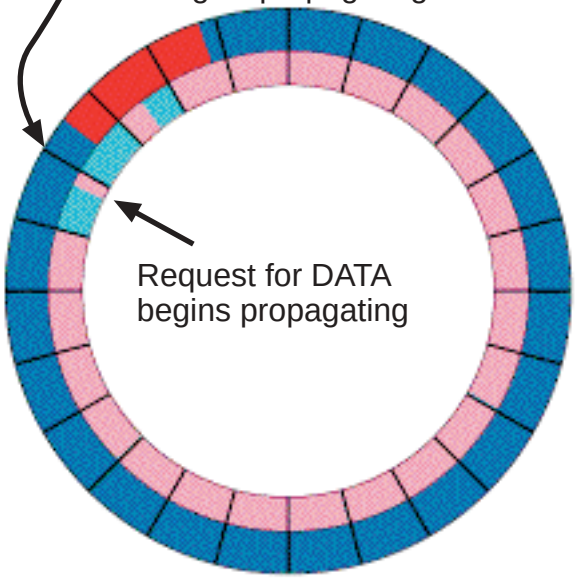


# Pipeline Ring Movie Dynamics 2

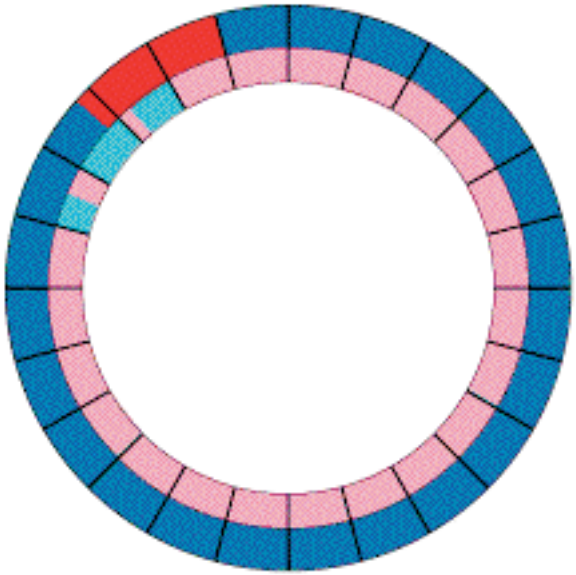
7 NULL wavefront begins to propagate through DATA bubble



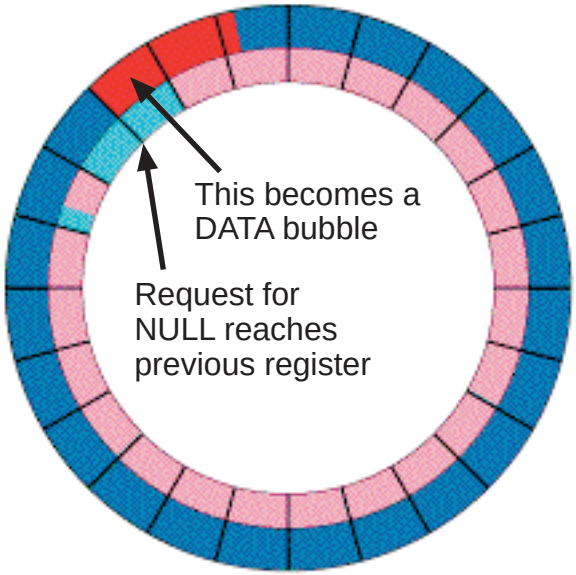

8 NULL completion is detected and request for DATA begins propagating



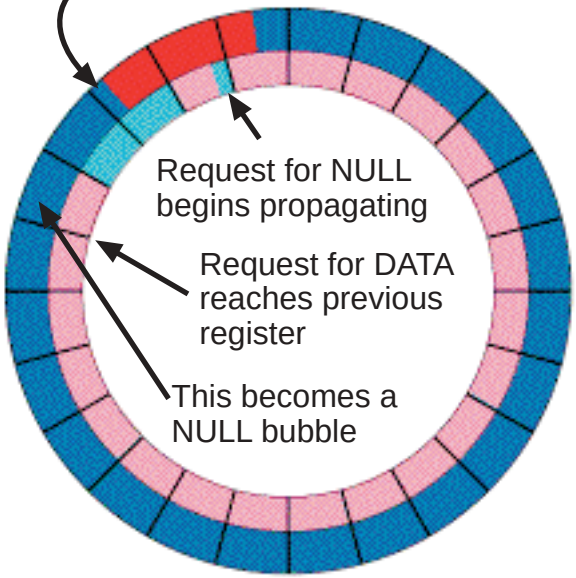

9 Propagations continue



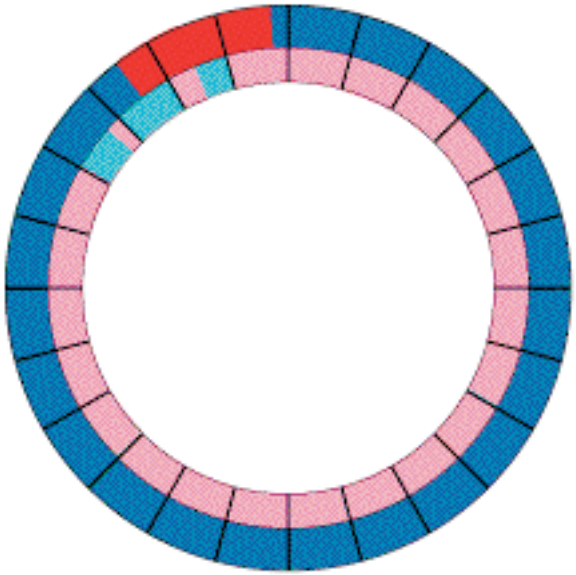
10 Request for NULL reaches previous register forming a DATA bubble




11 NULL wavefront begins to propagate through DATA bubble




12 And so on.....



# Severely Wavefront Limited Ring Movie
# Two wavefronts.mov
## One DATA wavefront, one NULL wavefront and twenty two bubbles

If the wavefront population period is considerably less than the wavefront rejoin period, the ring is severely wavefront limited. there are few wavefronts and lots of bubbles. Wavefronts free flow around the ring through a long train of bubbles never catching up with each other and never having to wait. The throughput of the ring is the number of wavefronts in the ring per the time it takes them to flow around the ring (wavefront rejoin period). For this example the throughput of the ring is two wavefronts (one DATA wavefront) per 96 steps.

If there are 4 wavefronts the throughput doubles. If there are 6 wavefronts the throughput triples and so on until the wavefront population period exceeds the wavefront rejoin period, wavefronts start bumping into each other and having to wait on bubbles.

24 cycles
2 wavefronts
24 - 2 = 22 bubbles

Wavefront population period = 2 * 9 = 18 steps
Wavefront rejoin period = 96 steps
Bubble population period = 22 * 9 = 198 steps
Bubble rejoin period = 120 steps

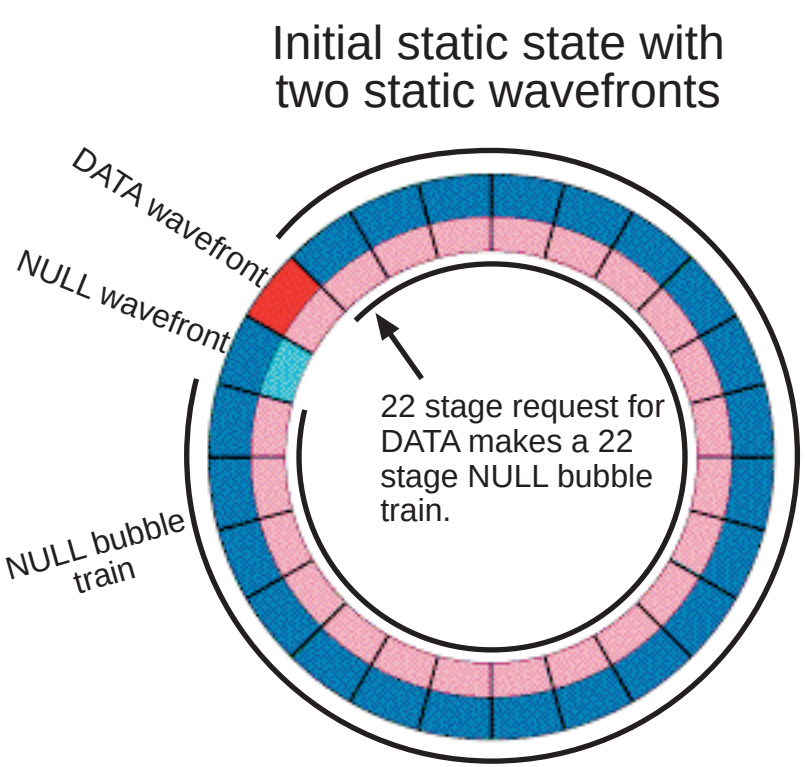
Wavefront limited:
2 wavefronts (1 DATA wavefront) per 96 steps
Two wavefronts pass through a cycle then the cycle waits 96 - 18 = 78 steps
for the wavefronts to arrive again.

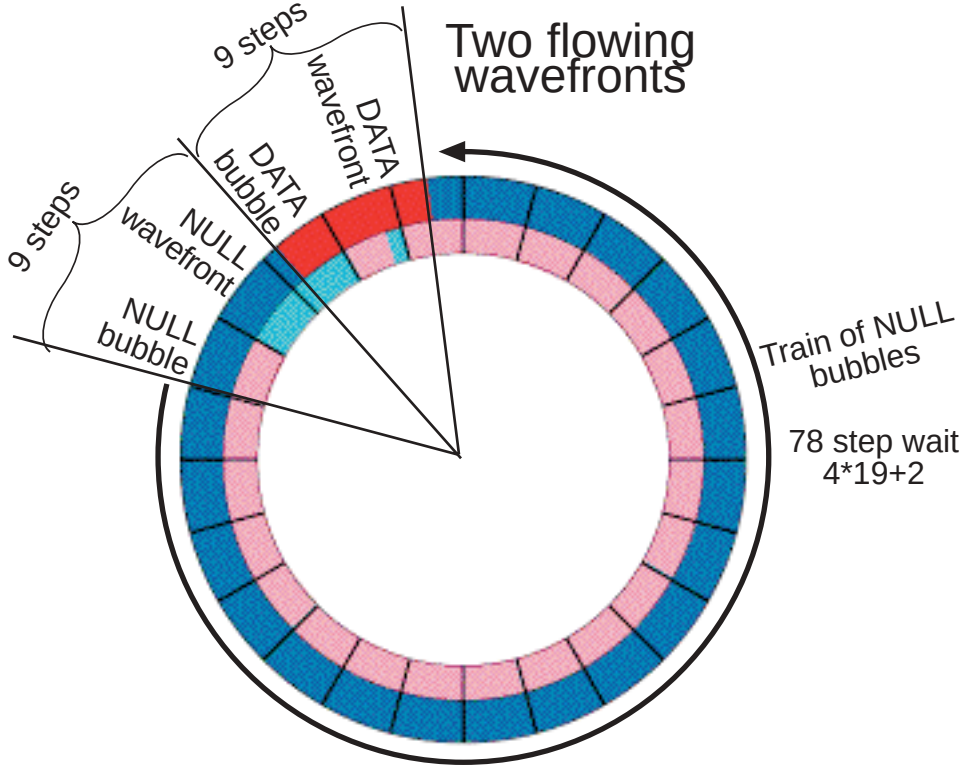
# Severely Wavefront Limited Ring Movie
# Two wavefronts.mov

## One DATA wavefront, one NULL wavefront and twenty two bubbles

A flowing wavefront enters a cycle as a stable wavefront. It exits the cycle as a bubble being overwritten by the next wavefront. These two phases together comprise the wavefront's tenure in the cycle. The duration of this tenure is one cycle period. Looking at a signal anywhere in a cycle this tenure is expressed as the interval between transitions from DATA to NULL or from NULL to DATA.

