Presentation Slides

Chapter 13

Interacting Pipeline Structures

Logically Determined Design:

Clockless System Design With NULL Convention Logic

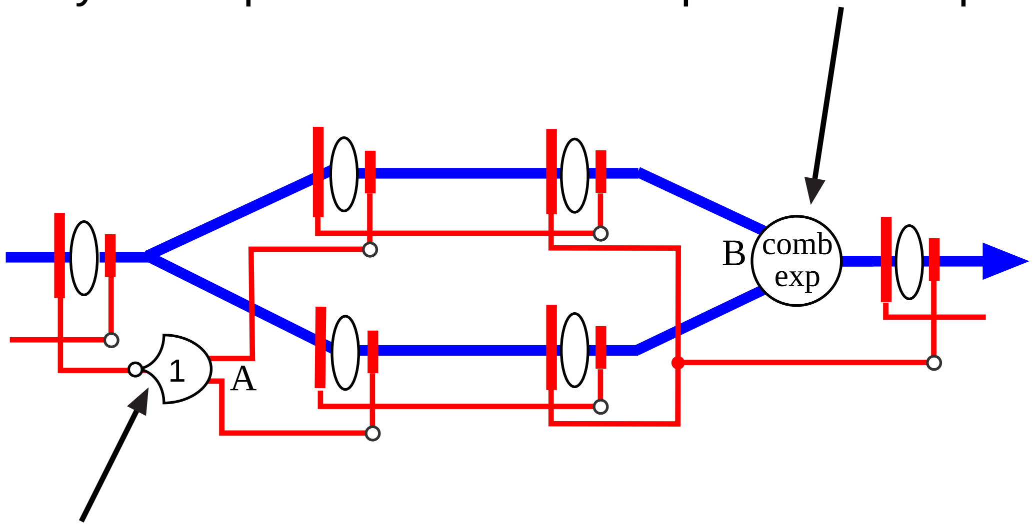
by Karl Fant

John Wiley & Sons, Inc.

A Two Pipeline Structure

The pipelines form a closed structure with two points of coordination: The fan-out and the fan-in

Fan-in is coordinated by a completeness relationship in the data path.



Fan-out is coordinated by a completeness relationships in the acknowledge path.

The behavior of the structure is limited by the structure itself.

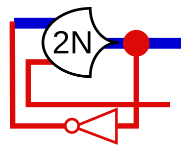
Auto Produce and Auto Consume

The auto consume and auto produce provide a steady stream of input and output behaviors to drive the behavior of pipeline structures. If they cycle faster than any other cycle in a pipeline structure, they will not cast shadows into the structure and so will not affect the inherent throughput behavior of the structure.

The auto cycles allow the isolated analysis of the inherent throughput behavior of a pipeline structure.

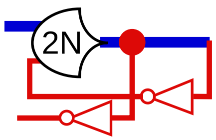
The auto produce cycle will produce a wavefront and consume a bubble every time a bubble flows into the cycle.

auto
produce
cycle



The auto consume cycle will consume a wavefront and produce a bubble every time a wavefront flows into the cycle.

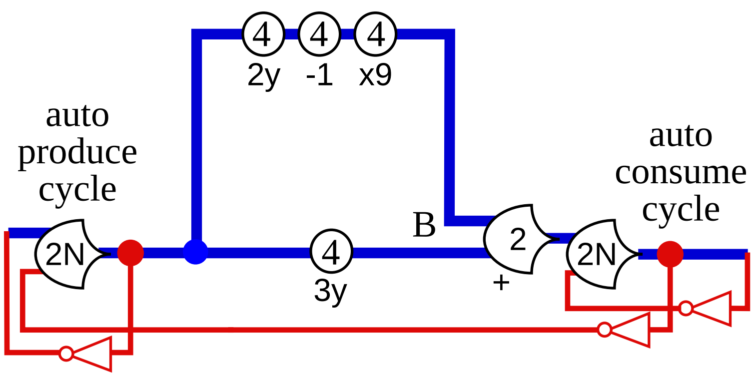
auto
consume
cycle

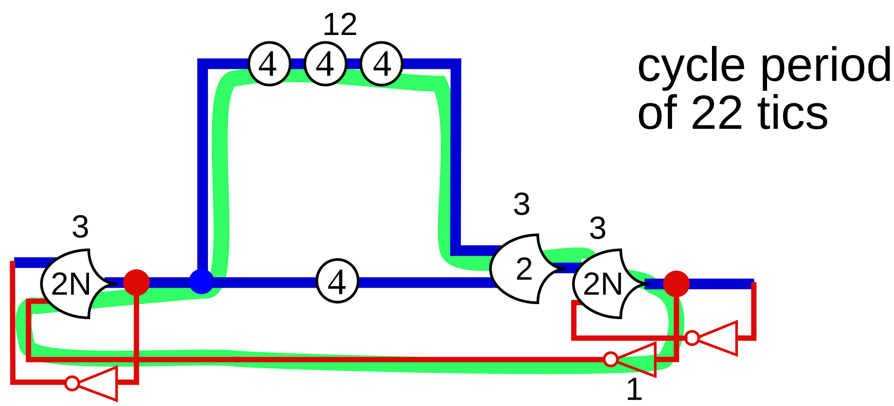


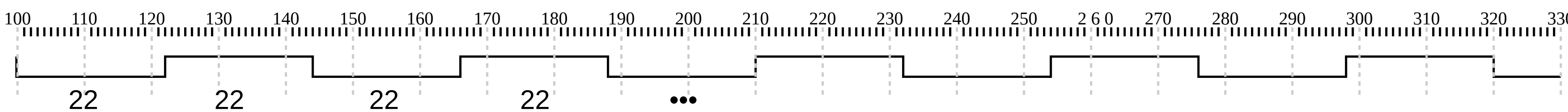
Example 1

The throughput of this example is determined by the slowest path which in this case is the upper path. The cycle period of the structure is 22 tics. The throughput is one wavefront every 22 tics. In analyzing throughput individual wavefronts are considered regardless of whether they are data or NULL. Data wavefront throughput will be 1/2 the wavefront throughput. In this case, one data wavefront every 44 tics.

F = 9(2y - 1) + 3y







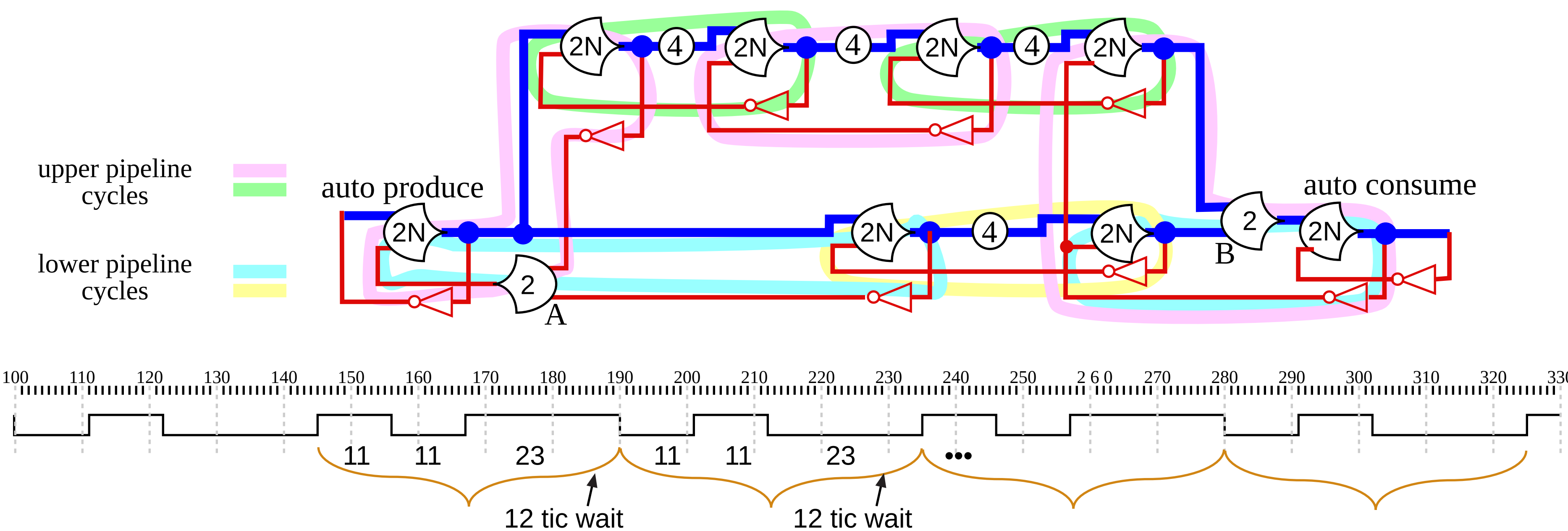
The timing diagrams are in terms of simulation tics.

Each NCL operator has a delay of 3 tics for both data and NULL. Functions have the delay indicated in the circle. The circuit has a throughput of 1 wavefront every 22 tics or 4.55 wavefronts per 100 tics.

Finer Grained Pipelining

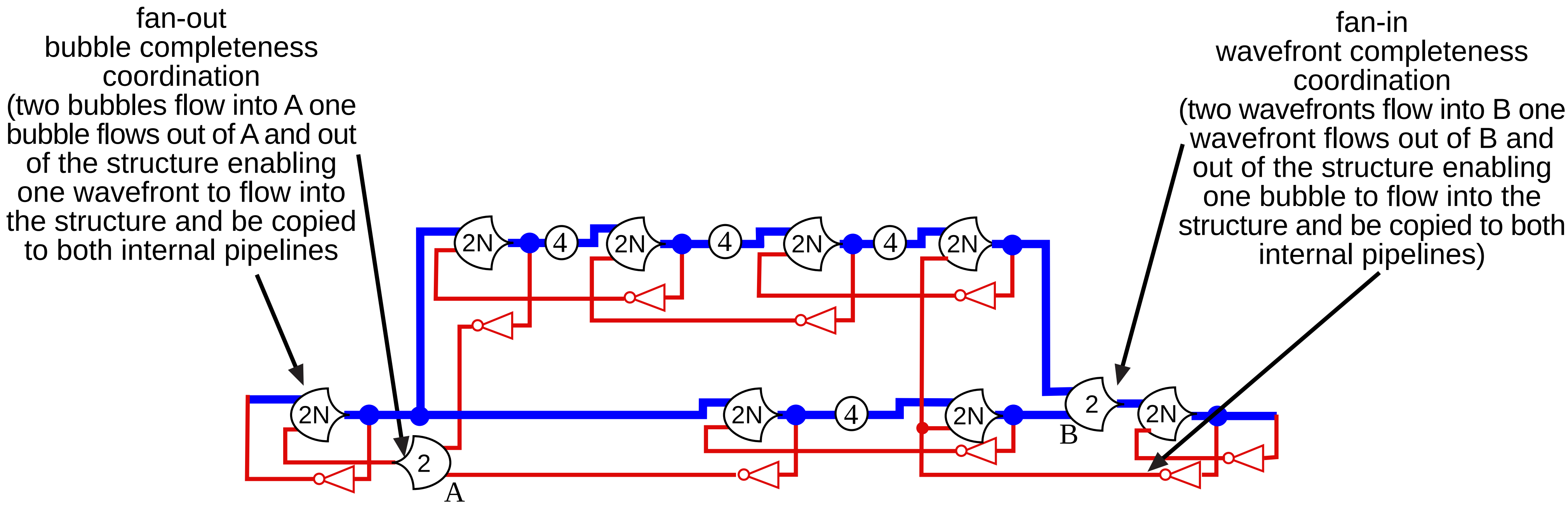
Pipelining the upper and lower data paths with a cycle per function results in a pipeline structure with an upper pipeline of five cycles and a lower pipeline of three cyclesThe pipelining has not changed the functionality of the expression but what is the throughput of the structure now?

From simulation: The structure produces a repeating period of three wavefronts every 45 tics or 6.67 wavefronts per 100 tics.



Why does it behave this way? Can the throughput be enhanced by adding buffer cycles to one of the pipelines? If so which pipeline, how many cycles and where in the pipeline should they be placed?

Basics of Wavefront Flow



For each wavefront that flows out of a pipeline a bubble flows in.

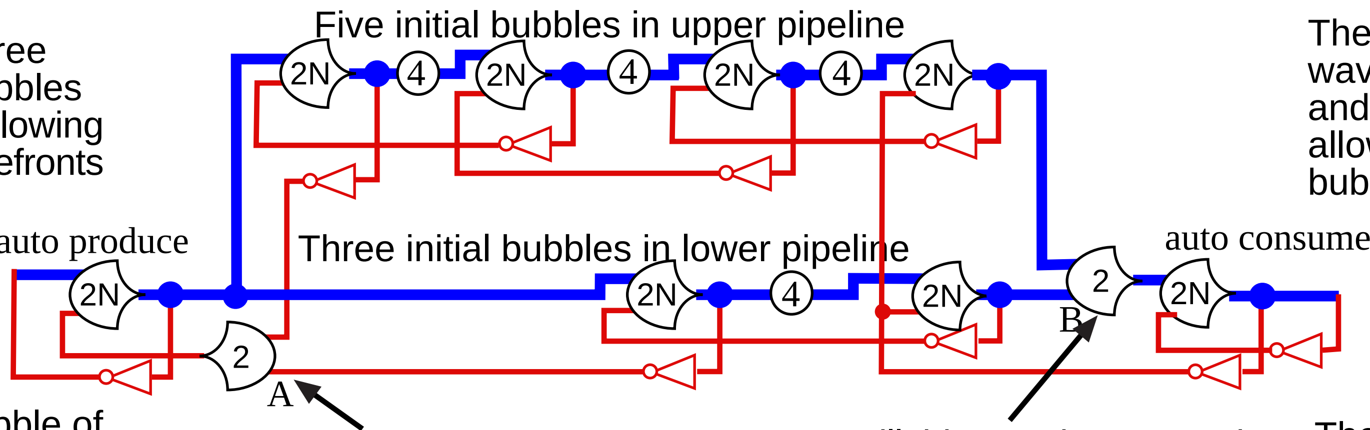
For each bubble that flows out of a pipeline a wavefront flows in.

The quantity of bubbles plus wavefronts in each pipeline will always be a constant equal to the number of cycles in the pipeline.

Flow Behavior of Structure

Initially three paired bubbles flow out allowing three wavefronts to flow in.

The three initial wavefronts pair and flow out allowing three bubbles to flow in.



The fourth bubble of the lower pipeline that will pair with the fourth bubble of the upper pipeline will be a new bubble that enters the structure when the first wavefront flows out of the structure.

Will this gate have to wait on the fourth bubble?

Will the population of 3 bubbles in the lower pipeline flow out of the structure before a new bubble can flow into the structure and catch up with the population?

Will this gate have to wait on the fourth wavefront?

Will the population of 3 wavefronts in both pipelines flow out of the structure before a new wavefront can flow into the structure and catch up with the population?

The fourth wavefront allowed into the system will be allowed into the structure by the fourth bubble pairing at A.

How quickly a population of wavefronts or bubbles can flow out of the structure we will call the population period. The wavefront renewal period is the time it takes for a bubble to flow from output to input, allow a wavefront in and for that wavefront to flow to the output. The bubble renewal period is the time it takes for a wavefront to flow from input to output, allow a bubble in and for that bubble to flow to the input.

A renewal period less than the population period = maximal throughput.

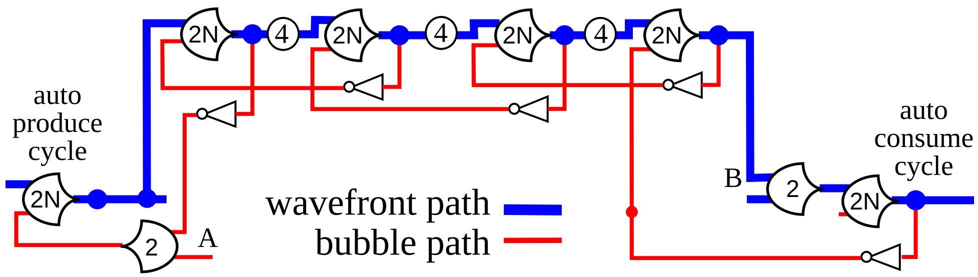
A renewal period greater than the population period < maximal throughput.

Each pipeline has a population of bubbles and wavefronts and each population has a path through the structure for member renewal.

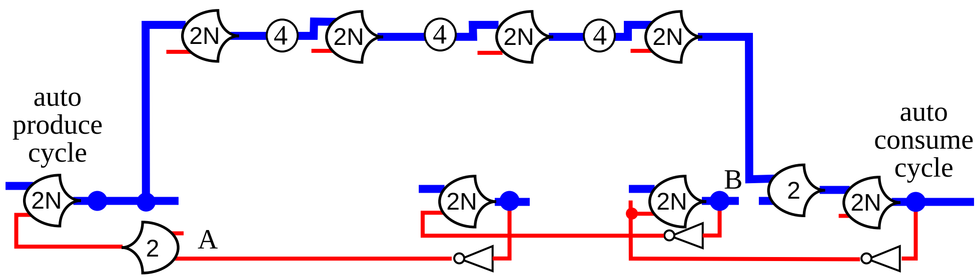
The Four Possible Renewal Paths

The renewal period for each population is determined by the renewal path for each population. A renewal path is a ring with two segments. The first segment is the path of the element that is going to allow the population member into the structure (Bubbles allow wavefronts and wavefronts allow bubbles) that causes a delay at the entry point A or B. The second segment is the path of the population itself.

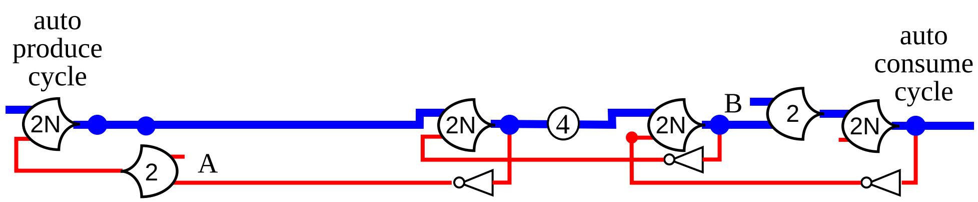
a. Upper wavefront path with upper bubble path.