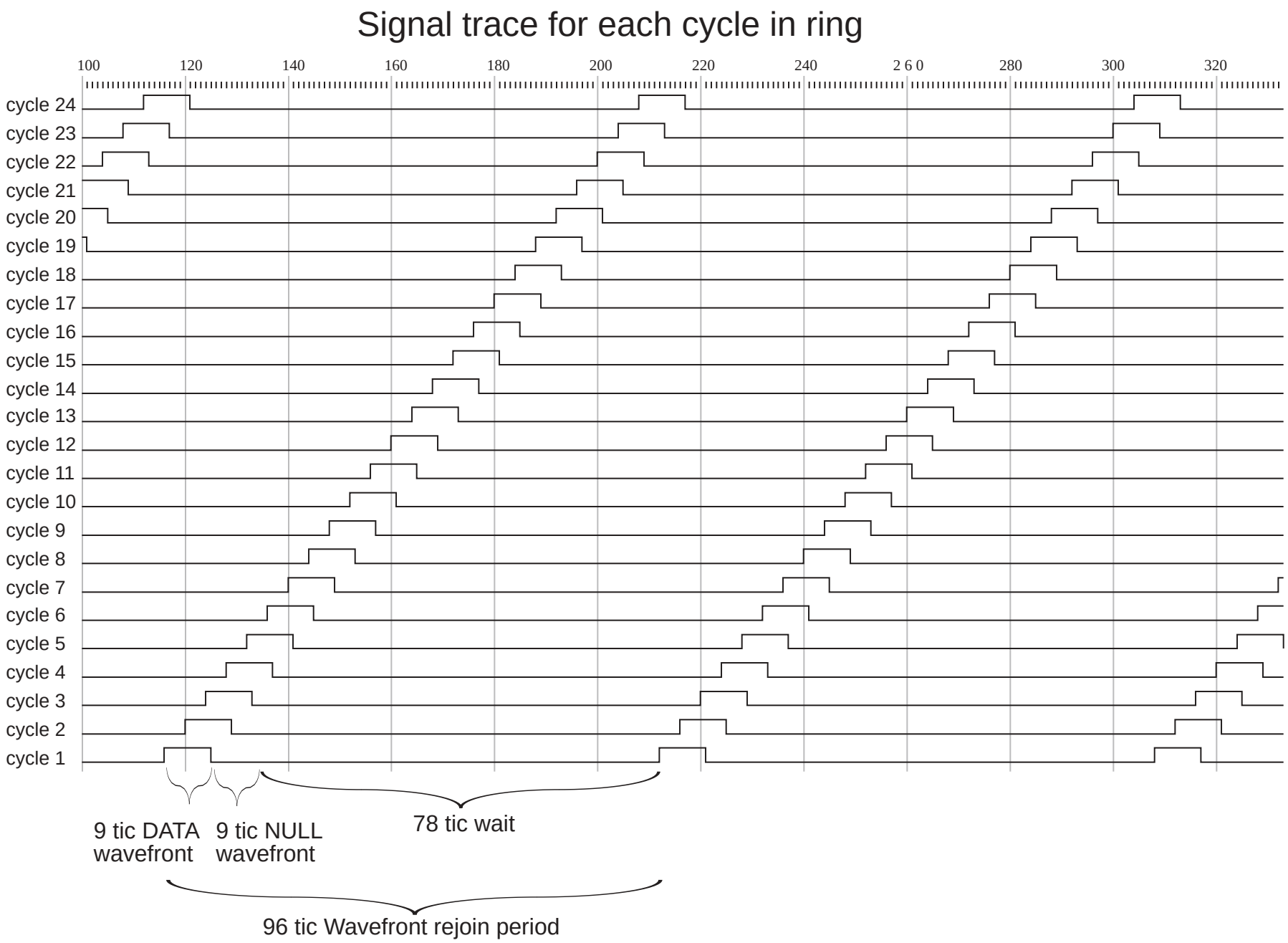
In terms of the spatial relationships a free flowing wavefront and its bubble will stretch through the data path a delay distance equal to the periods of the cycles it is passing through. Specifically in terms of the movie a wavefront, passing through cycles with periods of 9 steps, will stretch 9 steps along the data path of the ring.



# Severely Wavefront Limited Ring Movie
# Two wavefronts.mov

## One DATA wavefront, one NULL wavefront and twenty two bubbles



# Slightly Wavefront Limited Ring Movie
# Ten wavefronts.mov

## Five DATA wavefronts, Five NULL wavefronts and fourteen bubbles

If the wavefront population period is slightly less than the wavefront rejoin period, the ring is slightly wavefront limited. The lead DATA wavefront still freely propagates around the ring through continually sufficient bubbles never catching up with the tail wavefront and never having to wait. The throughput of the ring is 10 wavefronts (5 DATA wavefronts) per 96 steps.

24 cycles
10 wavefronts
24 - 10 = 14 bubbles

Wavefront population period = 10 * 9 = 190 steps
Wavefront rejoin period = 96 steps
Bubble population period = 14 * 9 = 126 steps
Bubble rejoin period = 120 steps

Wavefront limited:
10 wavefronts (5 DATA wavefronts) per 96 steps
Ten wavefronts pass through a cycle then the cycle waits 96 - 90 = 6 steps
for the wavefronts to arrive again.

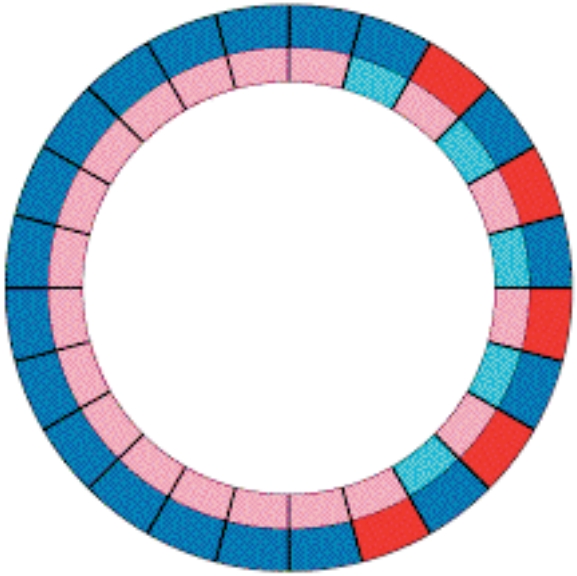
# Slightly Wavefront Limited Ring Movie
# Ten wavefronts.mov

## Five DATA wavefronts, five NULL wavefronts and fourteen bubbles

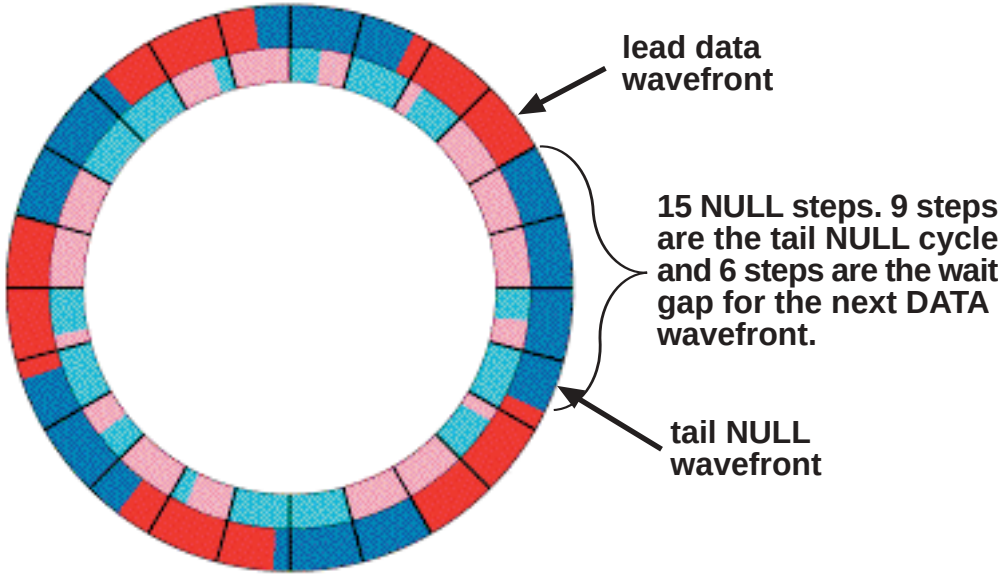
The bubble population period is slightly greater than the bubble rejoin period of the ring. So there is always a bubble waiting for the lead wavefront.

The wavefronts distribute themselves around the ring in data path delay lengths of 9 steps with a wait gap of 6 steps between the lead DATA wavefront and the tail NULL wavefront. Notice that the wait gap flows around the ring with the wavefronts.

Initial state of ring
with ten static wavefronts

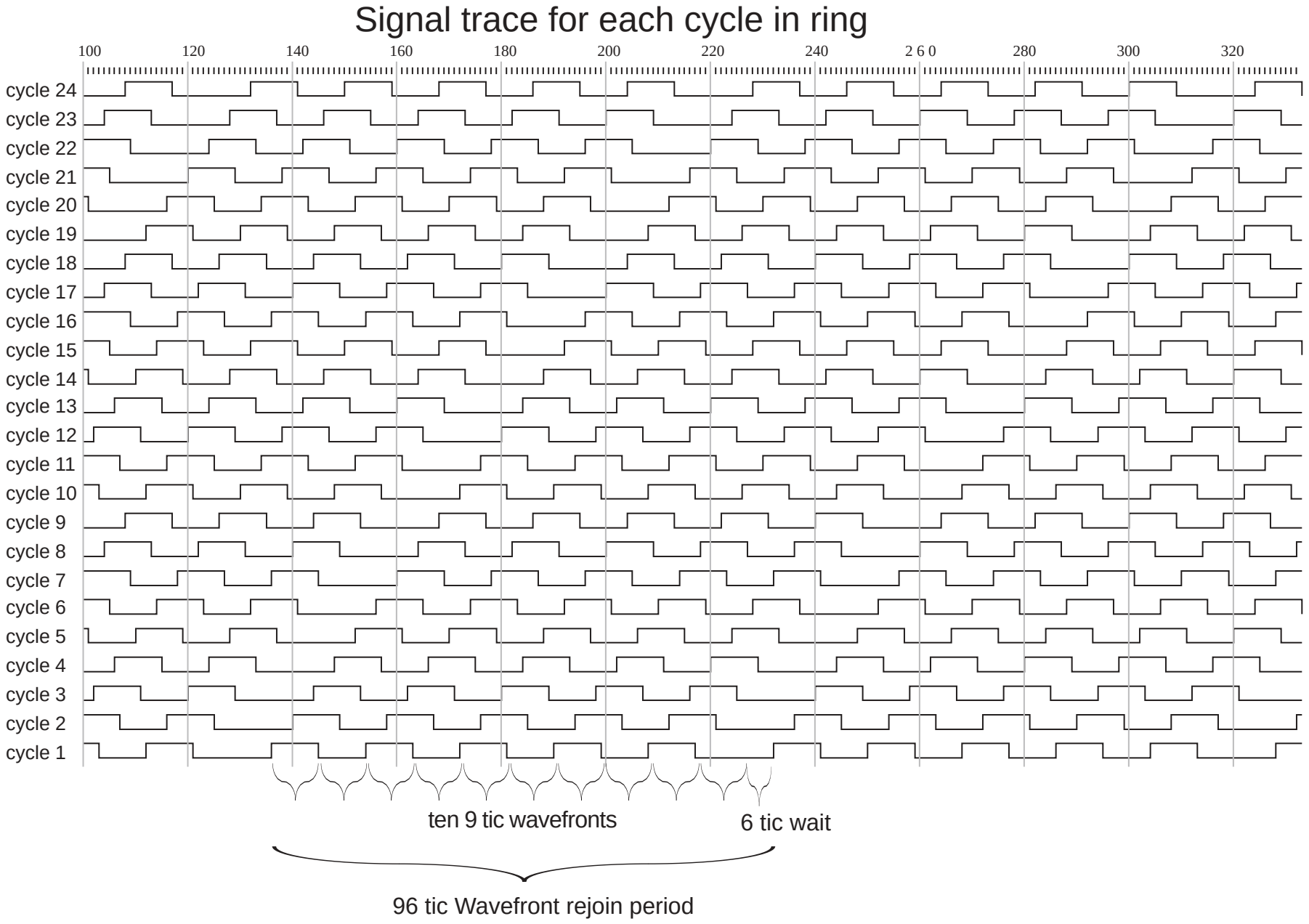


The flowing wavefronts distribute
themselves around the ring



# Slightly Wavefront Limited Ring Movie
# Ten wavefronts.mov

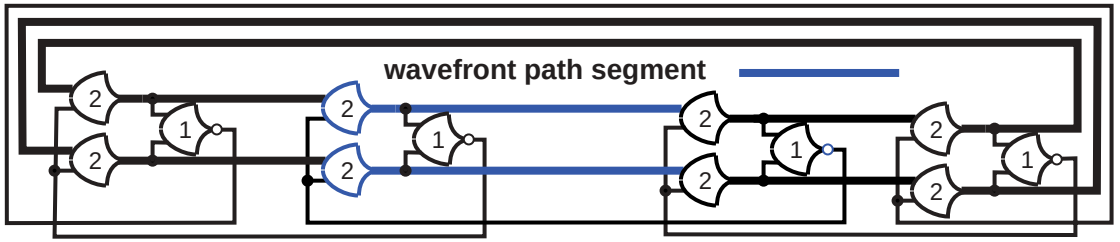
## Five DATA wavefronts, five NULL wavefronts and fourteen bubbles



# The Cycle Period and the Rejoin Periods

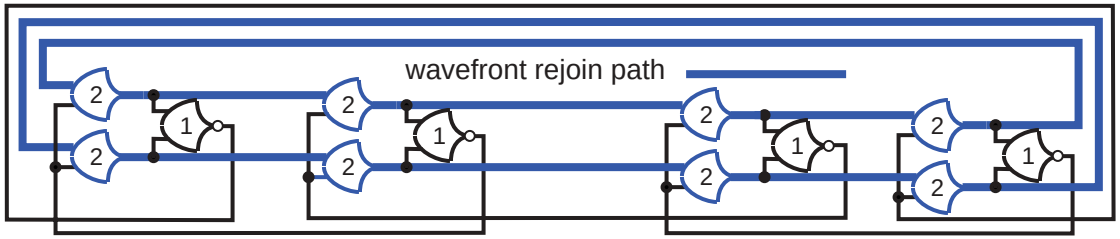
## All Cycles Being Equal

Delay of wavefront path segment = A = 4 steps



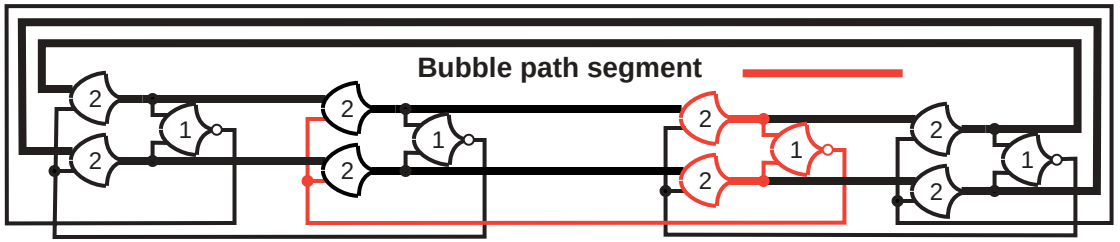

Number of cycles in ring = N = 24

The wavefront path and the wavefront rejoin path is the catenation of all the wavefront path segments of the ring.

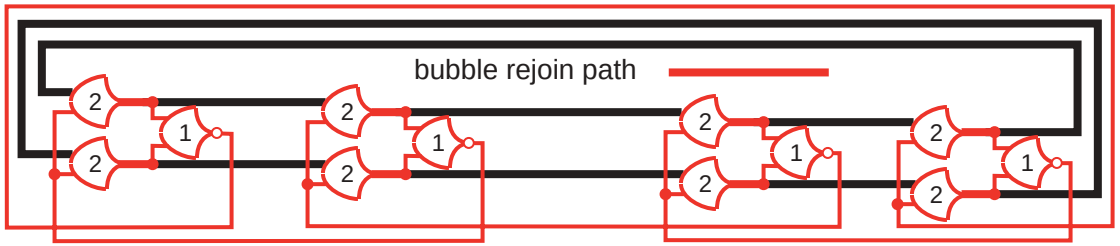



Wavefront rejoin period = N*A = 96

Delay of bubble path segment = B = 5 steps

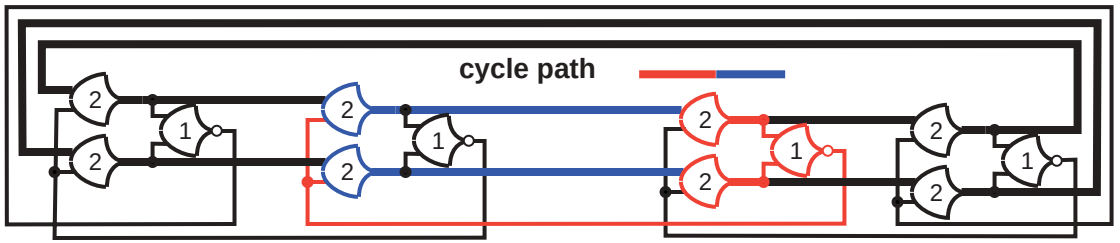



The bubble path and the bubble rejoin path is the catenation of all the bubble path segments of the ring.




Bubble rejoin period = N*B = 120

The cycle is the catenation of one bubble path segment and of one wavefront path segment.

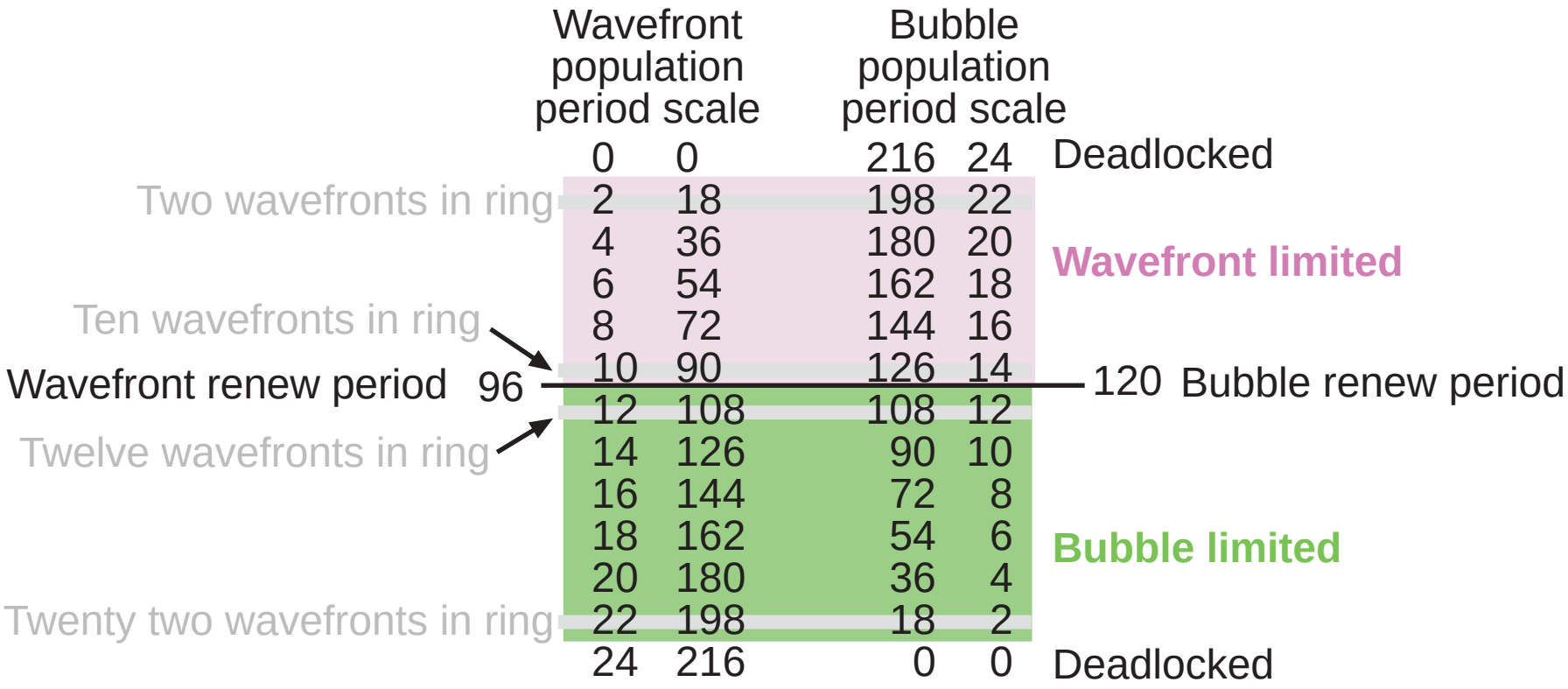



Cycle period = A + B = 9

# The Population Periods

## All Cycles Being Equal

**The ring can not be both wavefront limited and bubble limited. It must be one or the other.**




N(A + B) = range of population period = 216
W = number of wavefronts in ring
W(A + B) = wavefront population period
(N - W)(A + B) = bubble population period

W(A + B) + (N - W)(A + B) = N(A + B) which means that the two population periods define a common line between the two population period scales

NA + NB + N(A + B) which means that the two rejoin periods define a common line between the two population period scales

The position of the common population period line will depend on the number of wavefronts in the ring but it will be on one side or the other of the common renew period line. The ring will never be both wavefront limited and bubble limited. It must be one or the other.