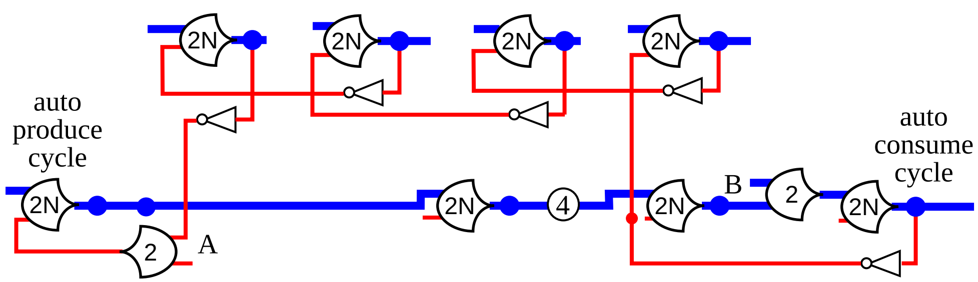
b. Upper wavefront path with lower bubble path.



c. Lower wavefront path with lower bubble path.



d. Lower wavefront path with upper bubble path.



For the example structure there are always bubbles in the upper bubble path presented to A so any wait at A will occur in the lower bubble path.

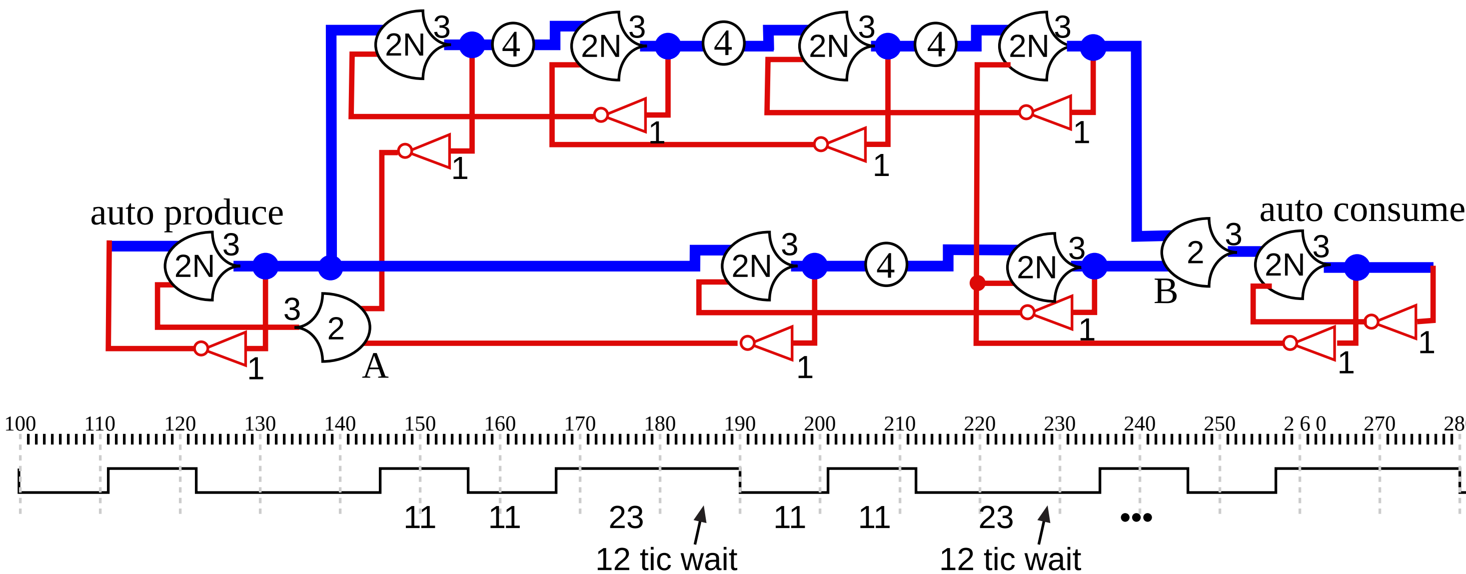
The upper wavefront path has the longest delay so any wait at B will be for a wavefront from the upper path.

So the first segment renewal paths for the example are

Flow Analysis of Structure

Each population period is the population times the slowest cycle period of the structure which for this example is 11 tics.

Simulations for example 1 in: NCL sims/pipeline structs/dual pipeline studies a.ckt
Simulations for example 1 in: NCL sims/pipeline structs/dual pipeline studies c.ckt



Static delays

upper wavefront path 33
Longest delay

upper bubble path 20

lower wavefront path 19

lower bubble path 12
Smallest population

Structure behavior table

Each renewal path has a Renewal period but the longest ones are operative ones.

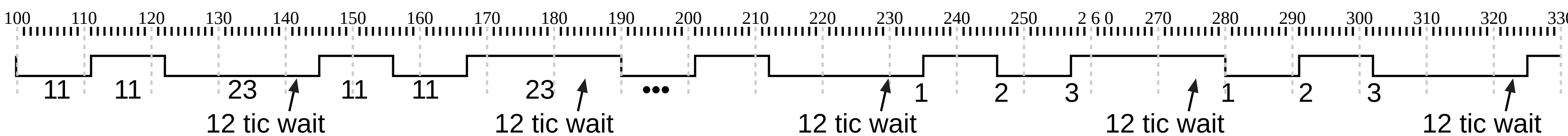
	bubble flow	wavefront flow	
The bubble population off the renewal path	Upper bubble population = 5 population period = 55 tics renewal period = 53		renewal period 53
both populations on the renewal path	Lower bubble population = 3 population period = 33 tics renewal period = 45	Upper wavefront population = 3 population period = 33 tics renewal period = 45	renewal period 45
The wavefront population off the renewal path		Lower wavefront population = 3 population period = 33 tics renewal period = 31	renewal period 31
			renewal period 29

Behavior Summary

Three bubbles will flow out of the input and three wavefronts will flow in through A in 33 tics. The time it takes for the first wavefront to flow out and a fourth bubble to flow to A is 45 tics. So A will wait 12 tics for the fourth bubble to arrive.

The three wavefronts will flow out of the output and three bubbles will flow in through B in 33 tics. The time it takes for the first renewal bubble (fourth bubble) to flow in and a fourth wavefront to flow to B is 45 tics. So B will wait 12 tics for a fourth wavefront to arrive.

The result is groups of three wavefronts flowing through the structure every 45 tics.



The slowest cycle period of the structure is 11 tics so the maximal throughput of the structure would be one wavefront every 11 tics or 9.09 wavefronts every 100 tics. The current throughput is three wavefronts every 45 tics or 6.67 wavefronts every 100 tics. This is an improvement on the baseline of 4.55 wavefronts every 100 tics. But can we do better?

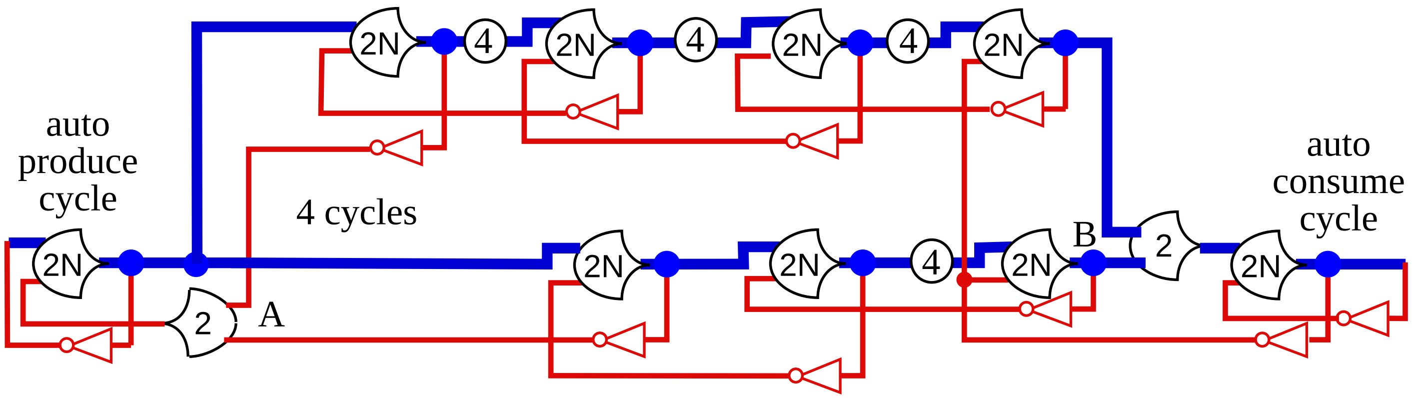
The throughput optimization goal is to make all renewal periods less than or equal to their population periods so that renewals will catch up with their populations without waiting.

We can either increase the population periods or decrease the renewal periods.

Adding Buffer Cycles: 4 Cycles

Adding buffer cycles can increase populations and hence population periods.

If there are four cycles in the lower pipeline the structure will allow four wavefronts into the structure before wavefront renewal is required. The wavefront population is now 4 wavefronts and the population period for wavefronts and bubbles in the lower pipeline is 44 tics.



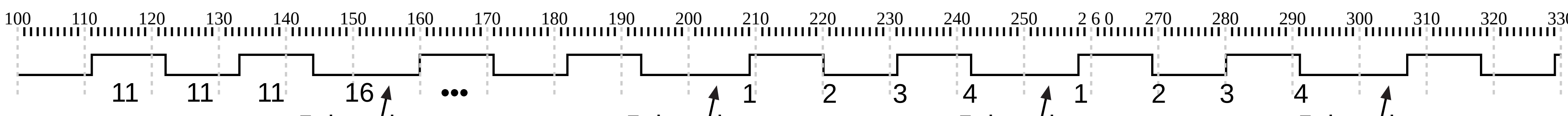
Static delays

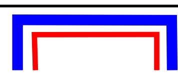
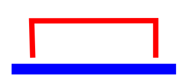
upper wavefront path 33
Longest delay

upper bubble path 20

lower wavefront path 22

lower bubble path 16
Smallest population

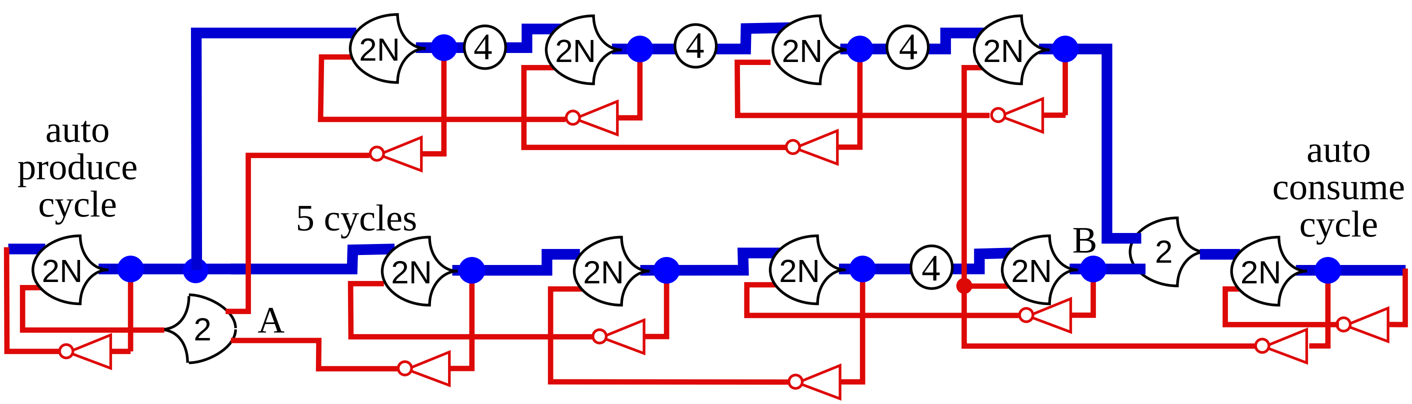


bubble flow		wavefront flow
Upper bubble population = 5 population period = 55 tics renewal period = 53		
Lower bubble population = 4 population period = 44 tics renewal period = 49		Upper wavefront population = 4 population period = 44 tics renewal period = 49
		Lower wavefront population = 4 population period = 44 tics renewal period = 38
		

Notice that the population period increased by 11 and the renewal period only increased by 4 and we are down to a 5 tic wait

Adding Buffer Cycles: 5 Cycles

If there are five cycles in the lower pipeline the structure the five initial bubbles will allow five wavefronts into the structure before bubble renewal is required. The wavefront population is now 5 wavefronts and the population period for both wavefronts and bubbles for both pipelines is 55 tics which overtakes the renewal period of 53 tics. There are no waits at either A or B.



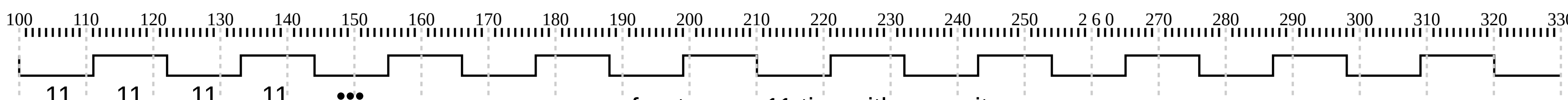
Static delays

upper wavefront path 33
Longest delay

upper bubble path 20
Equal population and delay

lower wavefront path 25

lower bubble path 20
Equal population and delay

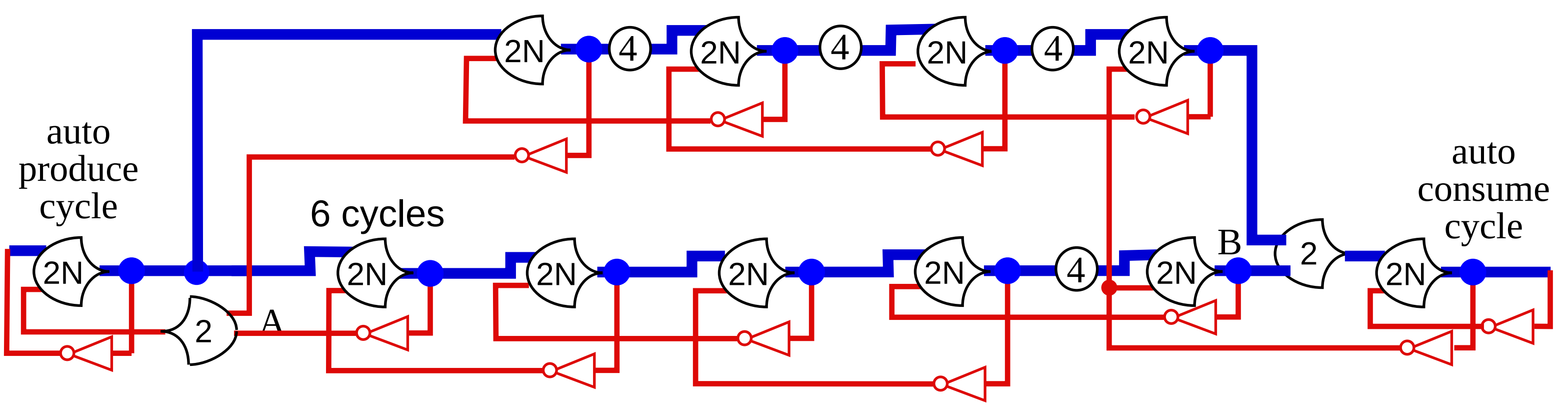


bubble flow	wavefront flow
Upper bubble population = 5 population period = 55 tics renewal period = 53	Upper wavefront population = 5 population period = 55 tics renewal period = 53
Lower bubble population = 5 population period = 55 tics renewal period = 53	Upper wavefront population = 5 population period = 55 tics renewal period = 53
Lower bubble population = 5 population period = 55 tics renewal period = 45	Lower wavefront population = 5 population period = 55 tics renewal period = 45
Upper bubble population = 5 population period = 55 tics renewal period = 45	Lower wavefront population = 5 population period = 55 tics renewal period = 45

All population periods are now greater than their renewal periods.

Adding Buffer Cycles: 6 Cycles

As we add cycles to the lower pipeline the upper pipeline becomes the one with the smallest bubble population. It will limit the wavefront population to 5 and it will cause a bubble wait at A. So the upper bubble path becomes the bubble component of the renewal path.



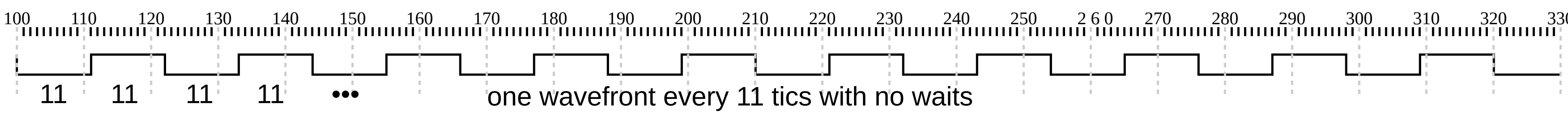
Static delays

upper wavefront path 33
Longest delay

upper bubble path 20
Smallest population

lower wavefront path 28

lower bubble path 24



bubble flow

wavefront flow

Upper bubble population = 5
population period = 55 tics
renewal period = 53

Upper wavefront population = 5
population period = 55 tics
renewal period = 53

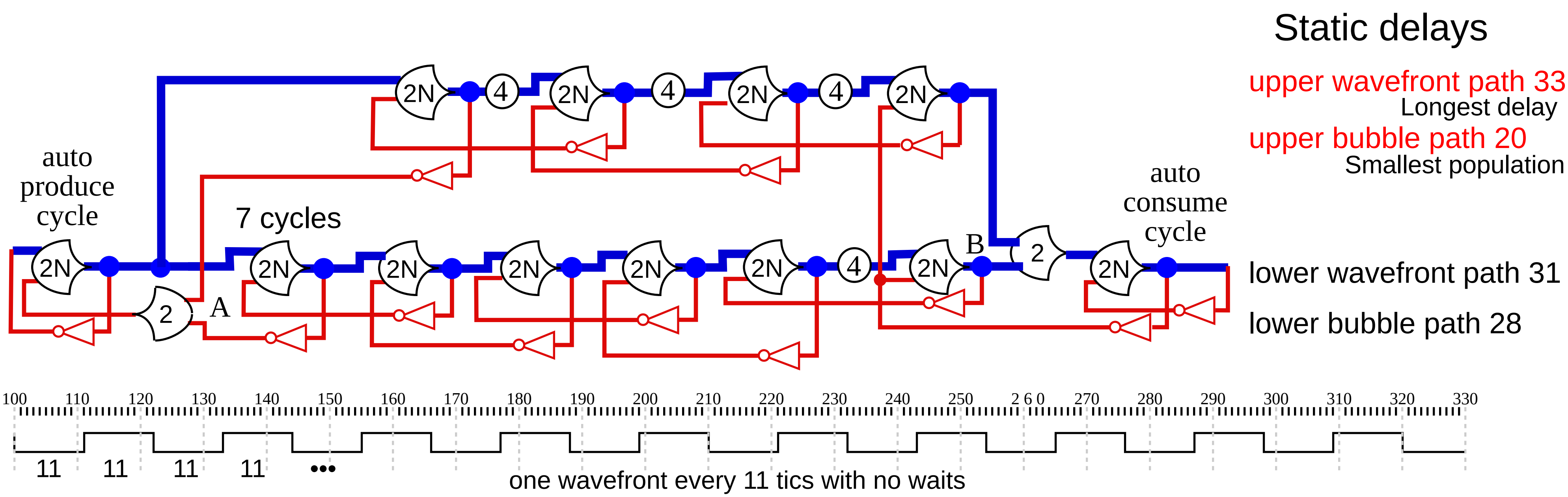
Lower bubble population = 6
population period = 66 tics
renewal period = 57

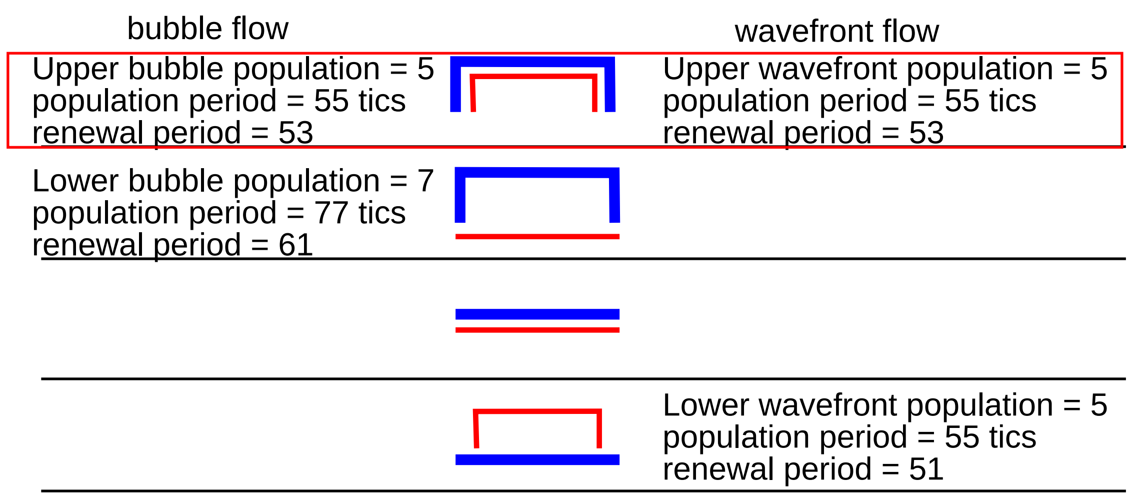
Lower wavefront population = 5
population period = 55 tics
renewal period = 48

All population periods remain greater than their renewal periods.