# Slightly Bubble Limited Ring Movie
# twelve wavefronts.mov

## Six DATA wavefronts, six NULL wavefronts and twelve bubbles

If the bubble population period is slightly less than the bubble rejoin period, the ring is slightly bubble limited. Bubbles flow freely around the ring never catching up with each other and never waiting.

As the bubbles flow they enable wavefronts to flow. The throughput of the ring is the number of bubbles per bubble rejoin period. In this case the throughput is twelve wavefronts (six DATA wavefronts) per 120 steps.

24 cycles
12 wavefronts
24 - 12 = 12 bubbles

Wavefront population period = 12 * 9 = 108 steps
Wavefront rejoin period = 96 steps
Bubble population period = 12 * 9 = 108 steps
Bubble rejoin period = 120 steps

Bubble limited:
12 wavefronts (6 DATA wavefronts) per 120 steps
Twelve bubbles pass through a cycle then the cycle waits 120 - 108 = 12 steps for a bubble to arrive again.

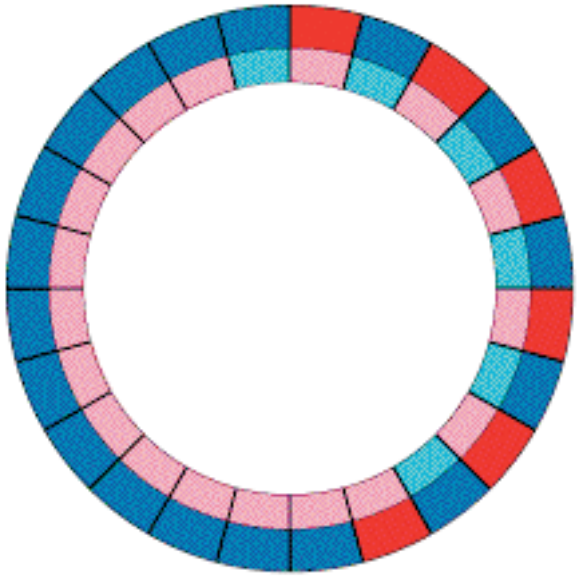
# Slightly Bubble Limited Ring Movie
# Twelve wavefronts.mov

## Six DATA wavefronts, six NULL wavefronts and twelve bubbles

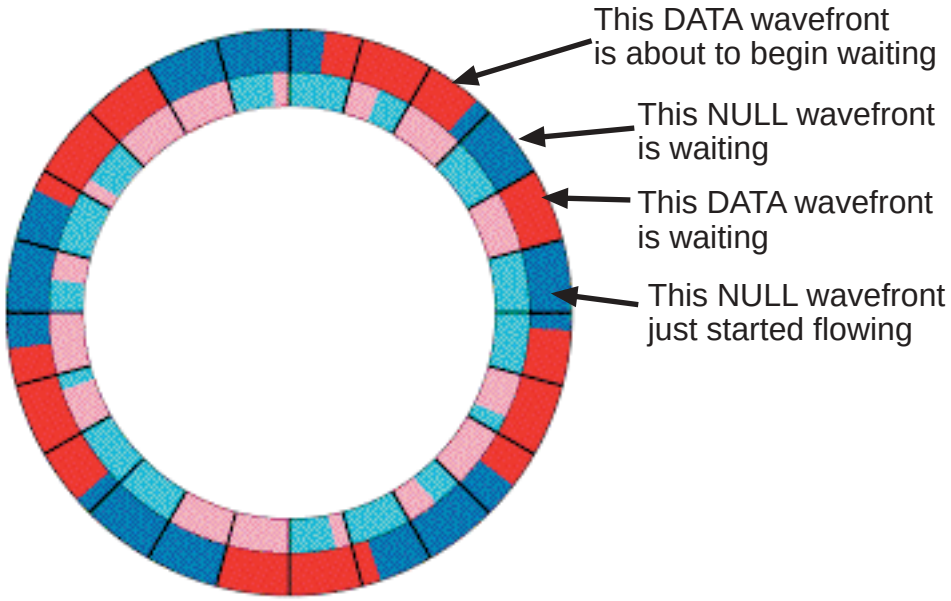
The wavefront population period will be slightly greater than the wavefront rejoin period. Wavefronts flow around the ring faster than the population flows through a cycle with the consequence that wavefronts collide The free flowing wavefronts distribute themselves around the ring in data path delay lengths of 9 steps until they bump into another wavefront and collapse into a train of waiting wavefronts waiting on bubbles.

Notice that the train of waiting wavefronts flows around the ring counterclockwise with the bubble flow.

Initial state of 24 stage ring
with twelve static wavefronts

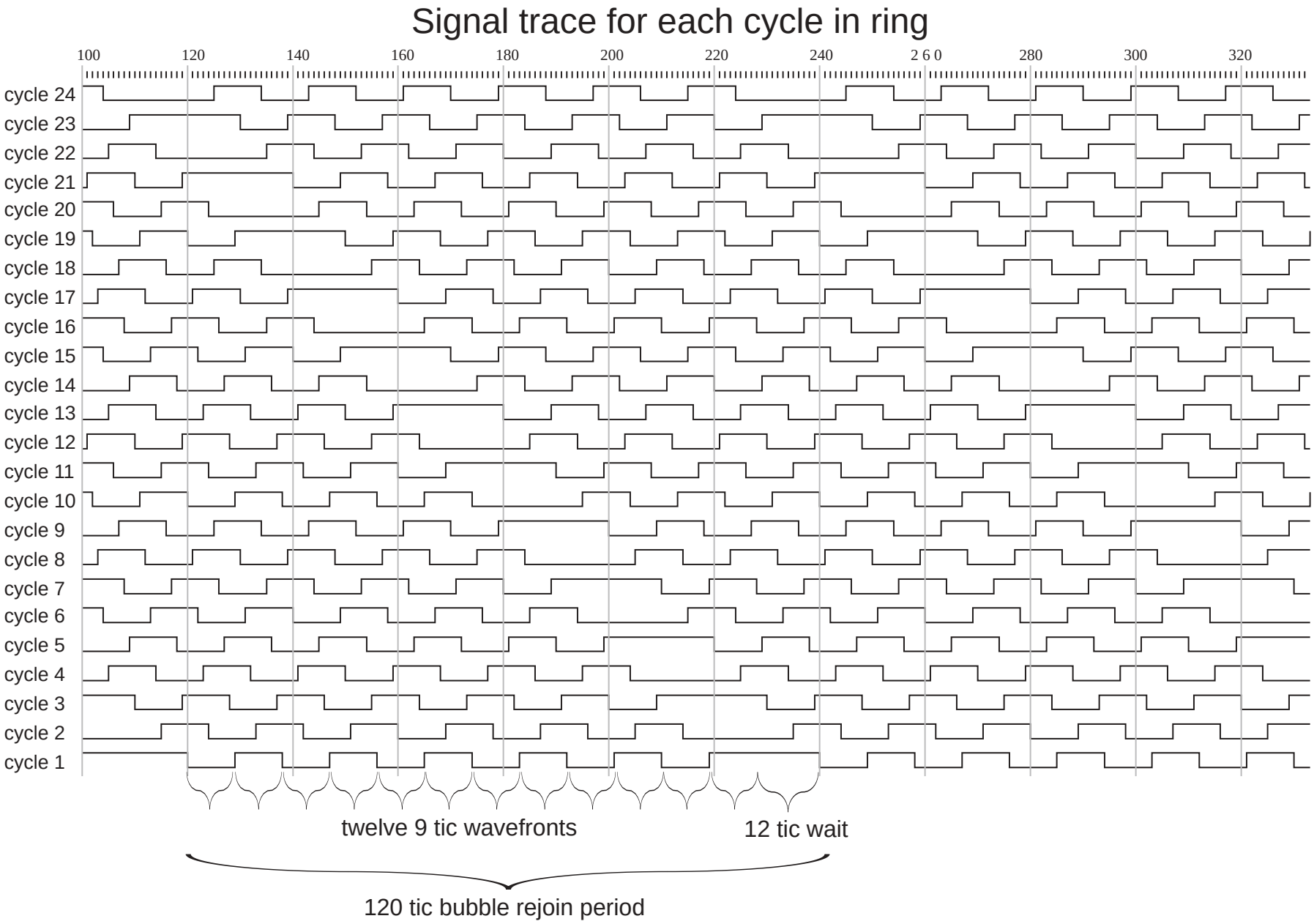


The flowing wavefronts bunch up in a
train of wavefronts waiting on bubbles



# Slightly Bubble Limited Ring Movie
# Twelve wavefronts.mov

## Six DATA wavefronts, six NULL wavefronts and twelve bubbles



# Severely Bubble Limited Ring Movie twenty two wavefronts.mov

## Eleven DATA wavefronts, eleven NULL wavefronts and two bubbles

If the bubble population period is significantly less than the bubble rejoin period then the ring is severely bubble limited. In this example there are only two bubbles in a 24 cycle ring with 22 wavefronts. The wavefronts bunch up in a long train that the bubbles freely flow through with no waiting. As the bubbles flow they enable wavefront flow. The throughput is the number of bubbles per the bubble rejoin period. In this case the throughput is two wavefronts (one DATA wavefront) per 120 steps.

24 cycles
22 wavefronts
24 - 22 = 2 bubbles

Wavefront population period = 22 * 9 = 198 steps
Wavefront rejoin period = 96 steps
Bubble population period = 2 * 9 = 18 steps
Bubble rejoin period = 120 steps

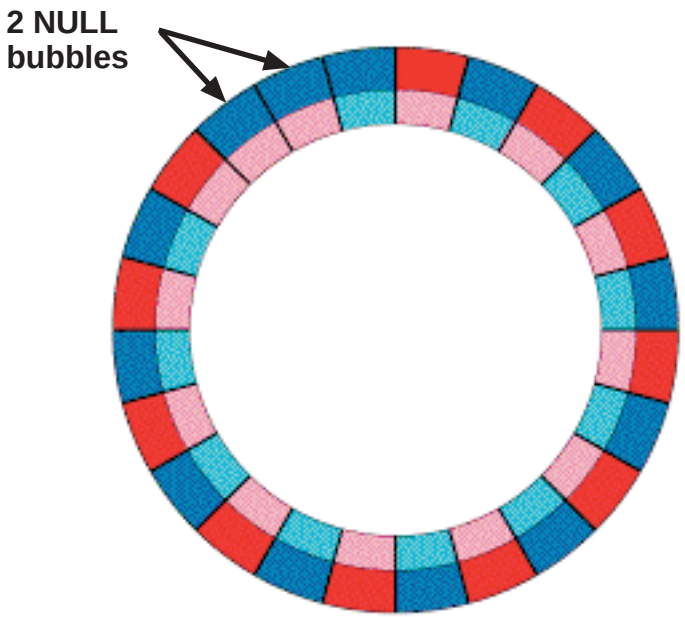
Bubble limited:
2 wavefronts (1 DATA wavefronts) per 120 steps
Two bubbles pass through a cycle then the cycle waits 120 - 18 = 102 steps for a bubble to arrive again.