Adding Buffer Cycles: 7 Cycles

With seven cycles in the lower pipeline the upper wavefront path remains the longest wavefront delay and the upper bubble path with the smallest bubble population causing the bubble wait at A. The wavefront population remains 5 wavefronts.

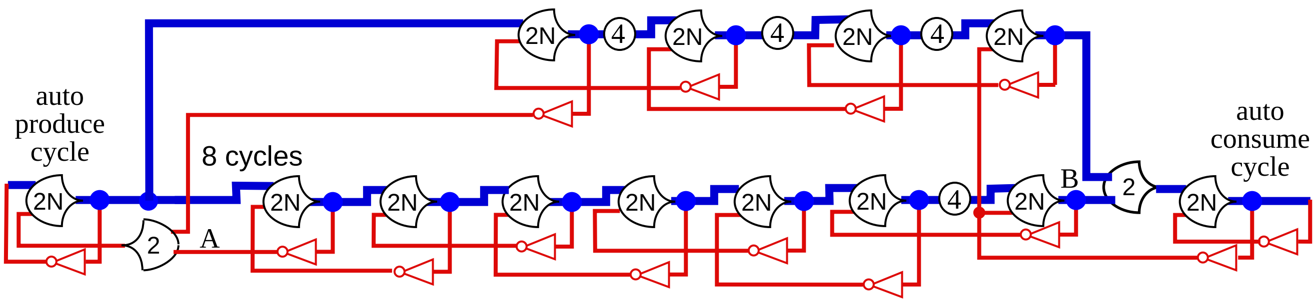




All population periods remain greater than their renewal periods.

Adding Buffer Cycles: 8 Cycles

With eight cycles in the lower pipeline the lower wavefront path becomes the longest wavefront delay causing a wait at B and the upper bubble path still causes the bubble wait at A. The wavefront population remains 5 wavefronts.



Static delays

upper wavefront path 33

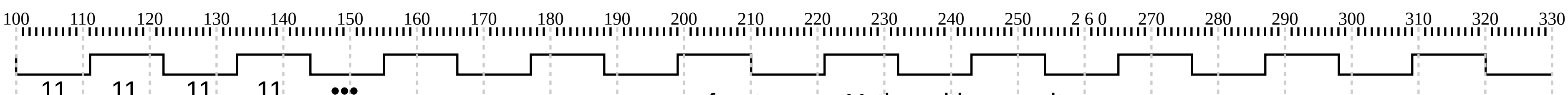
upper bubble path 20

Smallest population

lower wavefront path 34

Longest delay

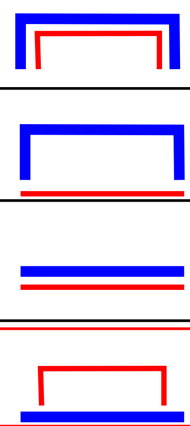
lower bubble path 32



one wavefront every 11 tics with no waits

bubble flow

wavefront flow



Upper wavefront population = 5
population period = 55 tics
renewal period = 53

renewal period 53

renewal period 65

Lower bubble population = 8
population period = 88 tics
renewal period = 66

renewal period 66

Upper bubble population = 5
population period = 55 tics
renewal period = 54

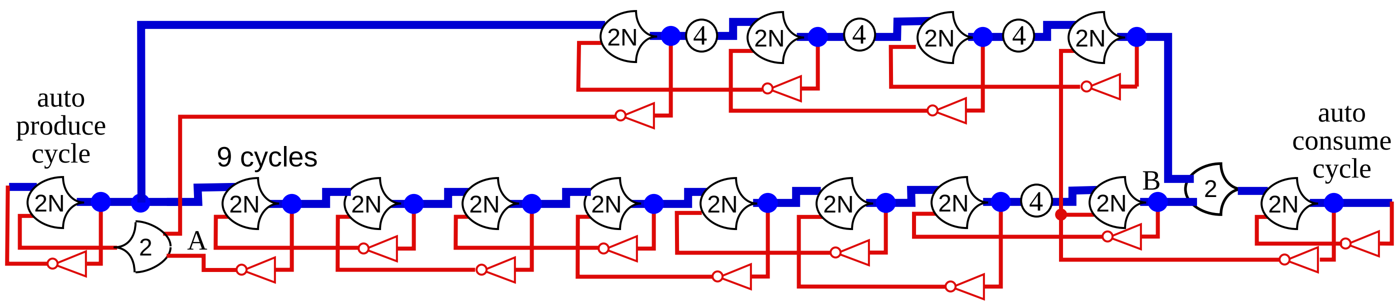
Lower wavefront population = 5
population period = 55 tics
renewal period = 54

renewal period 54

All population periods remain greater than their renewal periods.

Adding Buffer Cycles: 9 Cycles

With nine cycles in the lower pipeline renewal periods of 57 tics overtake the population periods of 55 tics and a 2 tic wait every five wavefronts appears in the throughput of the structure.



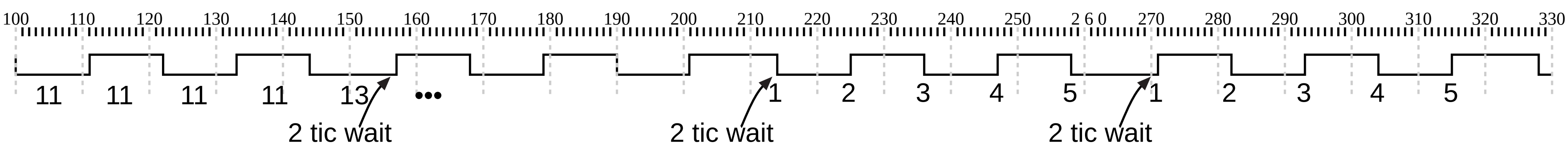
Static delays

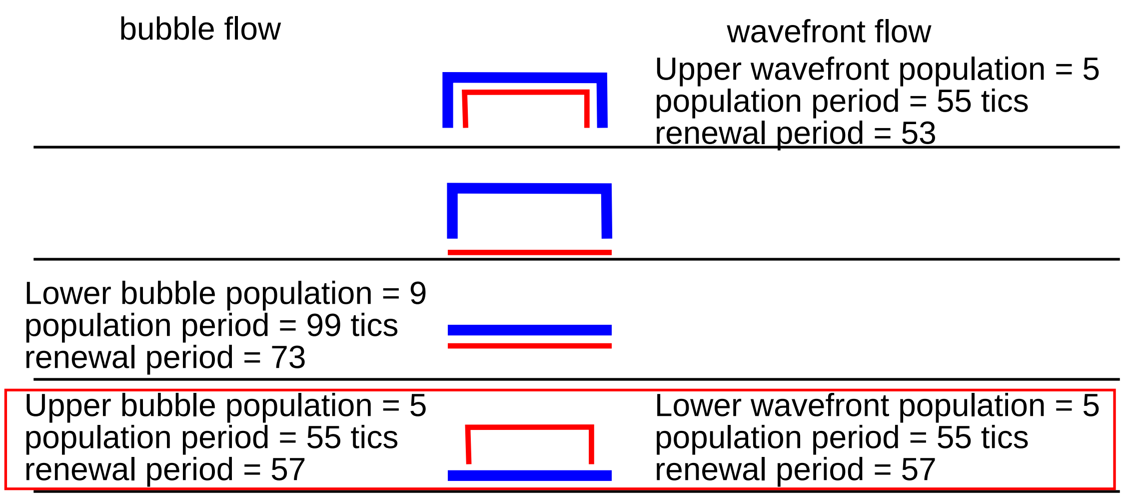
upper wavefront path 33

upper bubble path 20
Smallest population

lower wavefront path 37
Longest delay

lower bubble path 36

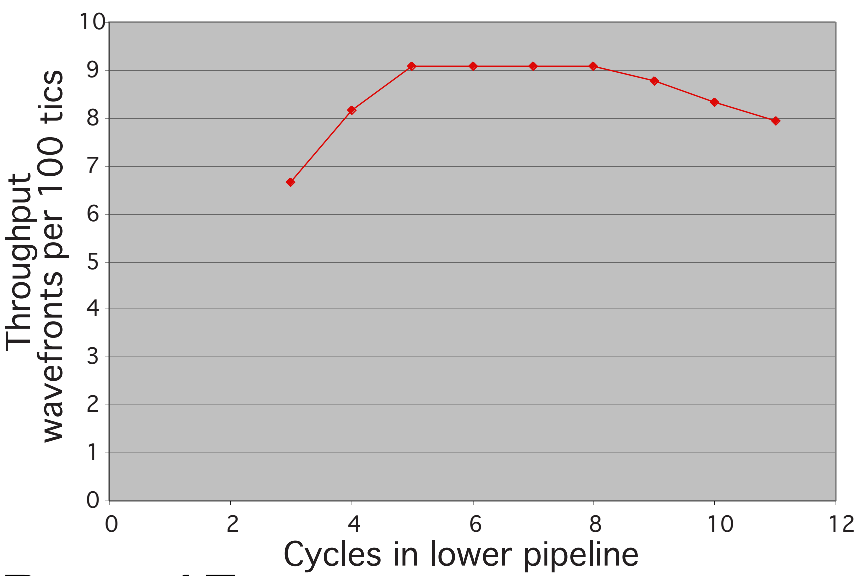


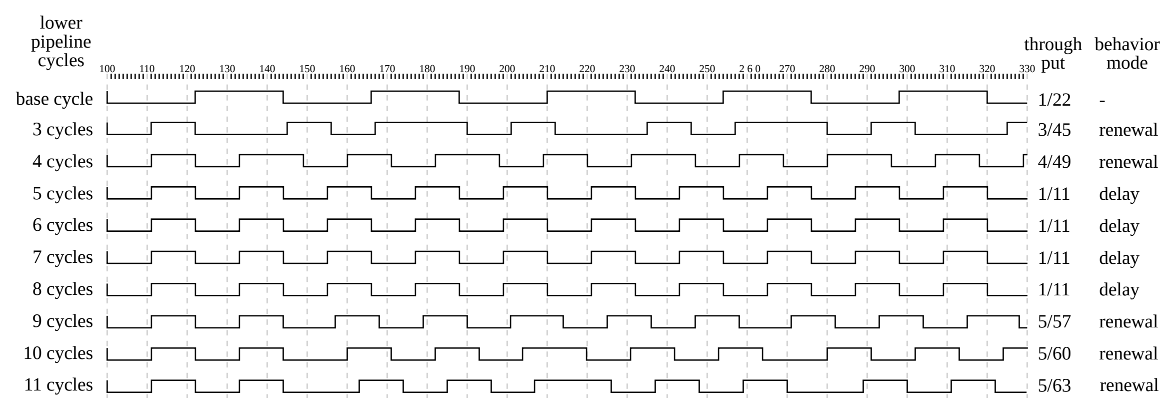


Some population periods fall behind their renewal periods.

Example 1 Summary

Cycles in lower pipeline	Limiting cycle period	Relevant population period	Relevant renewal period	Throughput waves/ period	Throughput waves/ 100 tics	Limiting behavior mode
base	22	-	-	1/22	4.55	-
3	11	33	45	3/45	6.67	renewal
4	11	44	49	4/49	8.16	renewal
5	11	55	53	1/11	9.09	delay
6	11	55	53	1/11	9.09	delay
7	11	55	53	1/11	9.09	delay
8	11	55	53	1/11	9.09	delay
9	11	55	57	5/57	8.77	renewal
10	11	55	60	5/60	8.33	renewal
11	11	55	63	5/63	7.94	renewal

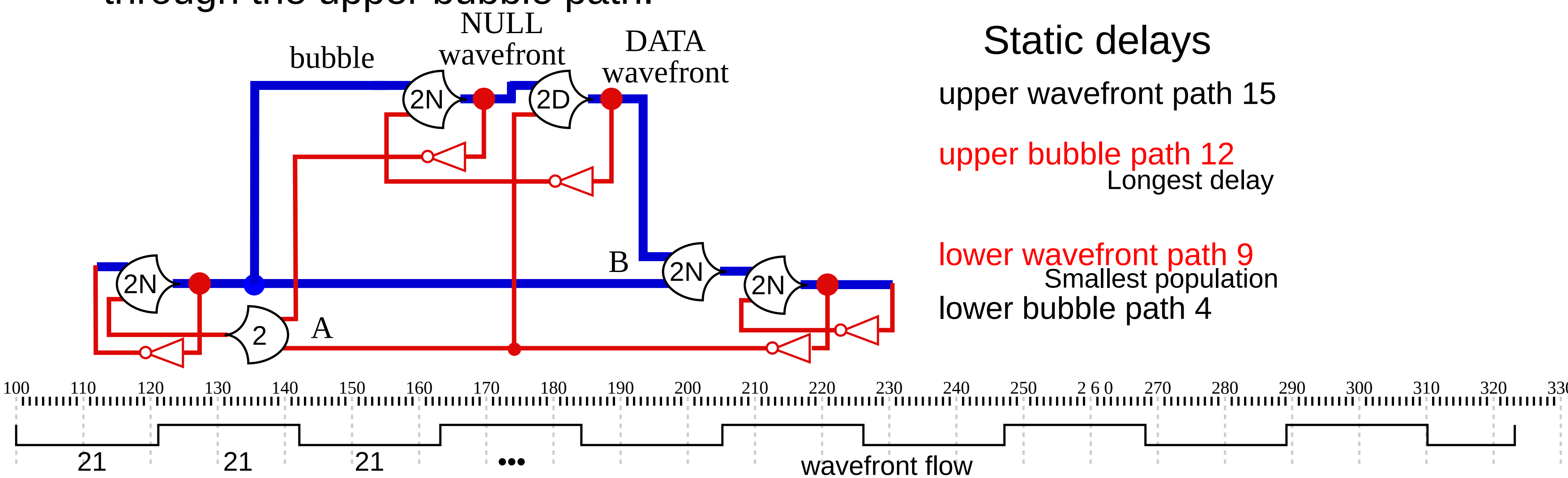




Example 2: Pipeline Delay

The upper pipeline is initialized with two wavefronts and one bubble. When a current wavefront enters the structure it is copied to both pipelines. It joins the population in the upper pipeline and combines at B with the front wavefront from the upper pipeline which is two wavefronts or one data wavefront previous to the current wavefront.

The slowest cycle is the cycle of the lower pipeline which is 13 tics. There are always wavefronts from the upper wavefront path presented to B so any wait at B will occur through the lower wavefront path. The bubble population in each pipeline is one and the upper bubble path is longer than the lower bubble path so any wait at A will occur through the upper bubble path.



Static delays

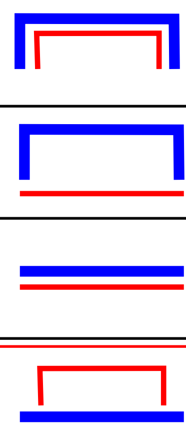
upper wavefront path 15

upper bubble path 12
Longest delay

lower wavefront path 9
Smallest population

lower bubble path 4

bubble flow



Upper wavefront population = 3
population period = 39 tics
renewal period = 27

Lower bubble population = 1
population period = 13 tics
renewal period = 13

Upper bubble population = 1
population period = 13 tics
renewal period = 21

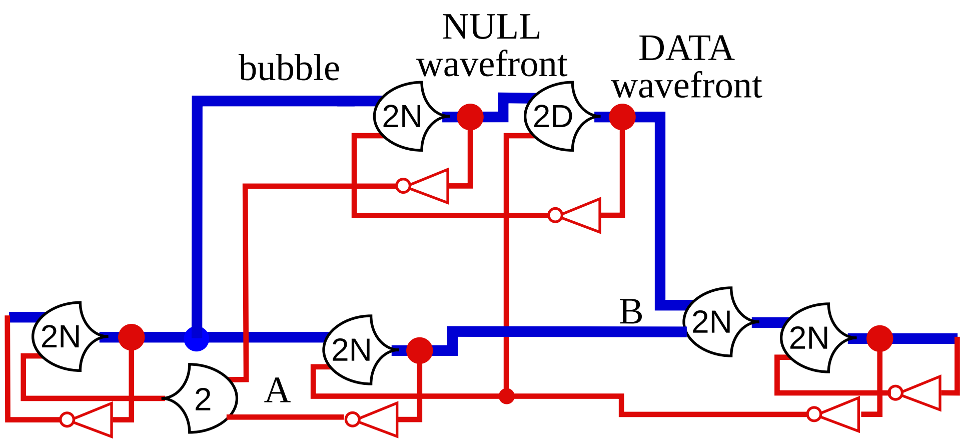
Lower wavefront population = 1
population period = 13 tics
renewal period = 21

The throughput is 1 wavefront every 21 tics.

Try Buffering Lower Pipeline

It is not immediately obvious where to add a cycle to enhance the throughput. We first attempt to add a cycle to the lower pipeline which divides the lower pipeline into two cycles each with a period of 10 tics so the slowest cycle period in the structure is now 10 tics.

Because of the one bubble in the upper pipeline there can still only be one wavefront at a time in the lower pipeline and now causes a wait at A because it is the smallest bubble population. The behavior of the structure remains renewal limited with a throughput of 1 wavefront every 24 tics which is a slower throughput than the initial configuration.



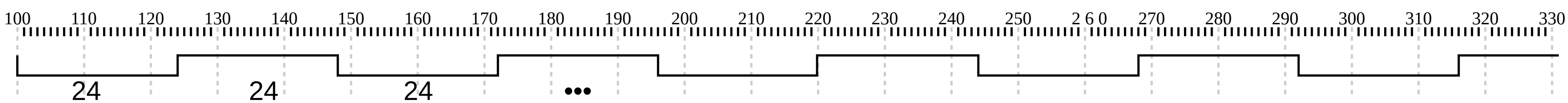
Static delays

upper wavefront path 15

upper bubble path 12
Longest delay

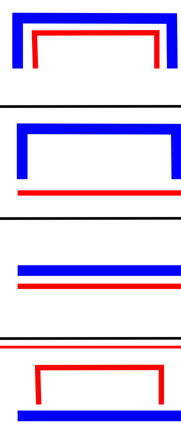
lower wavefront path 12
Smallest population

lower bubble path 8



bubble flow

wavefront flow



Upper wavefront population = 3
population period = 30 tics
renewal period = 27

Lower bubble population = 2
population period = 20 tics
renewal period = 20

Upper bubble population = 1
population period = 10 tics
renewal period = 24

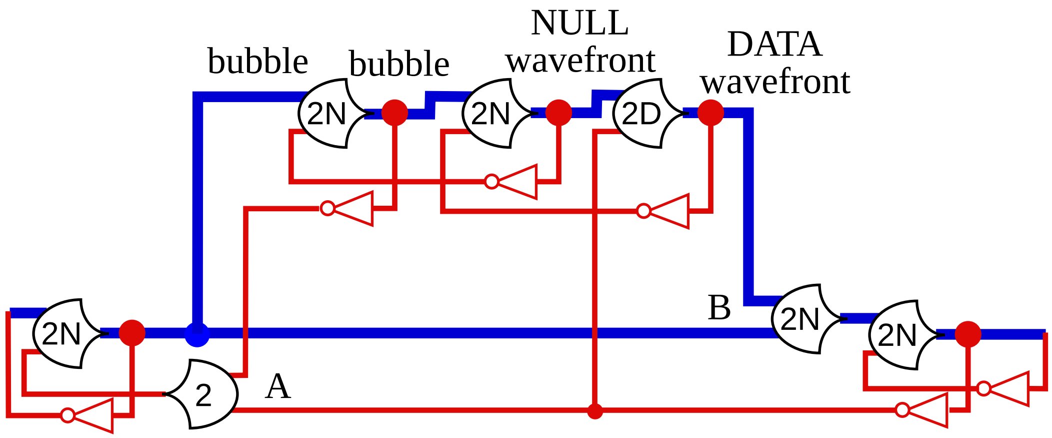
Lower wavefront population = 1
population period = 10 tics
renewal period = 24

The longest cycle period is reduced but the renewal period is increased and the population period is not increased.

Try Buffering Upper Pipeline

With a buffer cycle in the upper pipeline it now has both a larger bubble population as well as a larger wavefront population than the lower pipeline so the renew path becomes the lower wavefront path and the lower bubble path. All population periods exceed their renewal periods.

Simulations for example 2 in: NCL sims/pipeline structs/example 2 studies a.ckt



Static delays

upper wavefront path 18

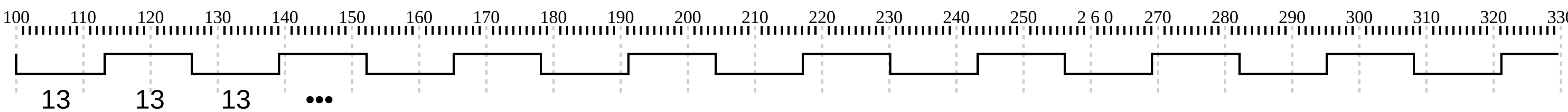
upper bubble path 16

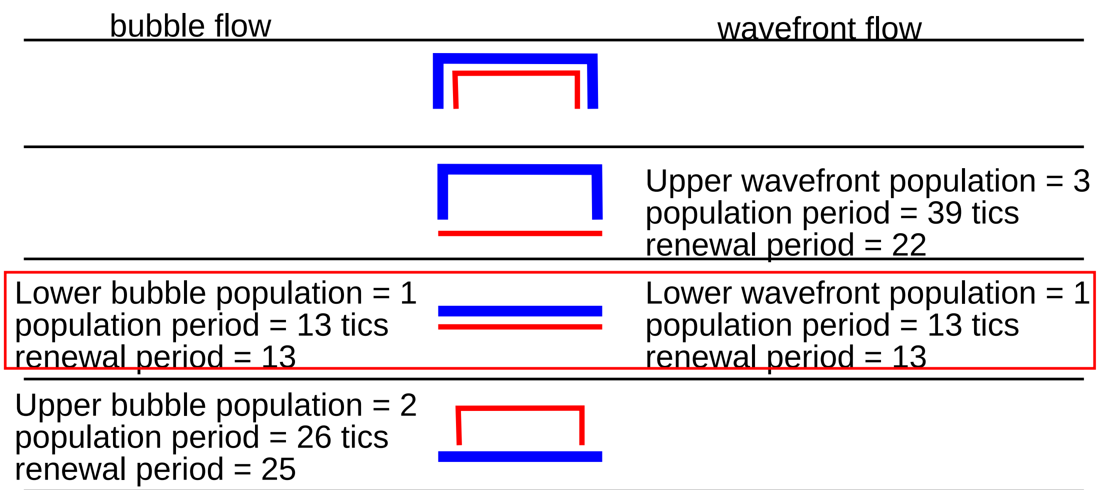
lower wavefront path 9

Smallest population

lower bubble path 4

Smallest population

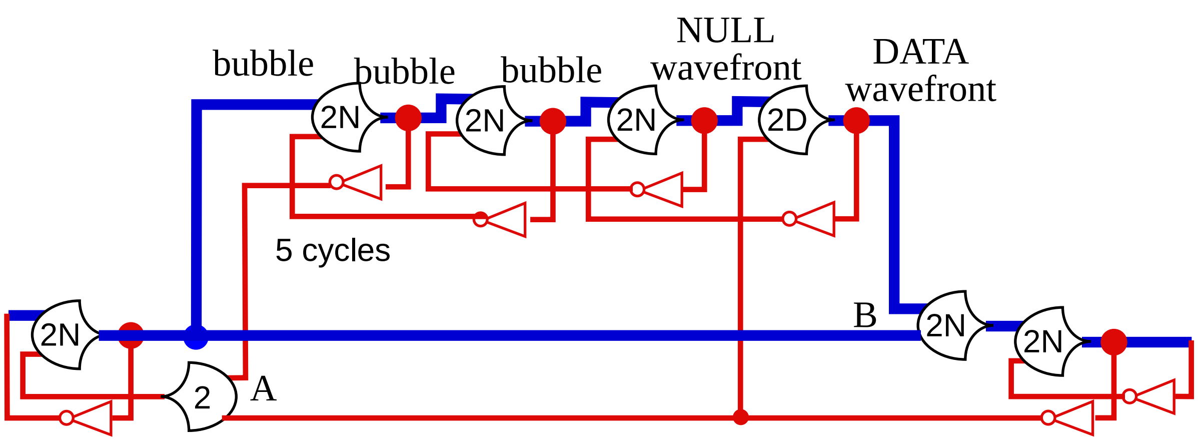




No limiting renewal wait
1 wavefront every 13 tics

More Buffering of Upper Pipeline
5 Cycles

As long as the upper pipeline has a wavefront at B and a bubble at A the lower pipeline never has to wait and the behavior of the structure is determined by the lower pipeline which cycles at its inherent period.



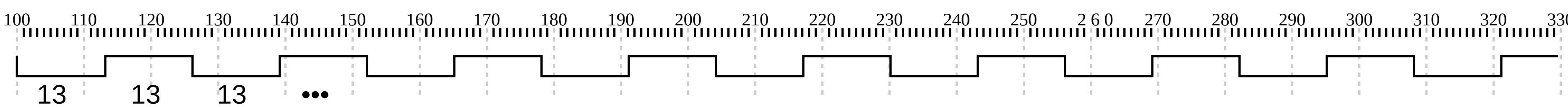
Static delays

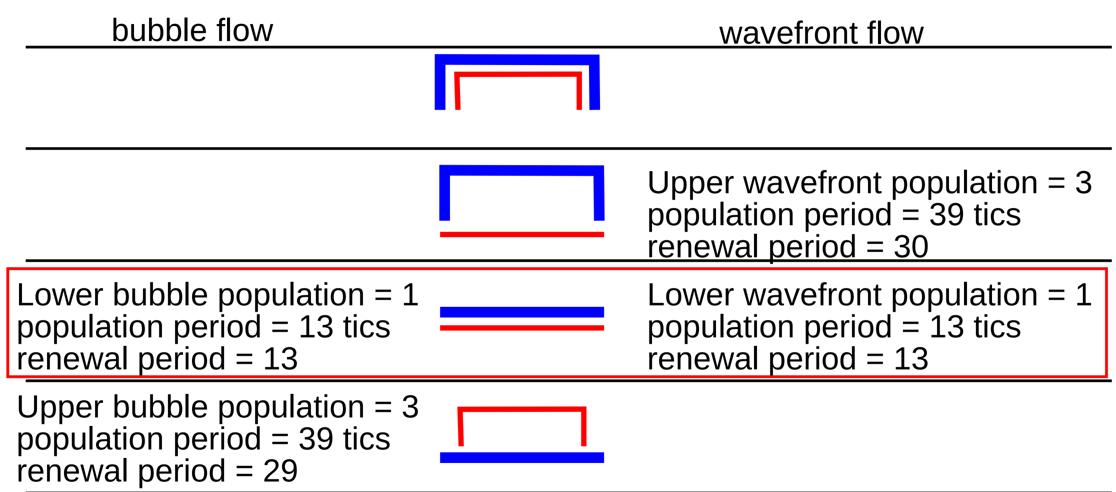
upper wavefront path 21

upper bubble path 20

lower wavefront path 9
Smallest population

lower bubble path 4
Smallest population

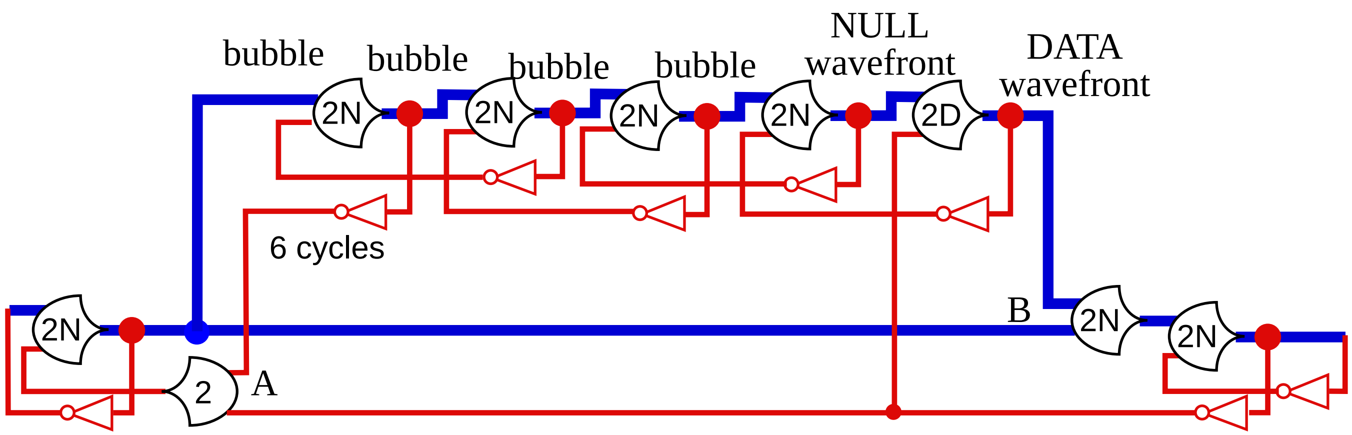




No limiting renewal wait
1 wavefront every 13 tics

More Buffering of Upper Pipeline
6 Cycles

As more buffering cycles are added to the upper pipeline there is no effect on throughput until with the tenth cycle the wavefront path delay of the upper wavefront path is so great that a new wavefront cannot catch up with its population. Then the upper wavefront path will cause a wait at B.

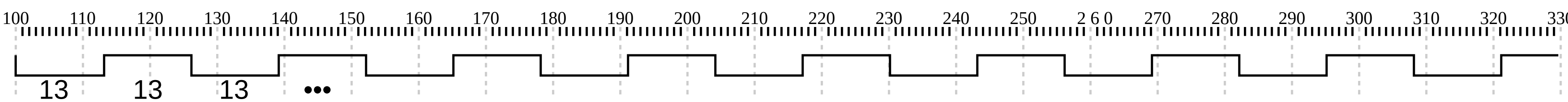


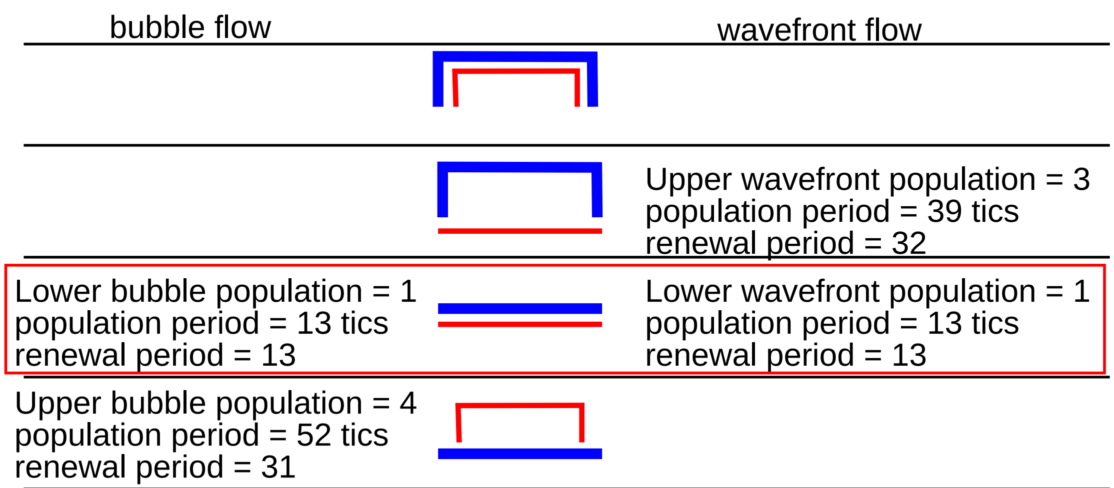
Static delays

upper wavefront path 24

upper bubble path 24

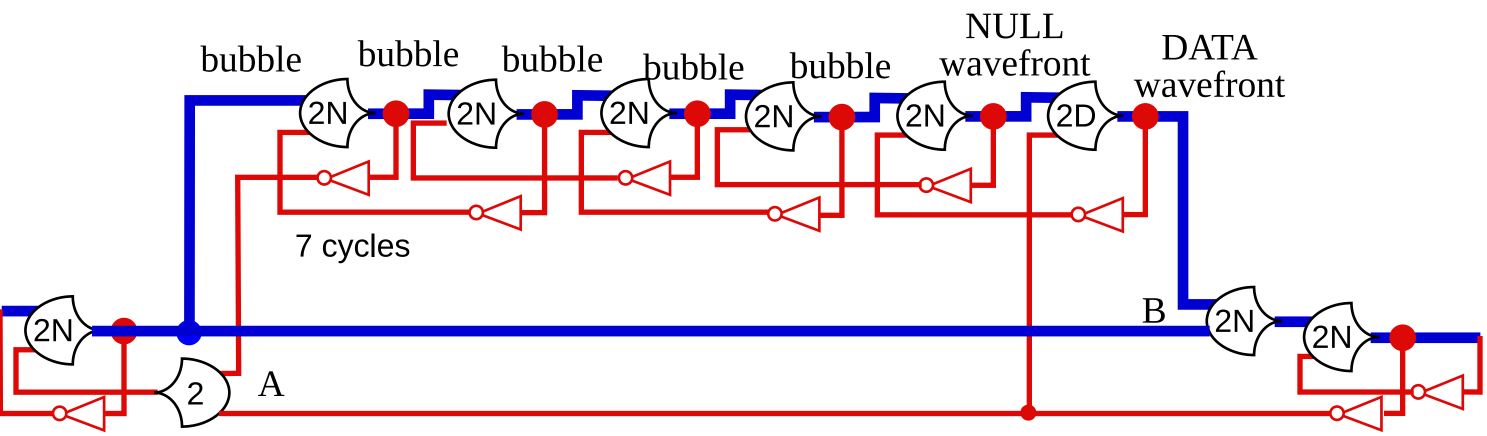
lower wavefront path 9
Smallest population
lower bubble path 4
Smallest population