# Severely Bubble Limited Ring Movie twenty two wavefronts.mov

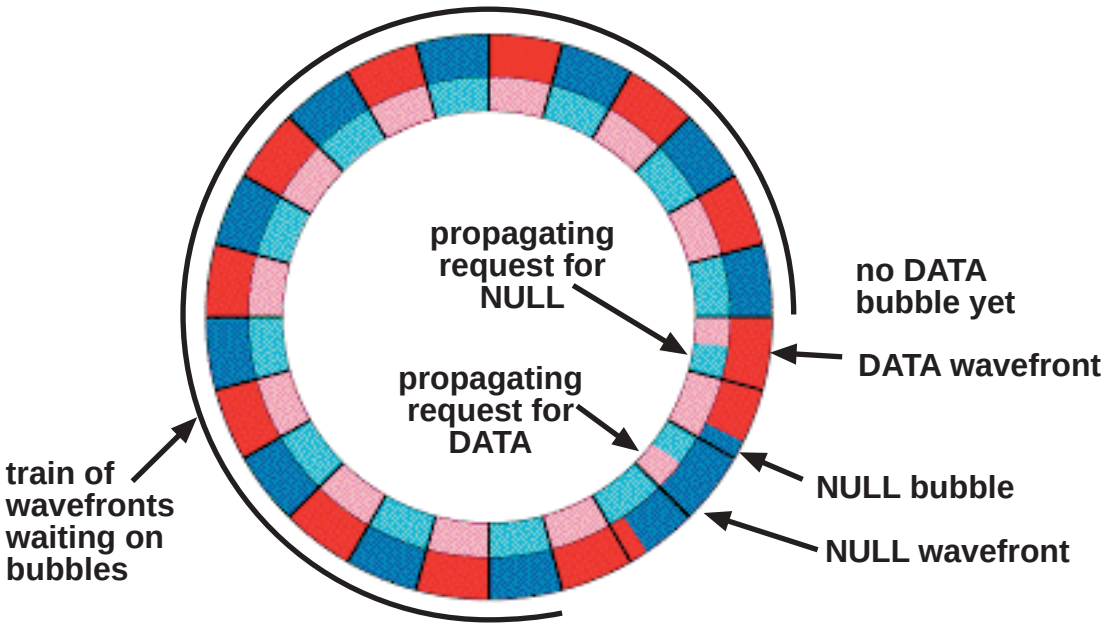
## Eleven DATA wavefronts, eleven NULL wavefronts and two bubbles

Bubbles travel around the ring in the opposite direction to the wavefronts sort of tunneling through the wavefronts. A DATA wavefront flows into a NULL bubble and after completion detection and request for NULL propagation a DATA bubble forms behind the DATA wavefront A NULL wavefront flows into the NULL bubble and after completion detection and request for DATA propagation a NULL bubble forms behind the NULL wavefront. And so on.

Initial state of 24 stage ring
with twenty two static wavefronts

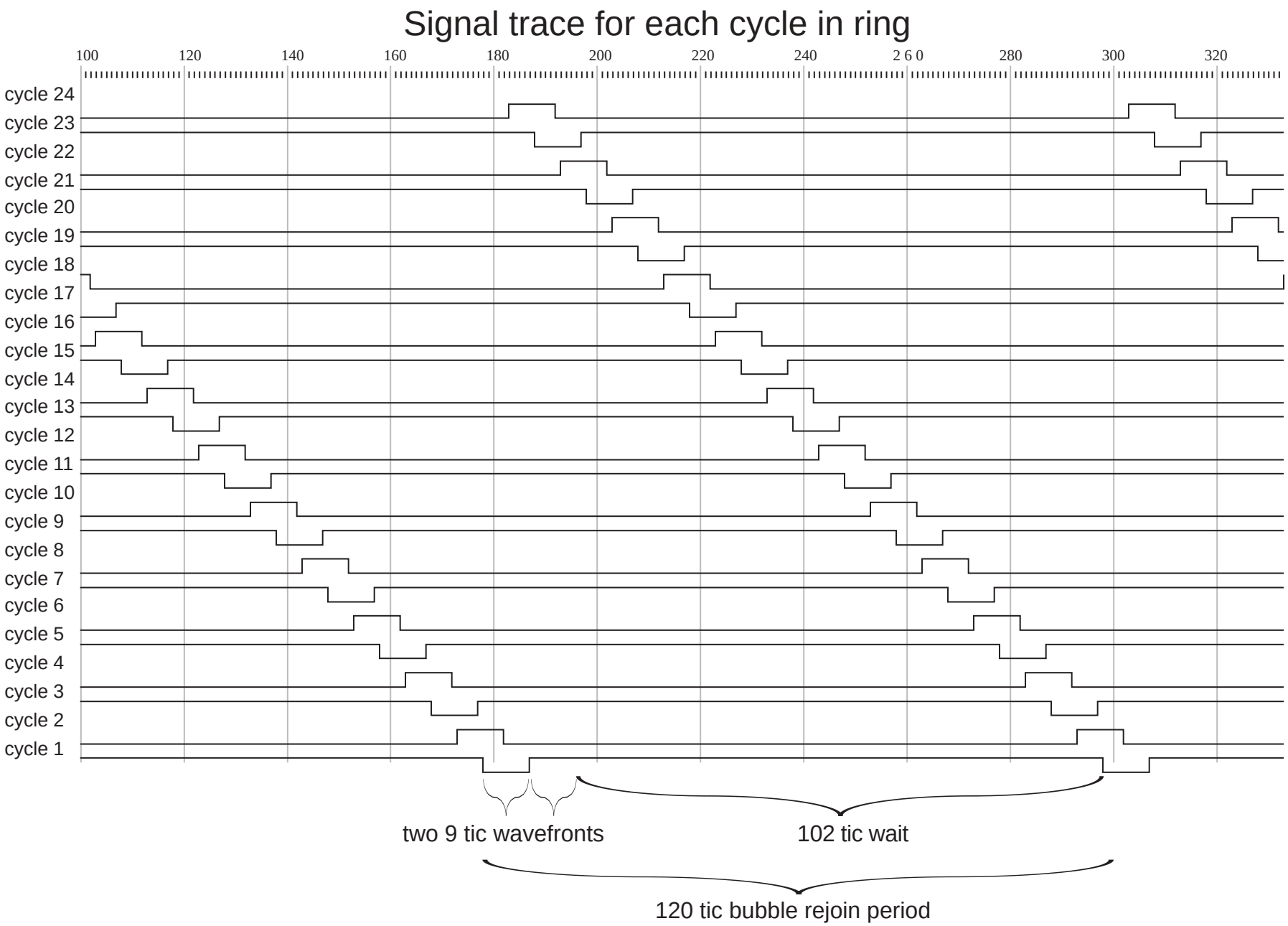



The two bubbles flowing
through the wavefronts



# Severely Bubble Limited Ring Movie twenty two wavefronts.mov

## Eleven DATA wavefronts, eleven NULL wavefronts and two bubbles

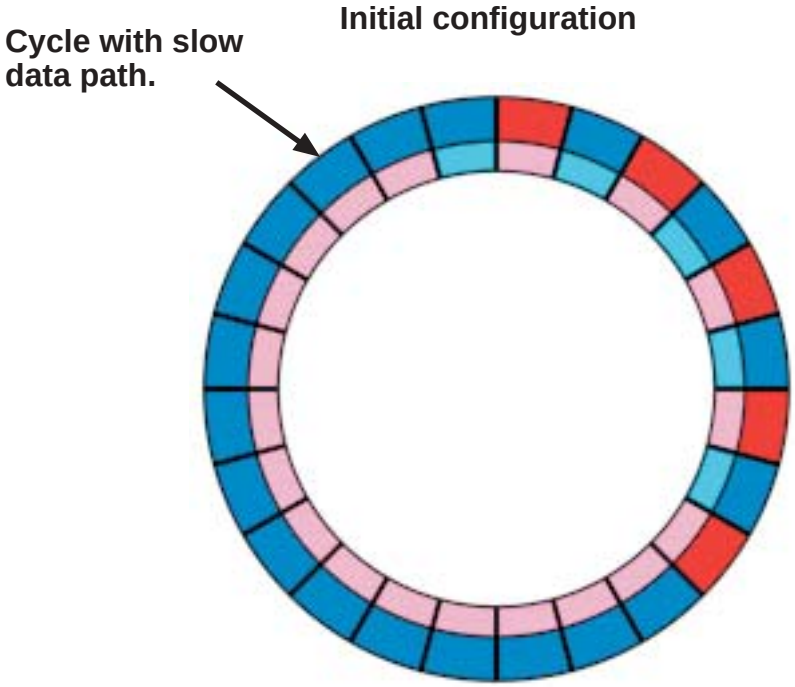


# Delay Limited Ring Movies
# delay 8.mov, delay 16.mov, delay 24.mov

## Five DATA wavefronts, five NULL wavefronts and fourteen bubbles

These rings contain one slow cycle with a data path delay of 8, 16 or 24 steps. All the other cycles in the ring have a data path delay of 4 steps. The acknowledge path delay of the slow cycle is the same as all the other cycles: 4 steps. The wavefront population period is greater than the wavefront rejoin period and the bubble population period is greater than the bubble rejoin period. Both wavefronts and bubbles are always waiting on the slow stage and the ring is delay limited.