No limiting renewal wait
1 wavefront every 13 tics

More Buffering of Upper Pipeline
7 Cycles



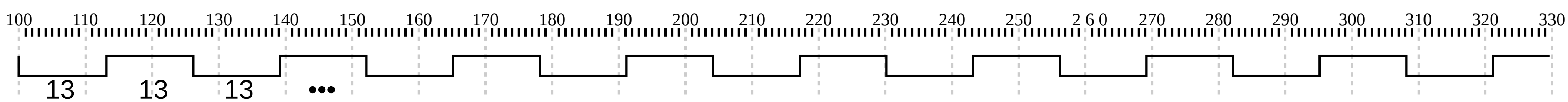
Static delays

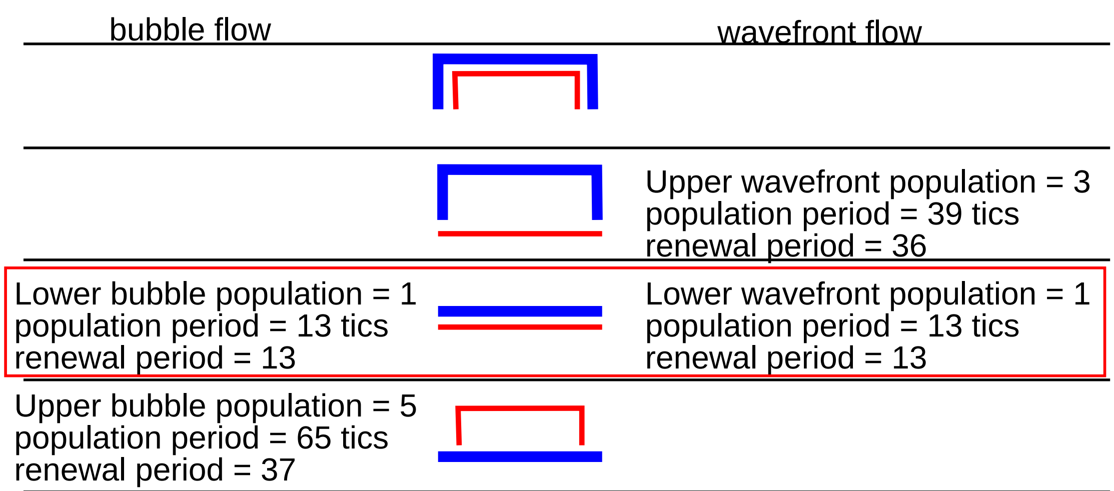
upper wavefront path 27

upper bubble path 28

lower wavefront path 9
Smallest population

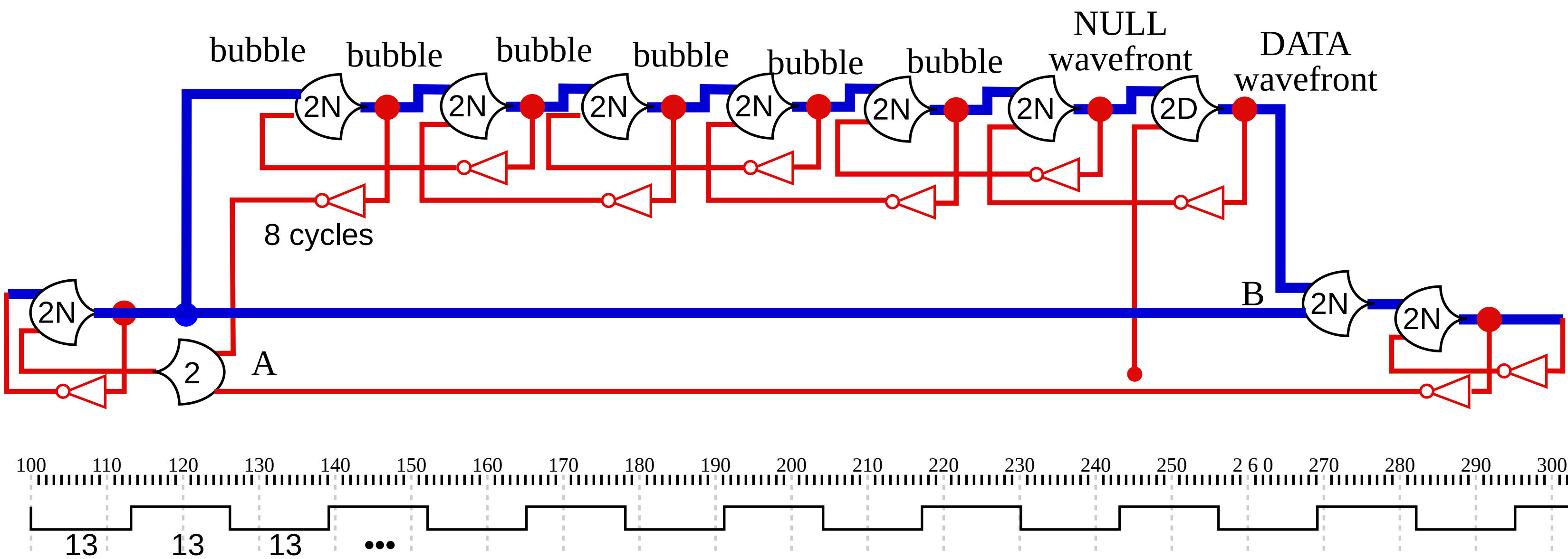
lower bubble path 4
Smallest population





No limiting renewal wait
1 wavefront every 13 tics

More Buffering of Upper Pipeline
8 Cycles



Static delays

upper wavefront path 30

upper bubble path 32

lower wavefront path 9
Smallest population

lower bubble path 4
Smallest population

bubble flow | wavefront flow

Upper wavefront population = 3
population period = 39 tics
renewal period = 39

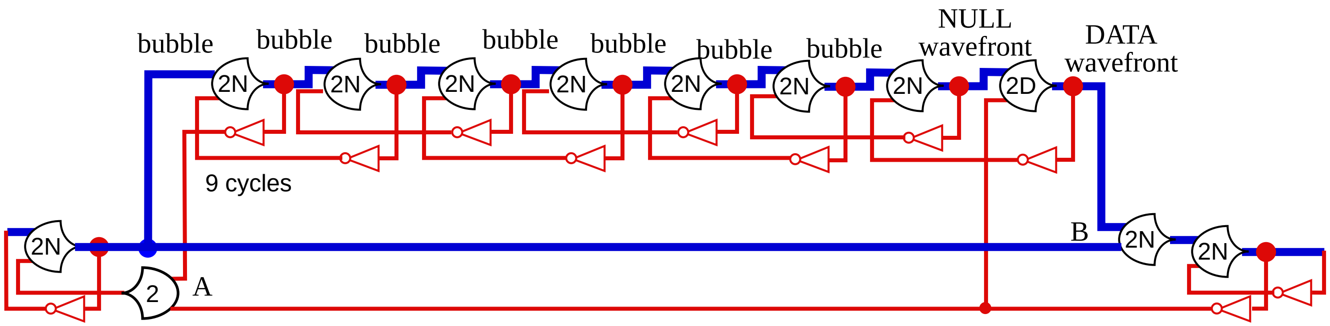
Lower bubble population = 1
population period = 13 tics
renewal period = 13

Lower wavefront population = 1
population period = 13 tics
renewal period = 13

Upper bubble population = 6
population period = 78 tics
renewal period = 41

No limiting renewal wait
1 wavefront every 13 tics

More Buffering of Upper Pipeline
9 Cycles



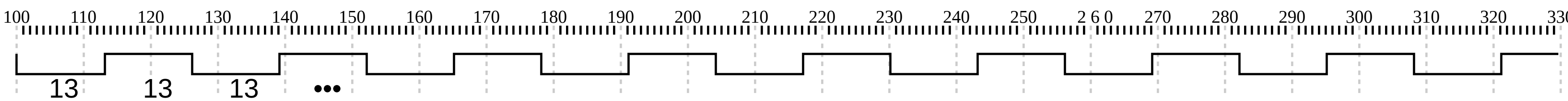
Static delays

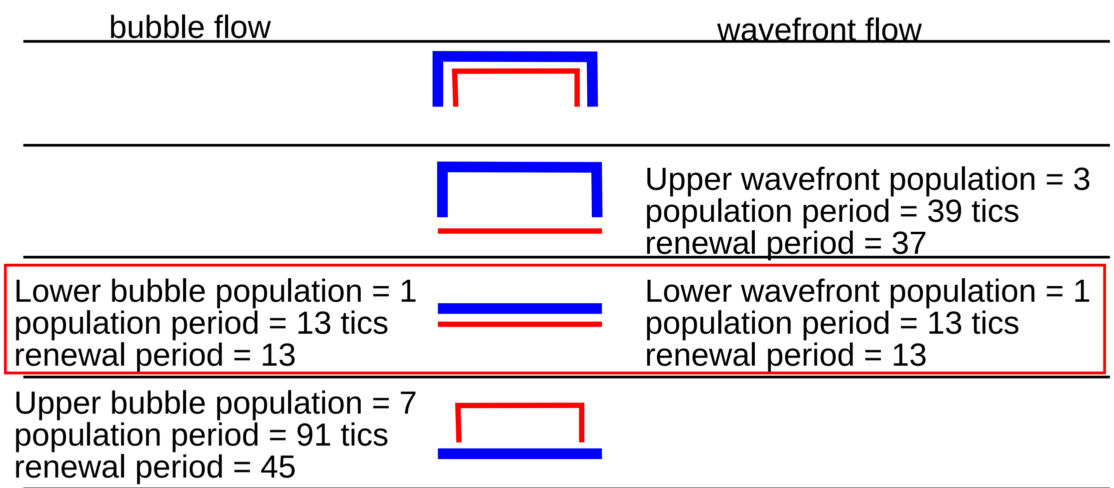
upper wavefront path 33

upper bubble path 36

lower wavefront path 9
Smallest population

lower bubble path 4
Smallest population

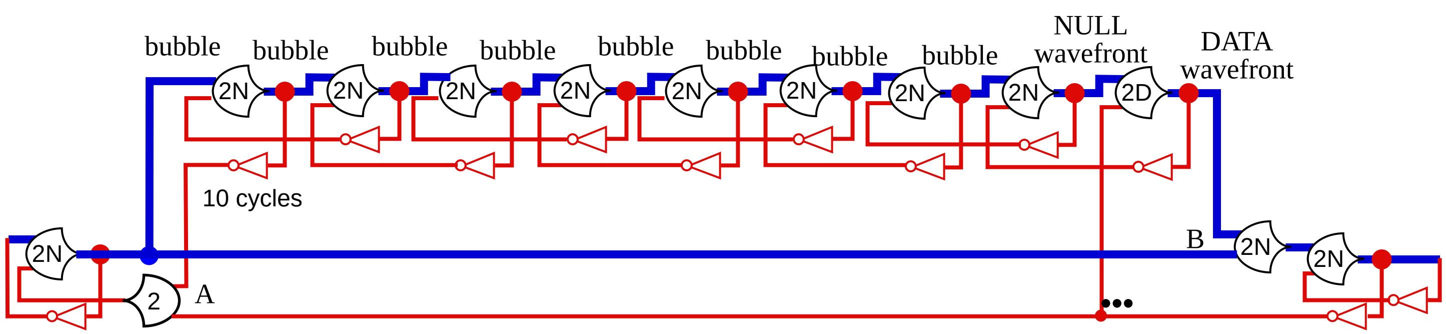




No limiting renewal wait
1 wavefront every 13 tics

More Buffering of Upper Pipeline
10 Cycles

The upper pipeline wavefront renewal period, 40 tics, becomes larger than the upper pipeline wavefront population period, 39 tics, which causes a 1 tic wait at B.



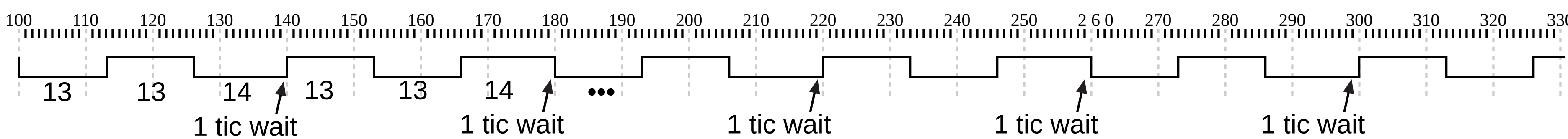
Static delays

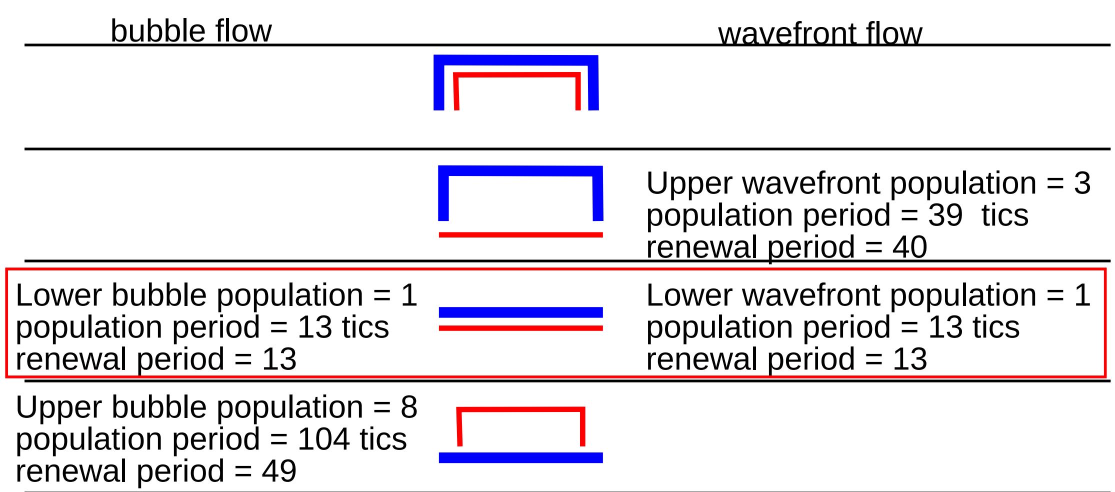
upper wavefront path 36

upper bubble path 40

lower wavefront path 9
Smallest population

lower bubble path 4
Smallest population

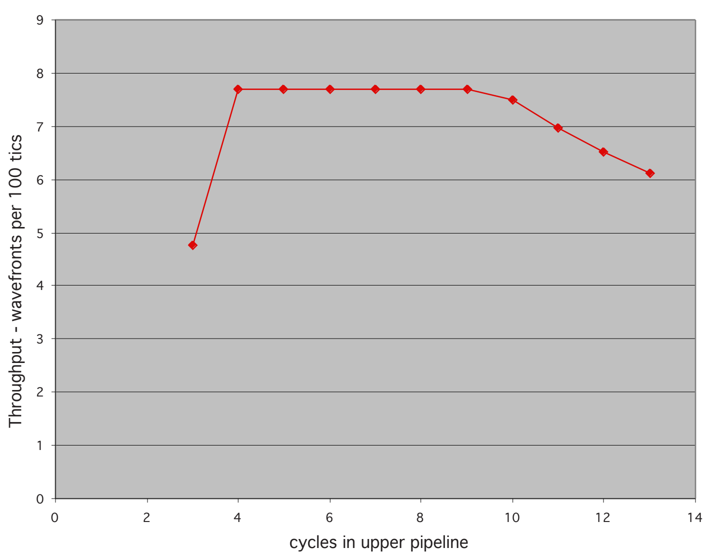


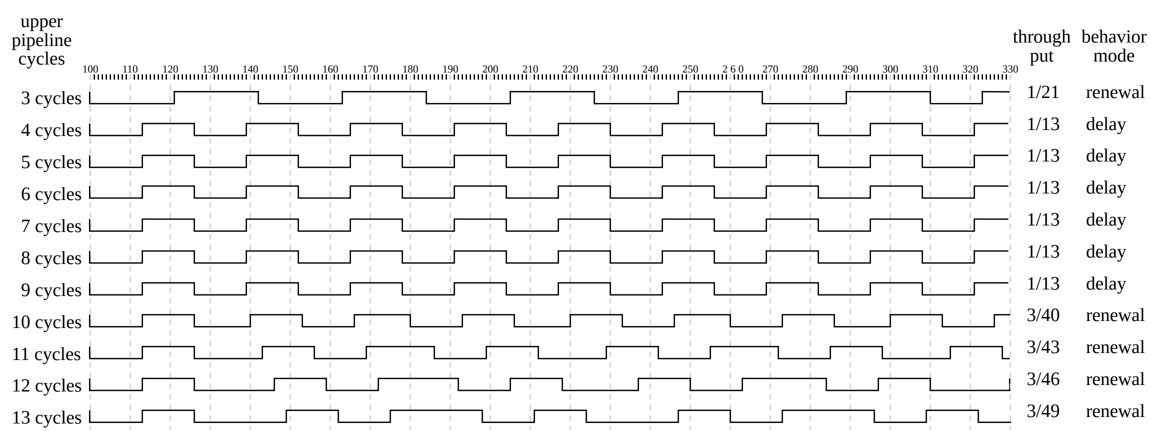


Limiting renewal wait
3 wavefronts in 40 tics

Example 2 Summary

Cycles in upper pipeline	Limiting cycle period	Relevant population period	Relevant renewal period	Throughput waves/ period	Throughput waves/ 100 tics	Limiting behavior mode
3	13	13	21	1/21	4.76	renewal
4	13	13	13	1/13	7.69	delay
5	13	13	13	1/13	7.69	delay
6	13	13	13	1/13	7.69	delay
7	13	13	13	1/13	7.69	delay
8	13	13	13	1/13	7.69	delay
9	13	13	13	1/13	7.69	delay
10	13	39	40	3/40	7.50	renewal
11	13	39	43	3/43	6.97	renewal
12	13	39	46	3/46	6.52	renewal
13	13	39	49	3/49	6.12	renewal

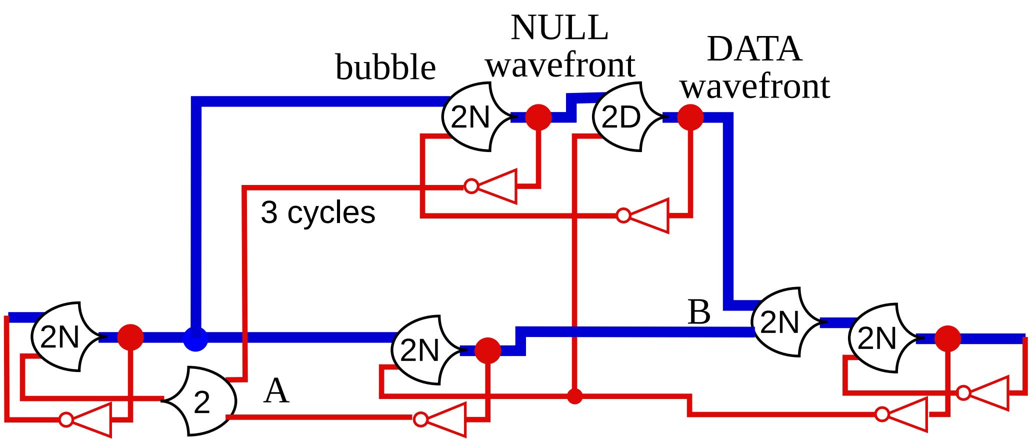




Example 3: Finer Grained Pipelining

We can increase throughput by speeding up the slowest cycle in the structure. This can be accomplished by splitting the 13 tic cycle into two smaller cycles each with a period of 10 tics. The slowest cycle period is now 10 tics. The next question is, can we achieve a 10 tic throughput for the structure as a whole.

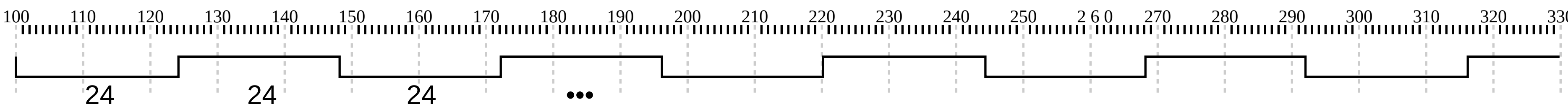
Simulations for example 3 in: NCL sims/pipeline structs/example 2 studies a.ckt

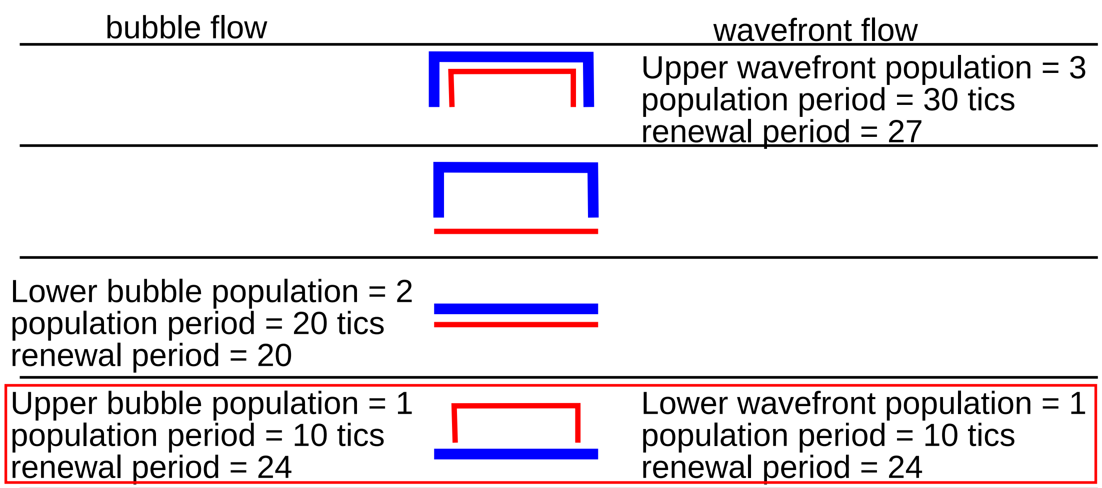


upper wavefront path 15

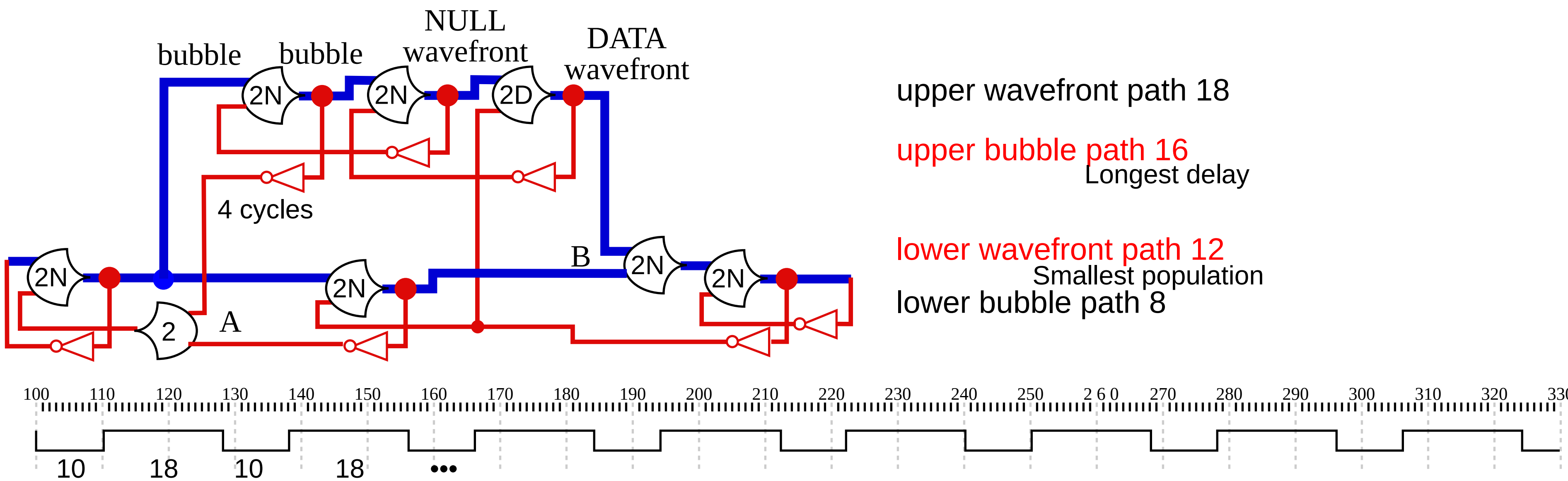
upper bubble path 12
Smallest population

lower wavefront path 12
Smallest population
lower bubble path 8





Finer Grained Pipelining: 4 Cycles



upper wavefront path 18

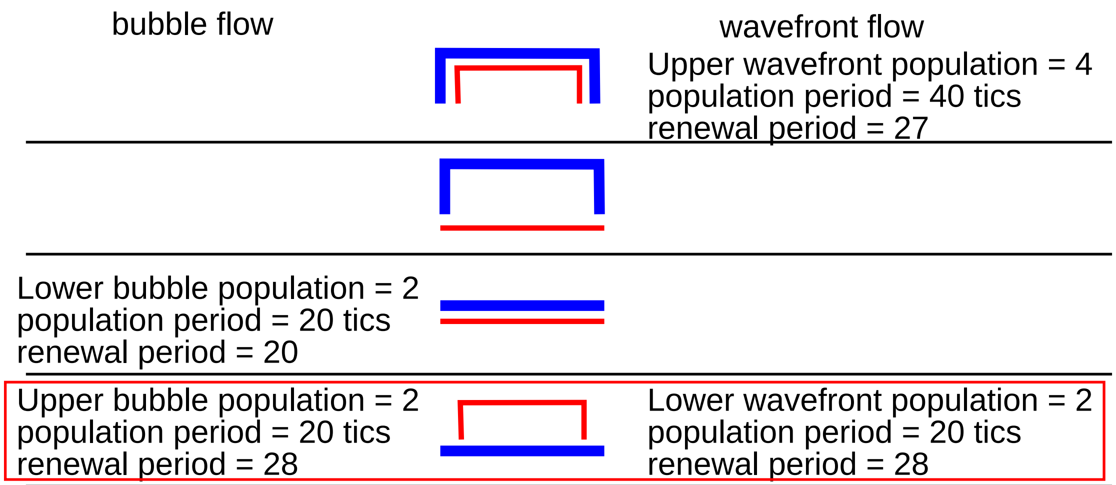
upper bubble path 16

Longest delay

lower wavefront path 12

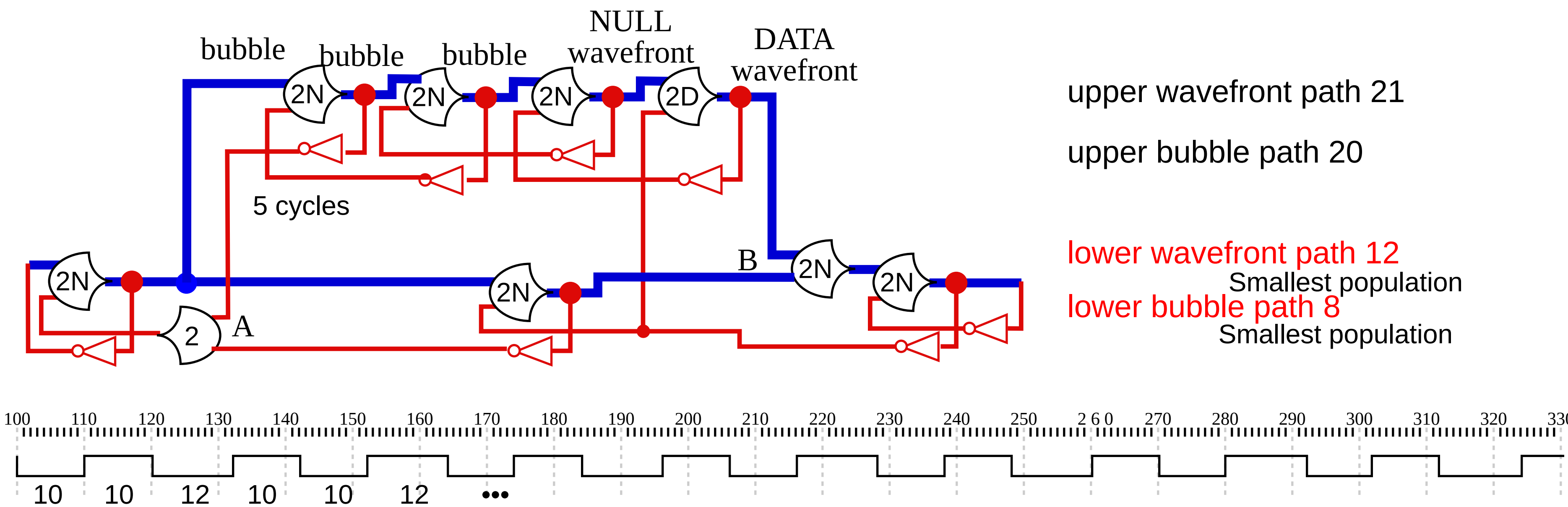
Smallest population

lower bubble path 8



Finer Grained Pipelining: 5 Cycles

Longest delay



upper wavefront path 21

upper bubble path 20

lower wavefront path 12

Smallest population

lower bubble path 8

Smallest population

bubble flow

wavefront flow

Upper wavefront population = 4
population period = 40 tics
renewal period = 29

Lower bubble population = 2
population period = 20 tics
renewal period = 20

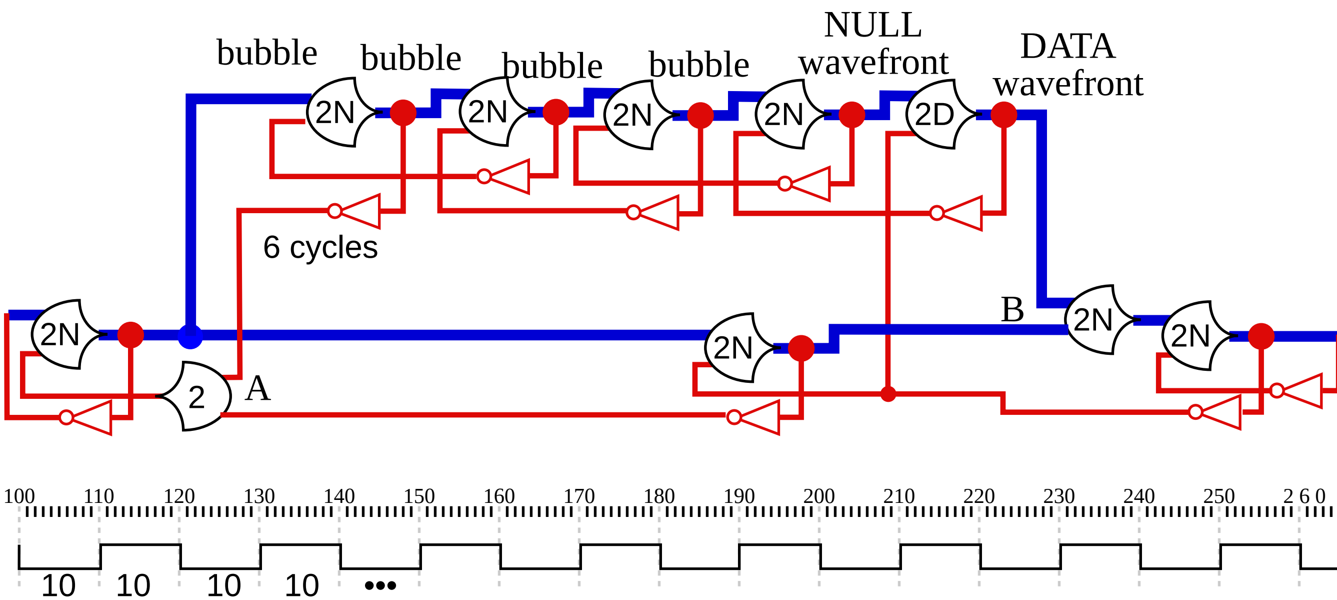
Lower wavefront population = 2
population period = 20 tics
renewal period = 20

Upper bubble population = 3
population period = 30 tics
renewal period = 32

limiting renewal flow

Finer Grained Pipelining: 6 Cycles

Longest delay



upper wavefront path 24

upper bubble path 24

lower wavefront path 12

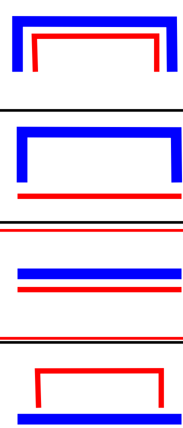
Smallest population

lower bubble path 8

Smallest population

bubble flow

wavefront flow



Upper wavefront population = 4
population period = 40 tics
renewal period = 32

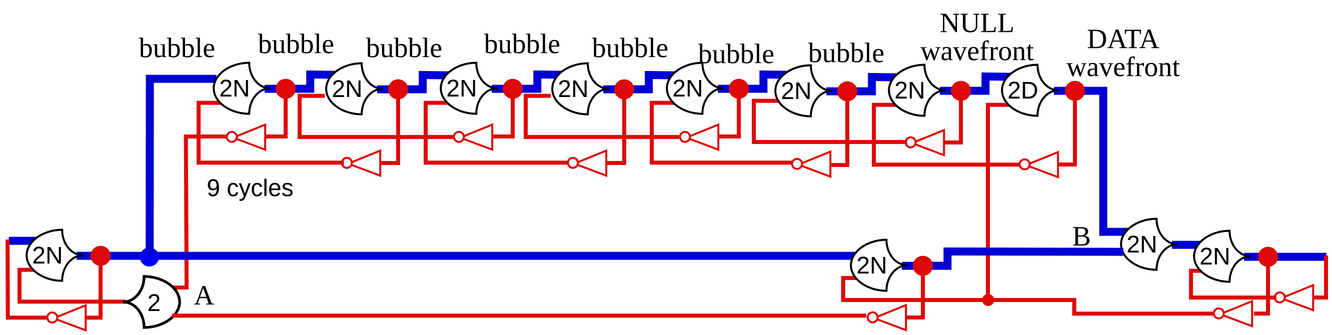
Lower bubble population = 2
population period = 20 tics
renewal period = 20