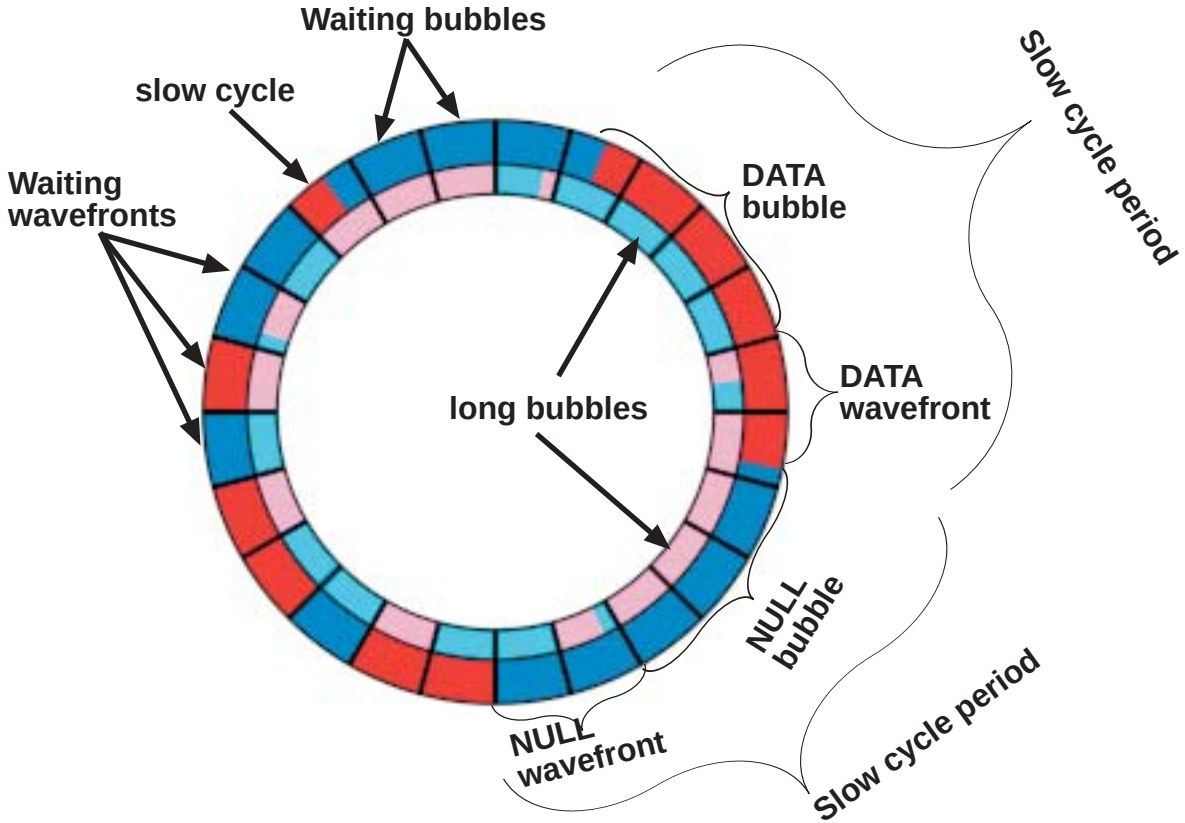
In the delay limited mode of operation the throughput of the ring is determined by this slowest cycle. An open pipeline with the same slowest cycle would deliver the same throughput.



# The Shadow of the Slow Cycle

The slow cycle transitions NULL to DATA and DATA to NULL at its cycle period. These wavefront transitions at the cycle rate are presented to the ring. A presented wavefront transition will begin freeflowing through the ring. As the wavefront flows it trails bubbles until the next wavefront transition occurs. Each wavefront/bubble stretches along the data path a delay distance equal to the period of the slow cycle. The wavefronts and bubbles bunched around the slow cycle wait on the transitions from the slow cycle.

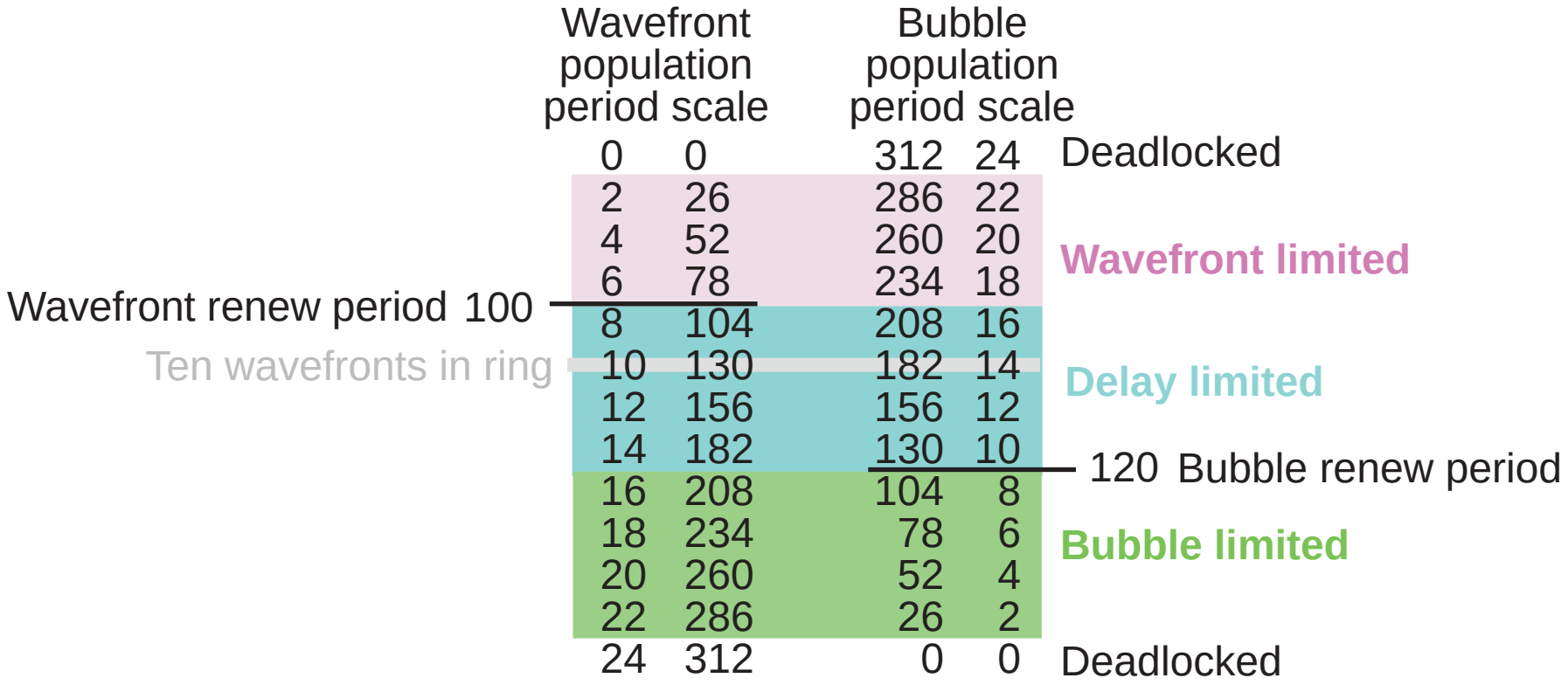
These are the effects of the shadow projected by the slow cycle. The result is that transition signals viewed in any cycle of the ring appear to be evenly distributed and of equal period.



# The Population Periods

## All Cycles not Being Equal

**If there is a slowest cycle it is possible for the ring to be neither wavefront limited nor bubble limited, but to be delay limited**




**The table represents delay 8.mov**
For slowest cycle:
Wavefront segment delay = A = 8
Bubble segment delay = B = 5
Cycle period = 13
Number of cycles in ring = N = 24
N(A + B) = range of population period = 312
W = number of wavefronts in ring
W(A + B) = wavefront population period
(N - W)(A + B) = bubble population period

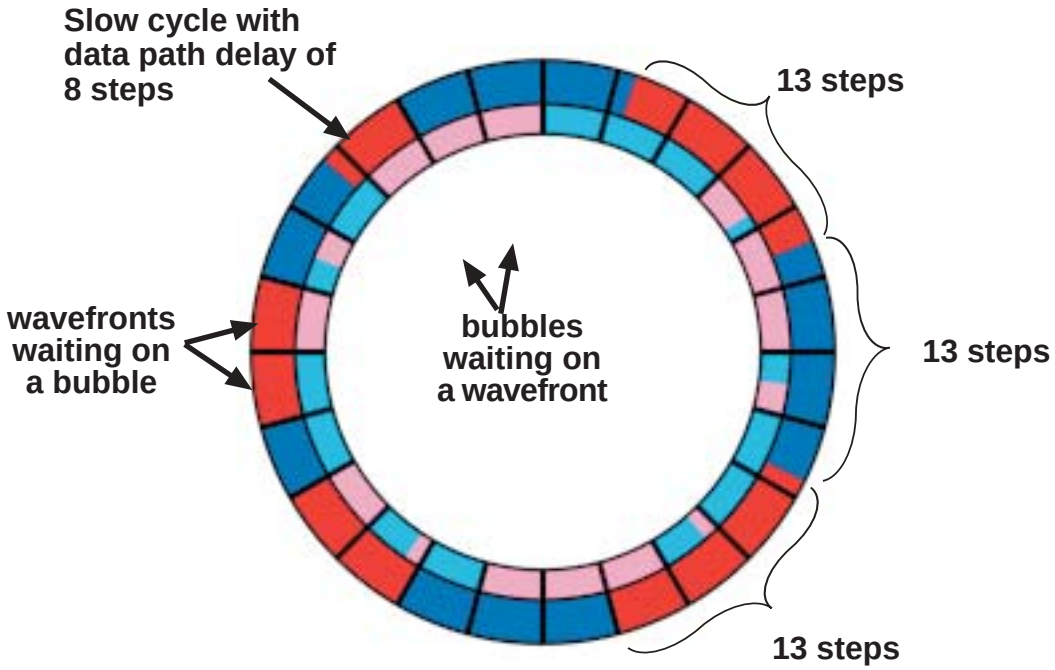
W(A + B) + (N - W)(A + B) = N(A + B) which means that the two population periods define a common line between the two population period scales

Wavefront rejoin period + bubble rejoin period < N(A + B) which means that the two rejoin periods do not define a common line between the two population period scales but are separated.