Lower wavefront population = 2
population period = 20 tics
renewal period = 20

Upper bubble population = 4
population period = 40 tics
renewal period = 36

No limiting renewal flow

Finer Grained Pipelining: 9 Cycles

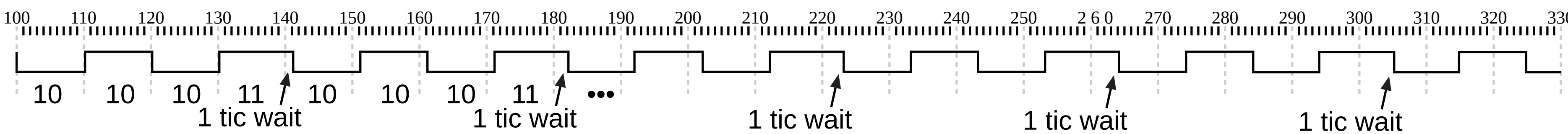


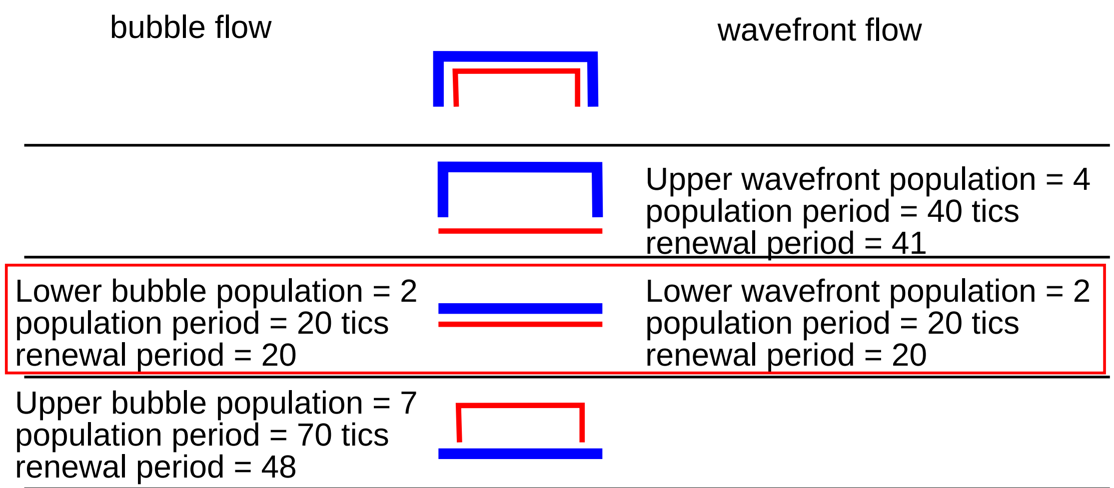
upper wavefront path 33

upper bubble path 36

lower wavefront path 12
Smallest population

lower bubble path 8
Smallest population

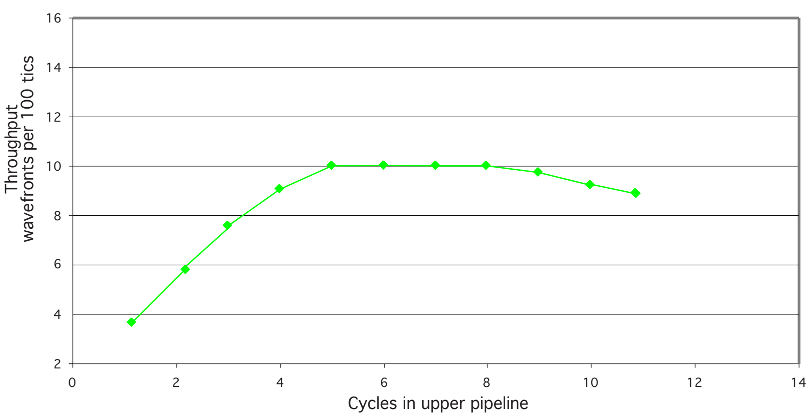


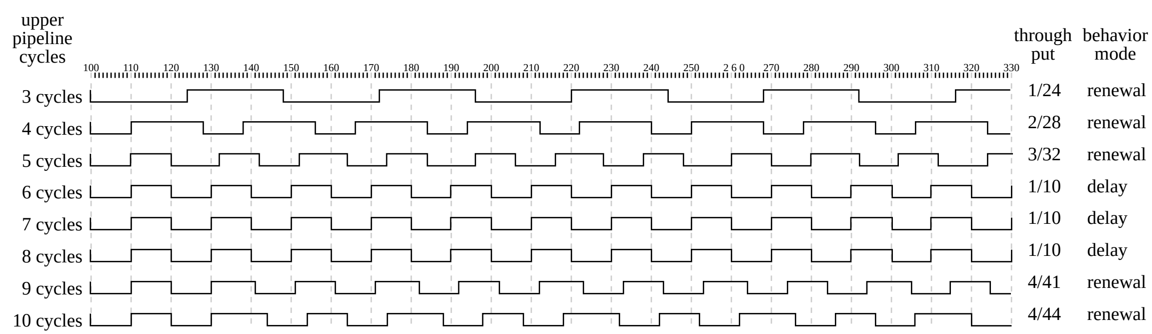


Limiting renewal flow

Summary Finer Grained Pipelining

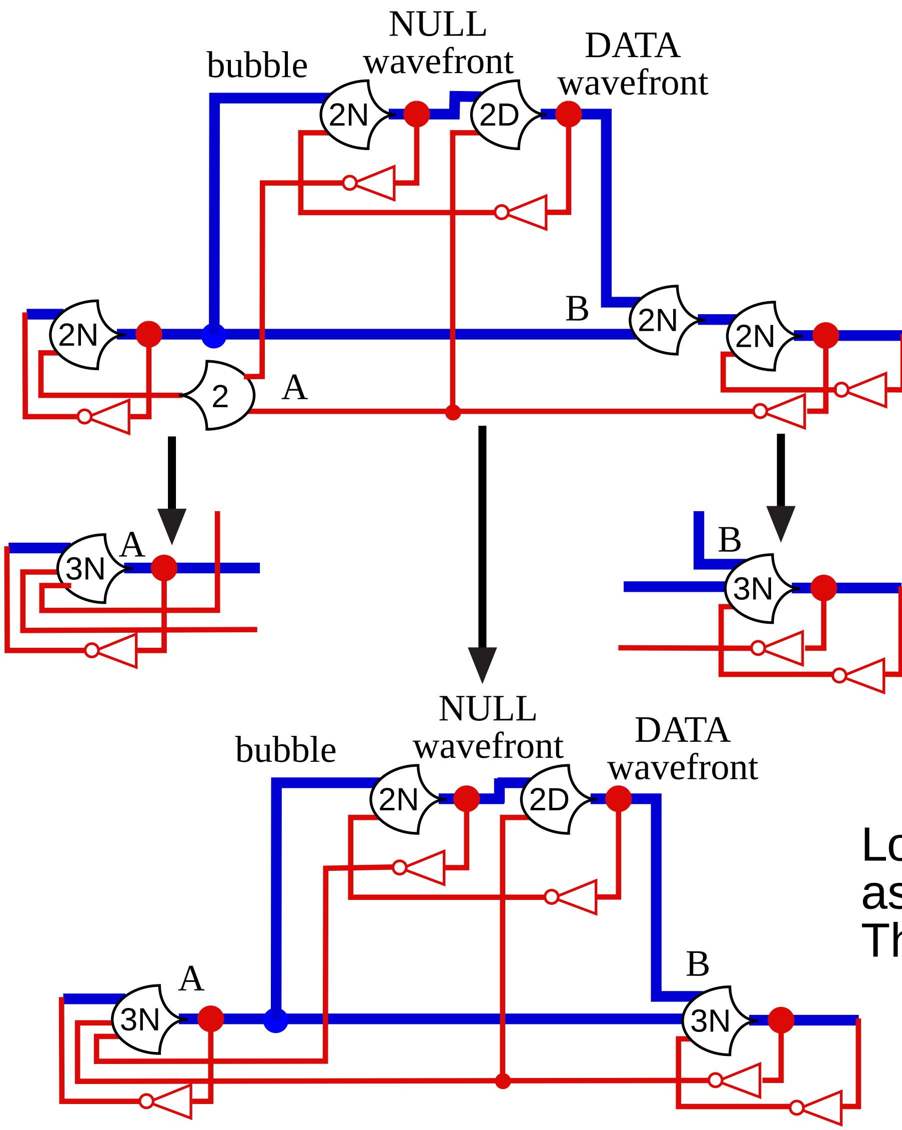
Cycles in upper pipeline	Limiting cycle period	Relevant population period	Relevant renewal period	Throughput waves/ period	Throughput waves/ 100 tics	Limiting behavior mode
3	10	10	24	1/24	4.16	renewal
4	10	20	28	2/28	7.14	renewal
5	10	30	32	3/32	9.37	renewal
6	10	20	20	1/10	10.0	delay
7	10	20	20	1/10	10.0	delay
8	10	20	20	1/10	10.0	delay
9	10	40	41	4/41	9.75	renewal
10	10	40	44	4/44	9.09	renewal





Example 4: Optimized Logic

The cycle periods can be reduced by optimizing the logic operators. In this example two operators are combined into a single operator reducing the wavefront path delay of both pipelines and reducing the cycle period of the lower pipeline cycle.

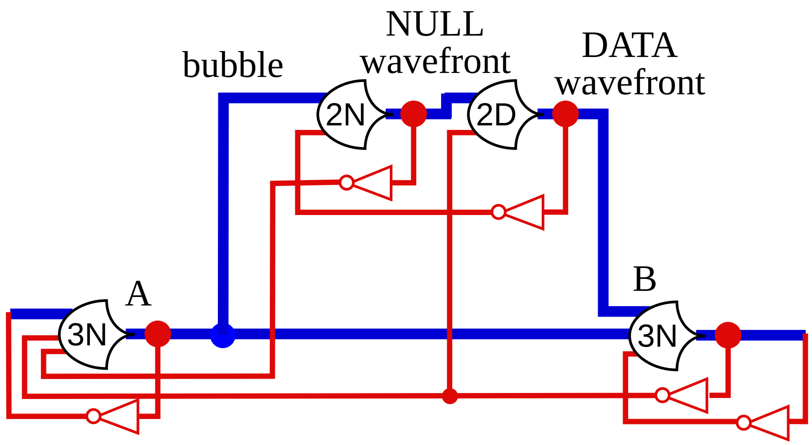


Combine operators

Lower pipeline cycle is now 7 tics as are all cycles in the structure. There is no slowest cycle.

Optimized Logic : 3 Cycles

With a buffer cycle in the upper pipeline it now has both a larger bubble population as well as a larger wavefront population than the lower pipeline so the renew path becomes the lower wavefront path and the lower bubble path. All population periods exceed their renewal periods.



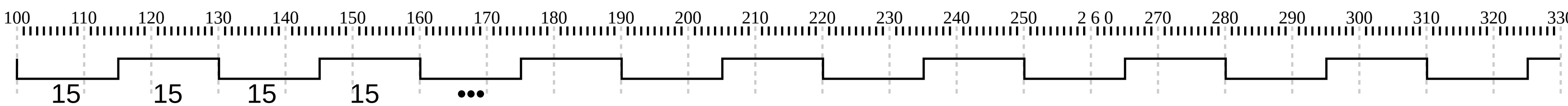
Static delays

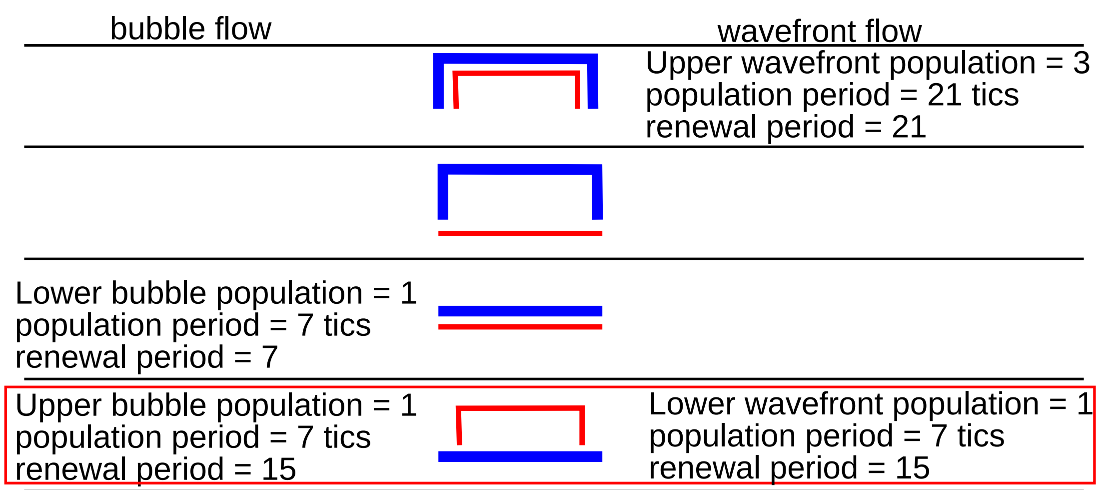
upper wavefront path 12

upper bubble path 9
Longest delay

lower wavefront path 6
Smallest population

lower bubble path 1

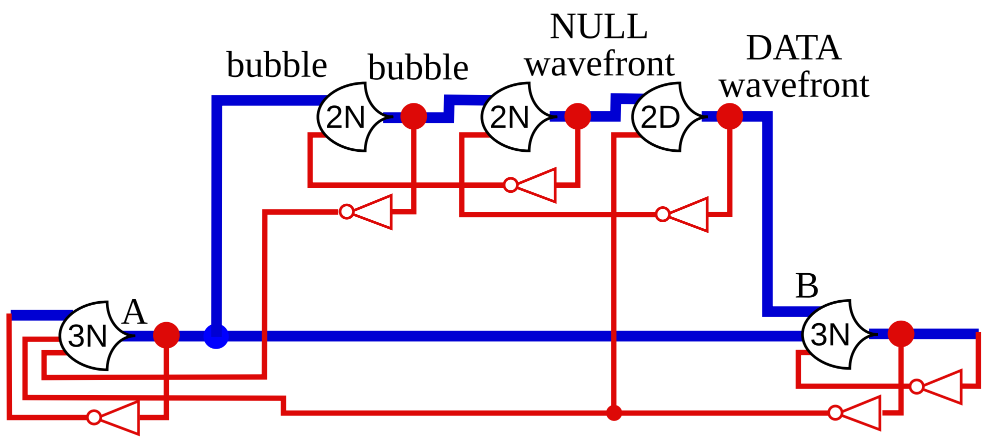




Limiting renewal wait
1 wavefront every 15 tics

Optimized Logic : 4 Cycles

With a buffer cycle in the upper pipeline it now has both a larger bubble population as well as a larger wavefront population than the lower pipeline so the renew path becomes the lower wavefront path and the lower bubble path. All population periods exceed their renewal periods.



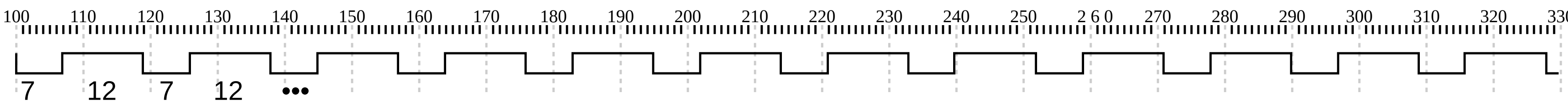
Static delays

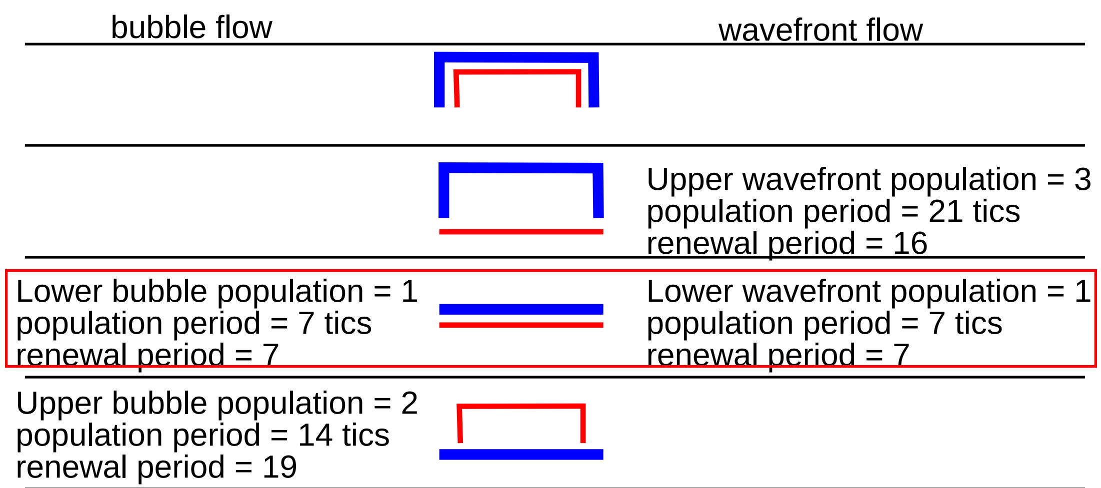
upper wavefront path 15

upper bubble path 13

lower wavefront path 6
Smallest population

lower bubble path 1
Smallest population

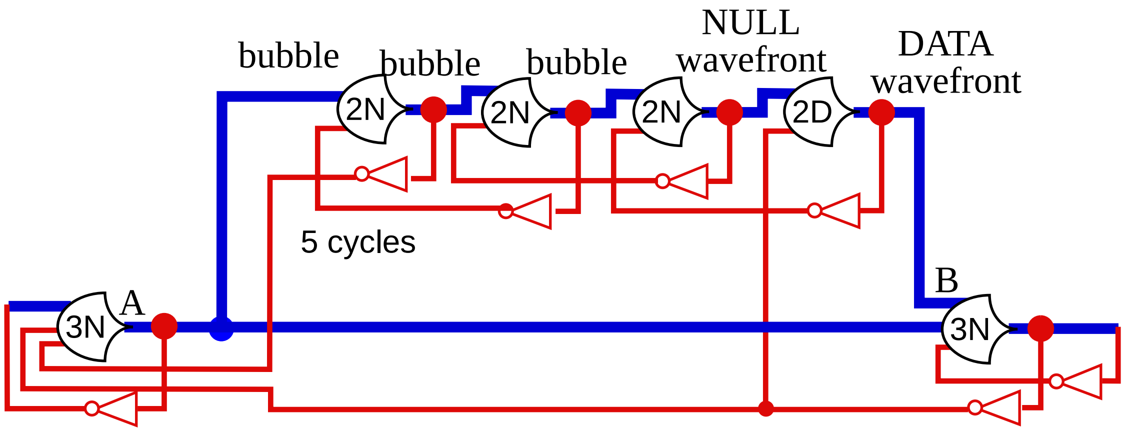




Limiting renewal wait
2 wavefronts every 19 tics

Optimized Logic : 5 Cycles

As long as the upper pipeline has a wavefront at B and a bubble at A the lower pipeline never has to wait and the behavior of the structure is determined by the lower pipeline which cycles at its inherent period.

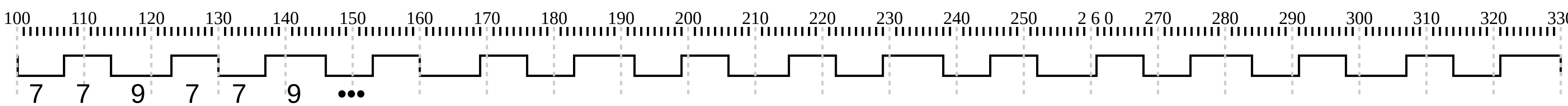


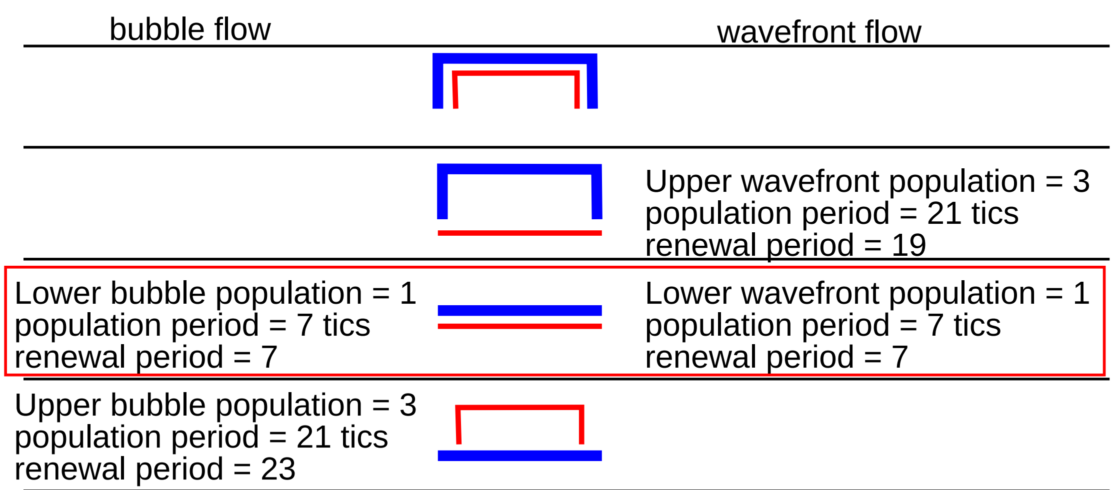
Static delays

upper wavefront path 18

upper bubble path 17

lower wavefront path 6
Smallest population
lower bubble path 1
Smallest population

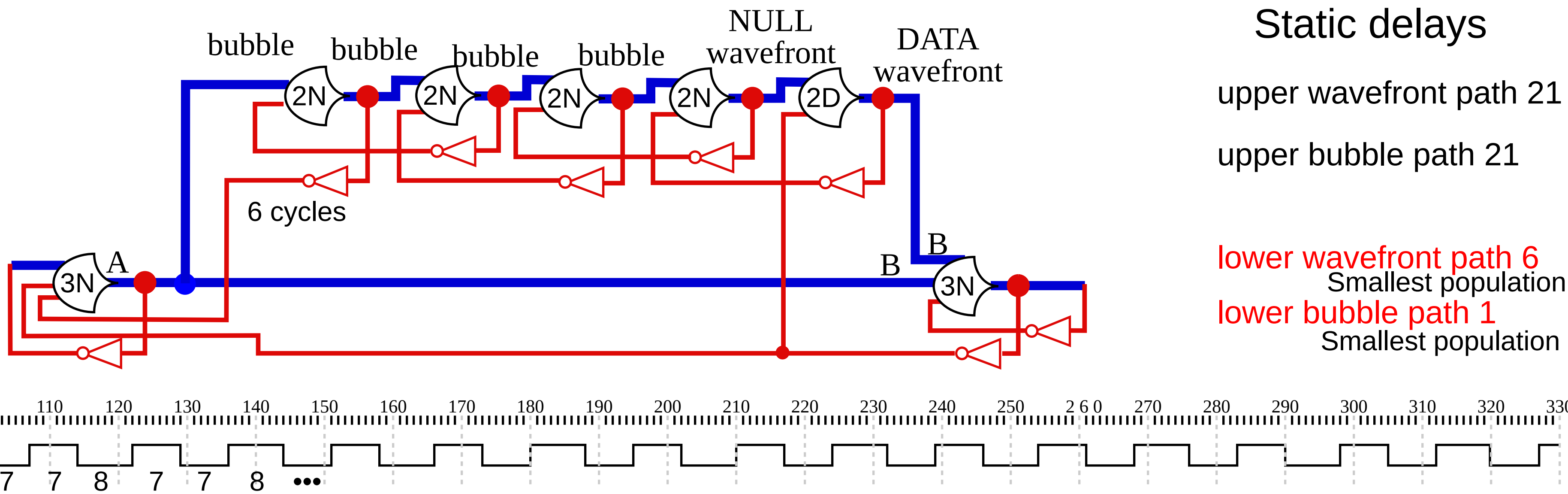




Limiting renewal wait
3 wavefronts every 23 tics

Optimized Logic : 6 Cycles

As more buffering cycles are added to the upper pipeline there is no effect on throughput until with the tenth cycle the wavefront path delay of the upper wavefront path is so great that a new wavefront cannot catch up with its population. Then the upper wavefront path will cause a wait at B.



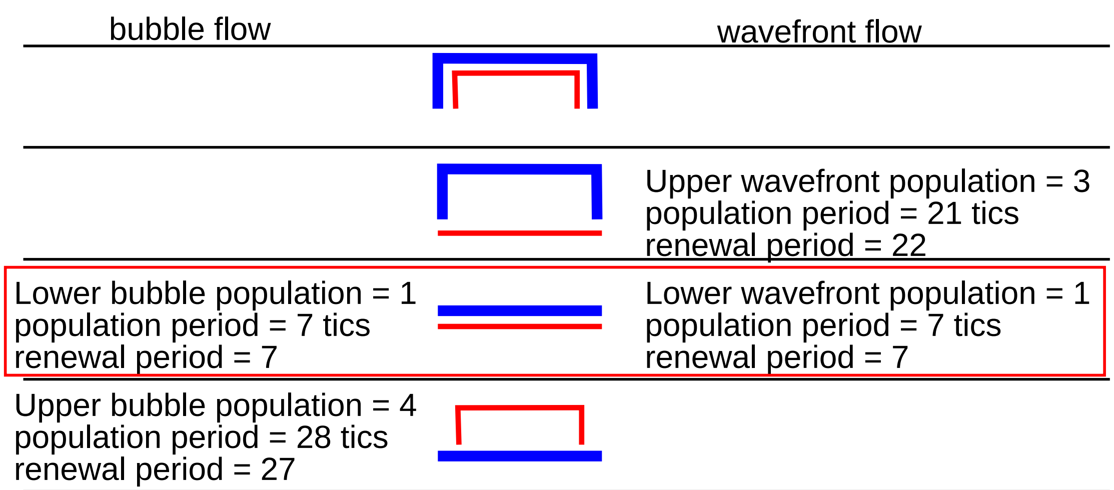
Static delays

upper wavefront path 21

upper bubble path 21

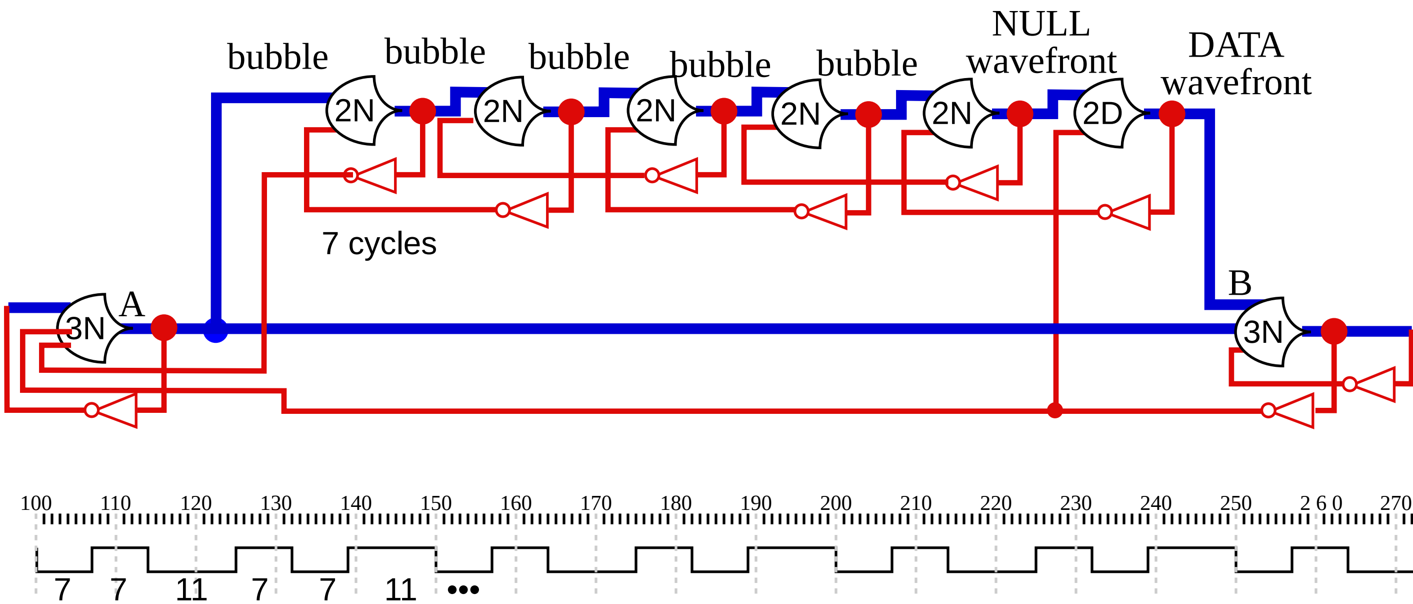
lower wavefront path 6
Smallest population

lower bubble path 1
Smallest population



Limiting renewal wait
3 wavefronts every 22 tics

Optimized Logic : 7 Cycles

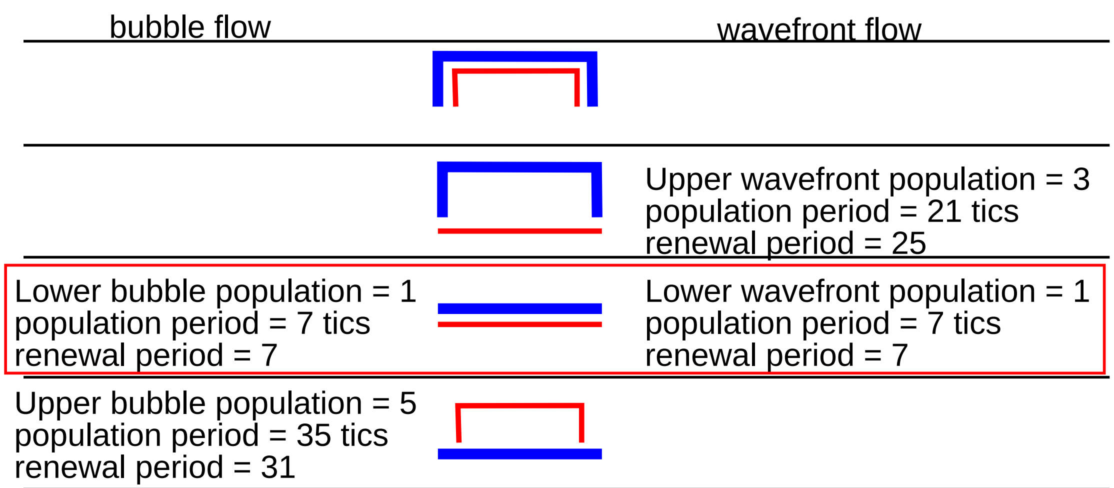


Static delays

upper wavefront path 24

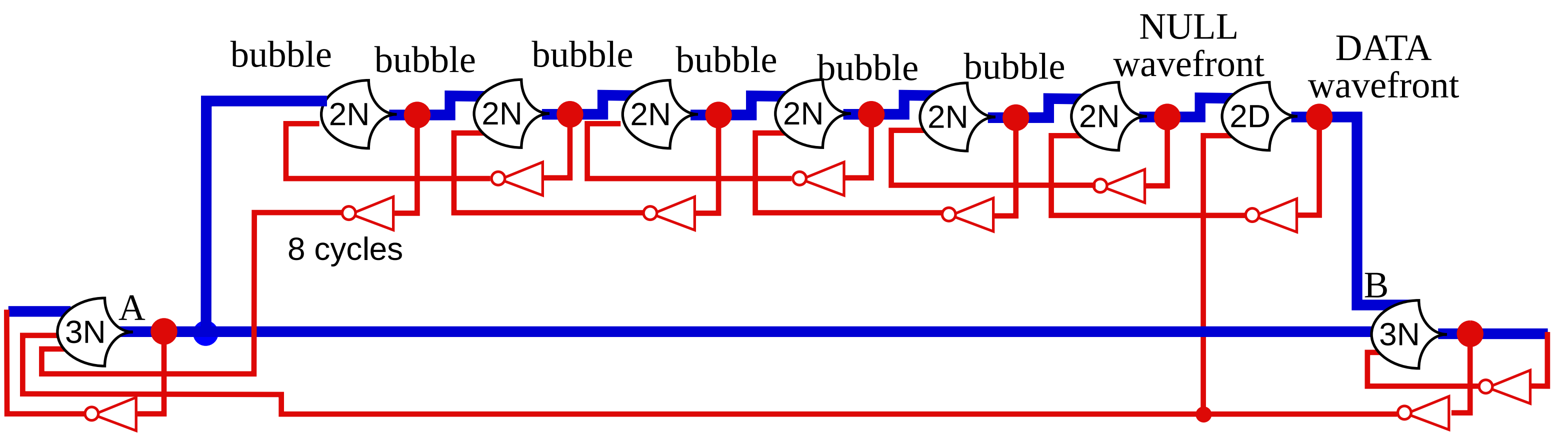
upper bubble path 25

lower wavefront path 6
Smallest population
lower bubble path 1
Smallest population



Limiting renewal wait
3 wavefront every 25 tics

Optimized Logic : 8 Cycles



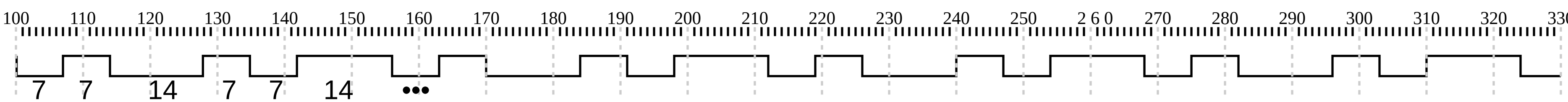
Static delays

upper wavefront path 27

upper bubble path 29

lower wavefront path 6
Smallest population

lower bubble path 1
Smallest population



bubble flow | wavefront flow

Upper wavefront population = 3
population period = 21 tics
renewal period = 28

Lower bubble population = 1
population period = 7 tics
renewal period = 7

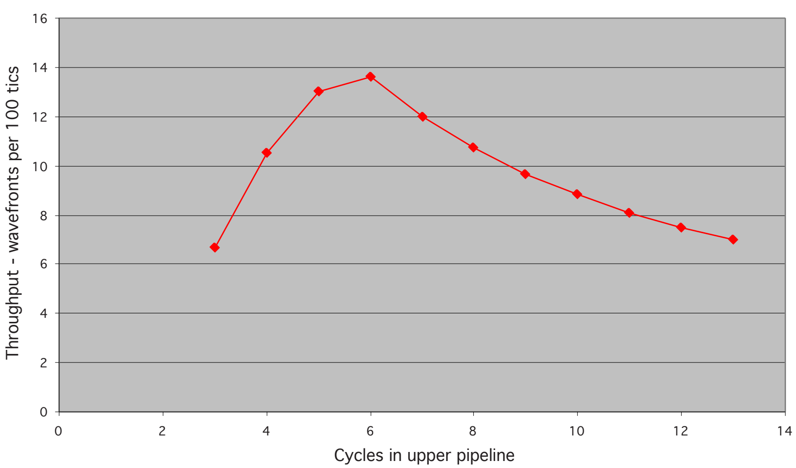
Lower wavefront population = 1
population period = 7 tics
renewal period = 7

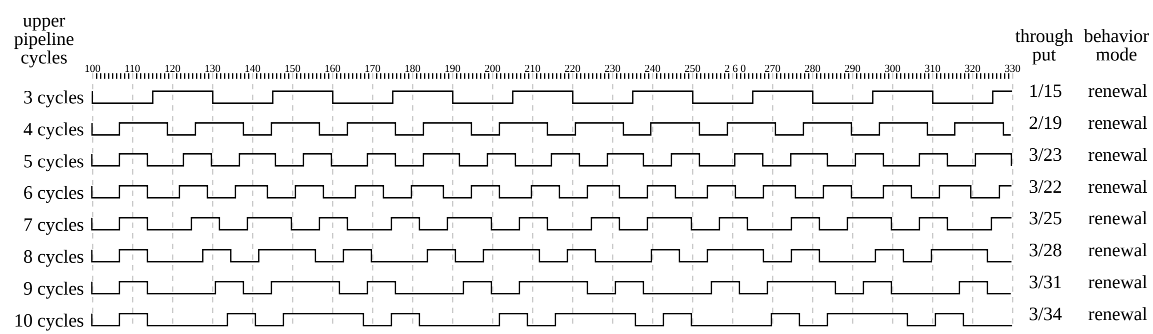
Upper bubble population = 6
population period = 42 tics
renewal period = 35

Limiting renewal wait
3 wavefronts every 28 tics

Summary Optimized Logic

Cycles in upper pipeline	Limiting cycle period	Relevant population period	Relevant renewal period	Throughput waves/ period	Throughput waves/ 100 tics	Limiting behavior mode
3	7	7	15	1/15	6.66	renewal
4	7	14	19	2/19	10.5	renewal
5	7	21	23	3/23	13.0	renewal
6	7	21	22	3/22	13.6	renewal
7	7	21	25	3/25	12.0	renewal
8	7	21	28	3/28	10.7	renewal
9	7	21	31	3/31	9.58	renewal
10	7	21	34	3/34	8.82	renewal

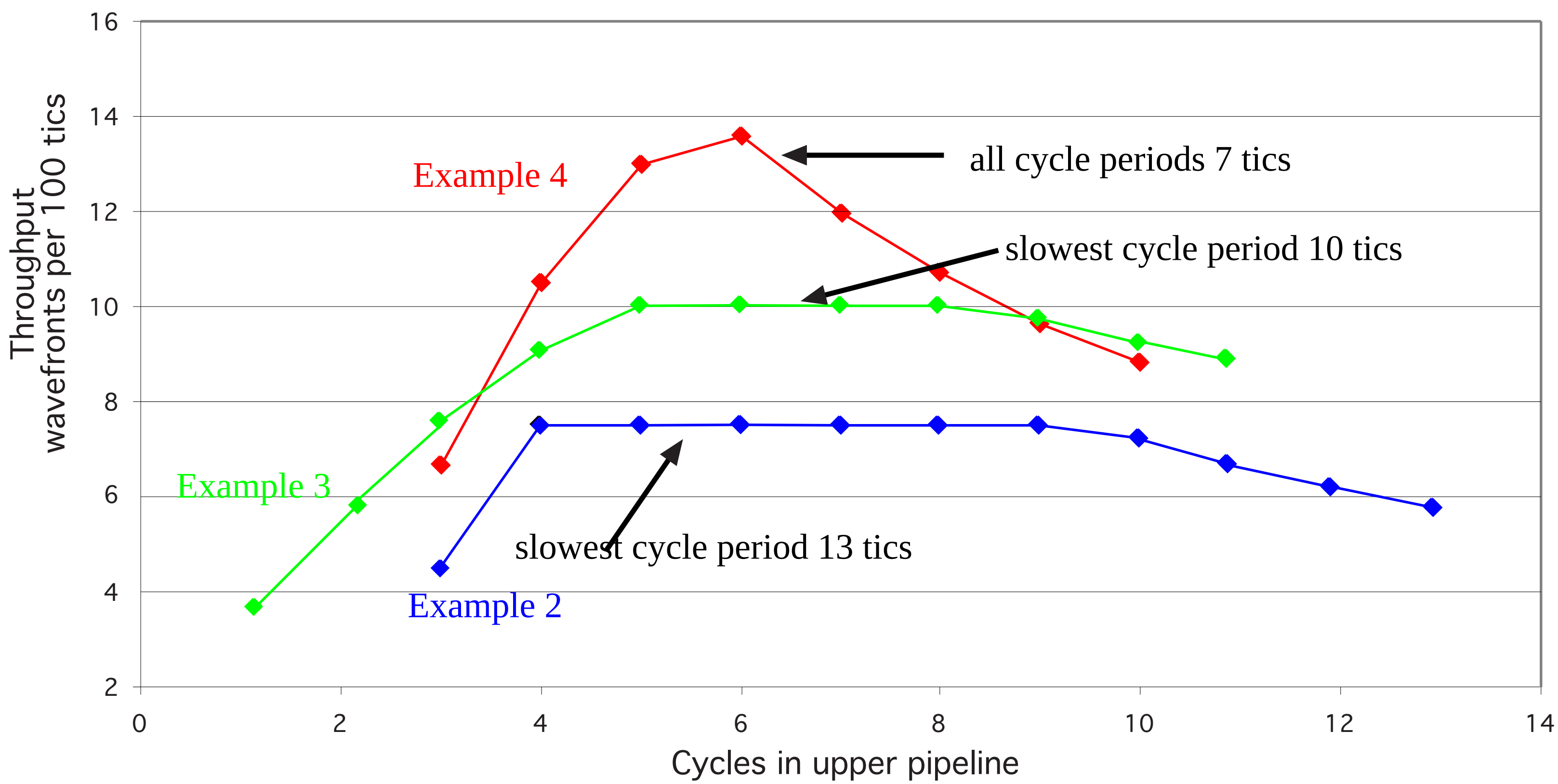




Summary

Each example was synthesized to an optimal configuration of maximal throughput with minimal resources entirely in terms of static relationships derived from the structure itself and the static delay components of the structure.

The easily automatable methodology consists of constructing behavior profile tables of static relationships among static parameters and searching the table for a maximum value.



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