There is a range on the scale where both population periods are greater than their respective rejoin periods and the ring is neither wavefront limited nor bubble limited

# Delay Limited Ring Movie
# delay 8.mov

## Five DATA wavefronts, five NULL wavefronts and fourteen bubbles




24 cycles
10 wavefronts
24 - 10 = 14 bubbles

Slowest cycle period = 9 + 4 = 13 steps

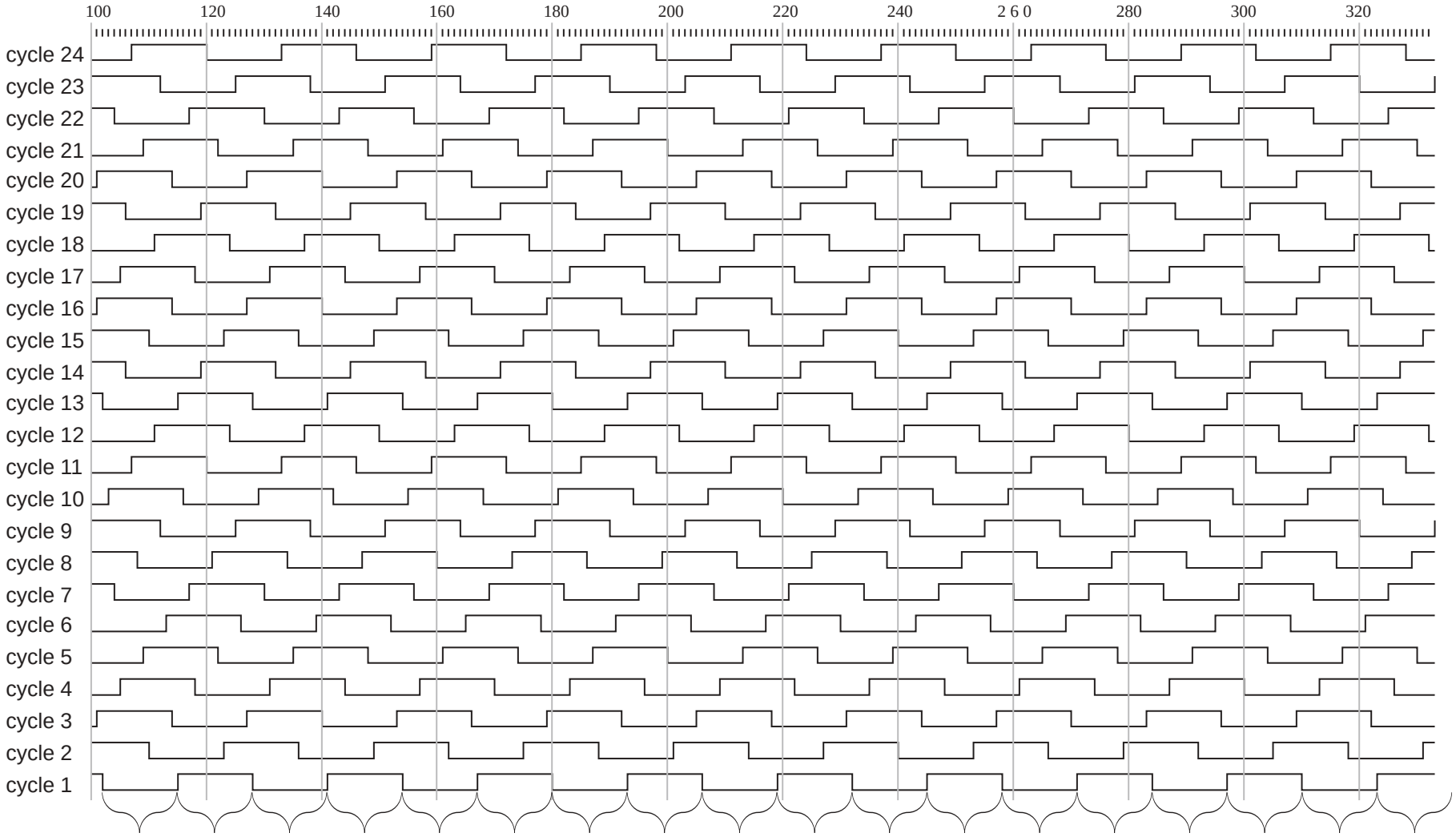
Wavefront population period = 10 * 13 = 130 steps
Wavefront rejoin period = 96 +4 = 100 steps
Bubble population period = 14 * 13 = 182 steps
Bubble rejoin period = 120 steps

Delay limited:
1 wavefront per 13 steps, 1 DATA wavefront per 26 steps

# Delay Limited Ring Movie
# delay 8.mov

## Five DATA wavefronts, five NULL wavefronts and fourteen bubbles

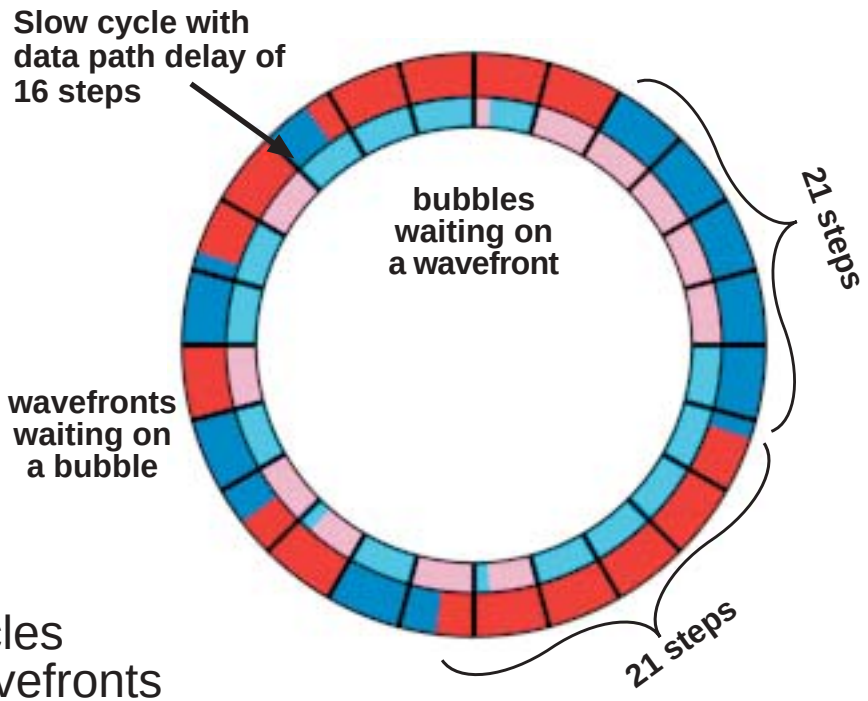
Signal trace for each cycle in ring




All wavefronts are uniformly distributed 13 tic wavefronts. There are no waiting gaps.

# More Delay Limited Ring Movie
# delay 16.mov

## Five DATA wavefronts, five NULL wavefronts and fourteen bubbles




| | | Wavefront population period scale | | Bubble population period scale | |
|---|---|---|---|---|---|
| | | 0 | 0 | 502 | 24 |
| | | 2 | 42 | 462 | 22 |
| Wavefront renew period | 108 | 4 | 84 | 420 | 20 |
| | | 6 | 126 | 378 | 18 |
| | | 8 | 168 | 336 | 16 |
| Ten wavefronts in ring | | 10 | 210 | 294 | 14 |
| | | 12 | 252 | 252 | 12 |
| | | 14 | 294 | 210 | 10 |
| | | 16 | 336 | 168 | 8 |
| Bubble renew period | 120 | 18 | 378 | 126 | 6 |
| | | 20 | 420 | 84 | 4 |
| | | 22 | 462 | 42 | 2 |
| | | 24 | 504 | 0 | 0 |

24 cycles
10 wavefronts
24 - 10 = 14 bubbles

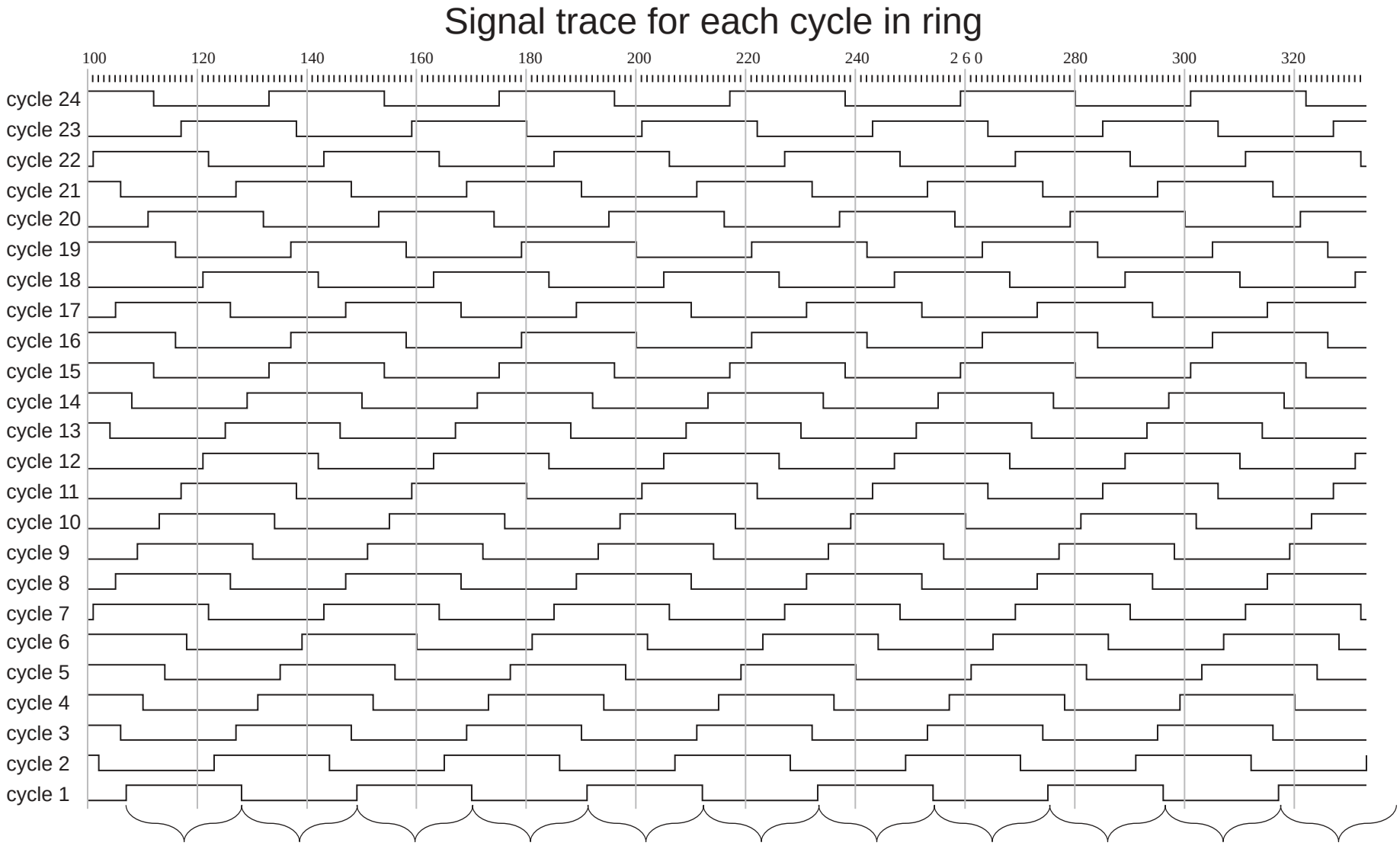
Slowest cycle period = 9 + 12 = 21 steps

Wavefront population period = 10 * 21 = 210 steps
Wavefront rejoin period = 96 +12 = 108 steps
Bubble population period = 14 * 21 = 294 steps
Bubble rejoin period = 120 steps

Delay limited:
1 wavefront per 21 steps, 1 DATA wavefront per 42 steps

# More Delay Limited Ring Movie
# delay 16.mov

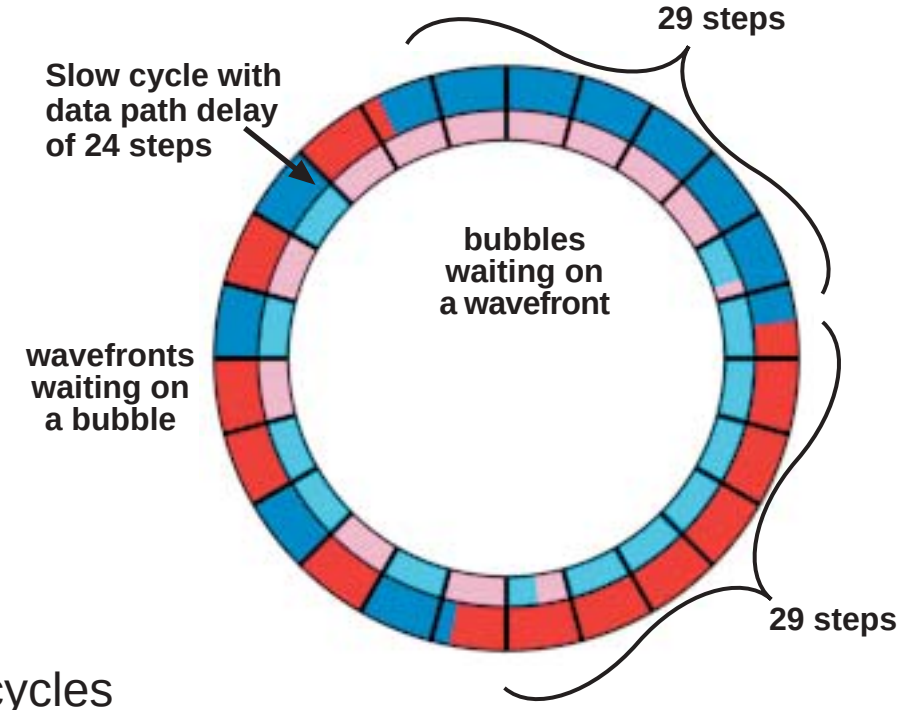
## Five DATA wavefronts, five NULL wavefronts and fourteen bubbles




All wavefronts are uniformly distributed 21 tic wavefronts. There are no waiting gaps.

# Even More Delay Limited Ring Movie
# delay 24.mov

## Five DATA wavefronts, five NULL wavefronts and fourteen bubbles




| | Wavefront population period scale | | Bubble population period scale | |
|---|---|---|---|---|
| | 0 | 0 | 696 | 24 |
| | 2 | 58 | 638 | 22 |
| Wavefront rejoin period 116 | 4 | 116 | 580 | 20 |
| | 6 | 174 | 522 | 18 |
| | 8 | 232 | 464 | 16 |
| Ten wavefronts in ring | 10 | 290 | 406 | 14 |
| | 12 | 348 | 348 | 12 |
| | 14 | 406 | 290 | 10 |
| | 16 | 464 | 232 | 8 |
| Bubble rejoin 120 period | 18 | 522 | 174 | 6 |
| | 20 | 580 | 116 | 4 |
| | 22 | 638 | 58 | 2 |
| | 24 | 696 | 0 | 0 |

24 cycles
10 wavefronts
24 - 10 = 14 bubbles

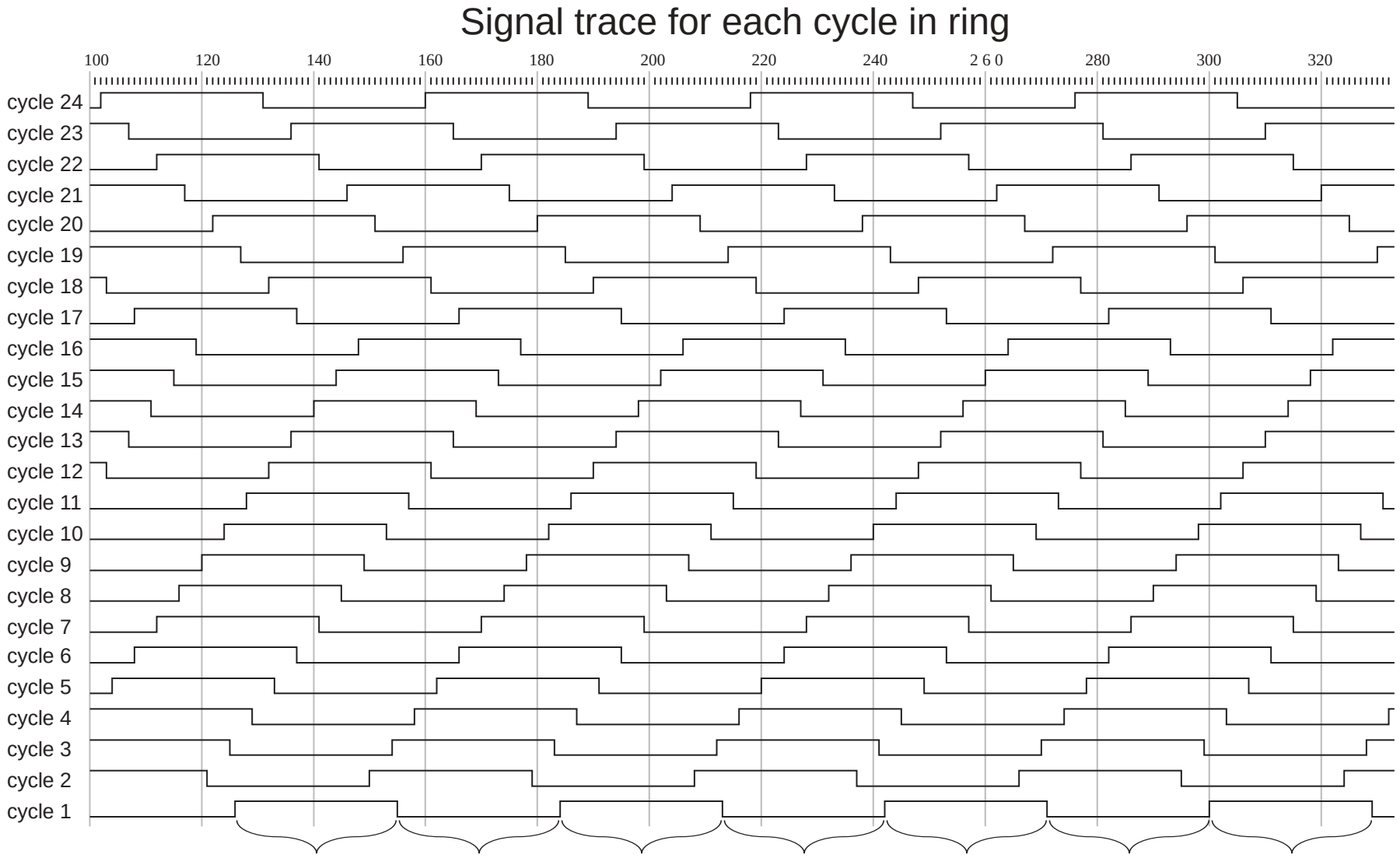
Slowest cycle period = 9 + 20 = 29 steps

Wavefront population period = 10 * 29 = 290 steps
Wavefront rejoin period = 96 +20 = 116 steps
Bubble population period = 14 * 29 = 406 steps
Bubble rejoin period = 120 steps

Delay limited:
1 wavefront per 29 steps, 1 DATA wavefront per 58 steps

# Even More Delay Limited Ring Movie
# delay 24.mov

## Five DATA wavefronts, five NULL wavefronts and fourteen bubbles

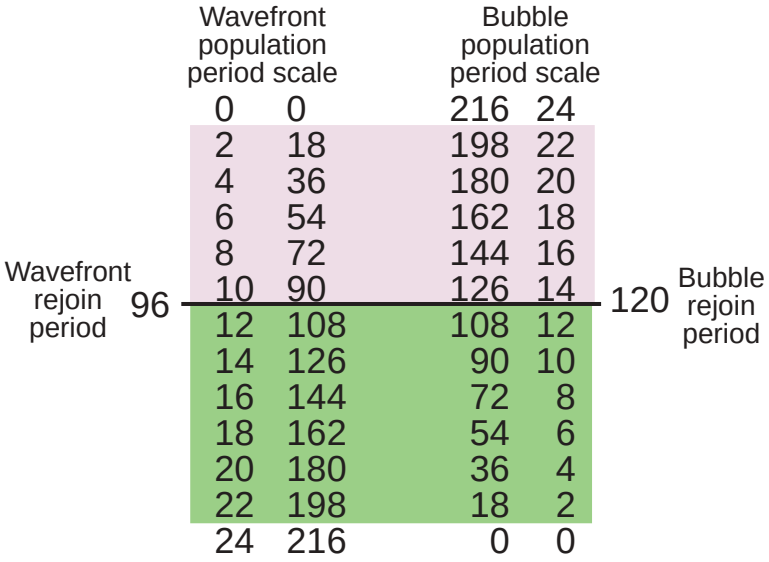



All wavefronts are uniformly distributed 29 tic wavefronts. There are no waiting gaps.

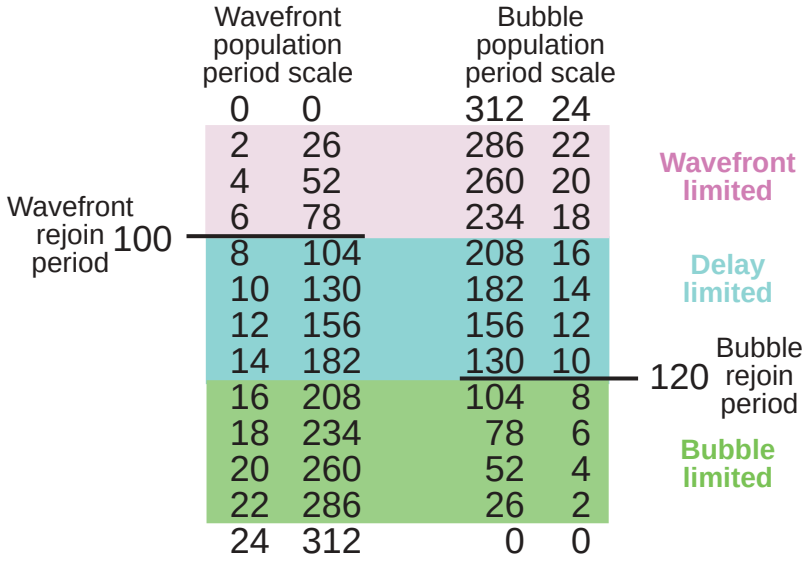
# The Rejoin Periods Again

## It is not possible for any ring to be both wavefront limited and bubble limited

### All cycles equal




### A slowest cycle




With all cycles equal the rejoin periods are coincident on the population period scales. With a slowest cycle the rejoin periods separate and leave a gap in the population period scales where the ring is neither wavefront limited nor bubble limited.

Since the population period scales are generated with a slowest cycle period it is not possible for the rejoin periods to overlap in relation to the population period scale.The population period scale will never be generated for a fastest cycle because fast cycles are shadowed by slower cycles and never determine pipeline behavior.

A ring can never be both wavefront limited and bubble limited. Every cycle in a ring contains either a wavefront or a bubble. No cycle can be empty of both and waiting on both.

# Throughput graphs for movie rings

The throughput profiles for each ring configuration in the movies. Each movie represents the indicated performance point on the graph.