Report

Critical Analysis

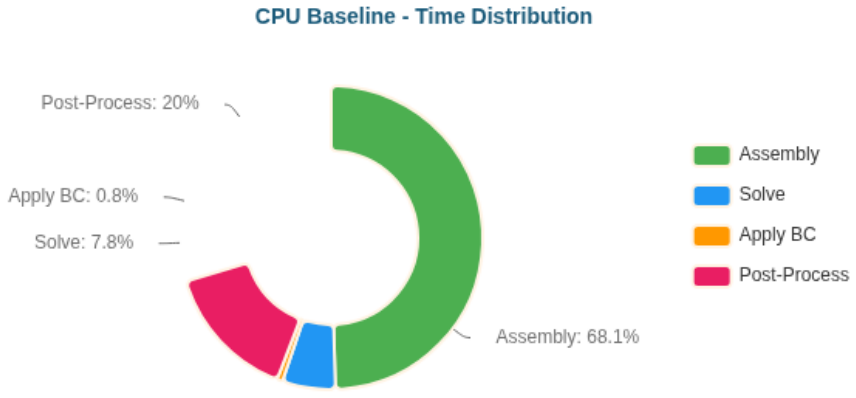
Bottleneck Evolution

As optimizations progress, the computational bottleneck shifts:

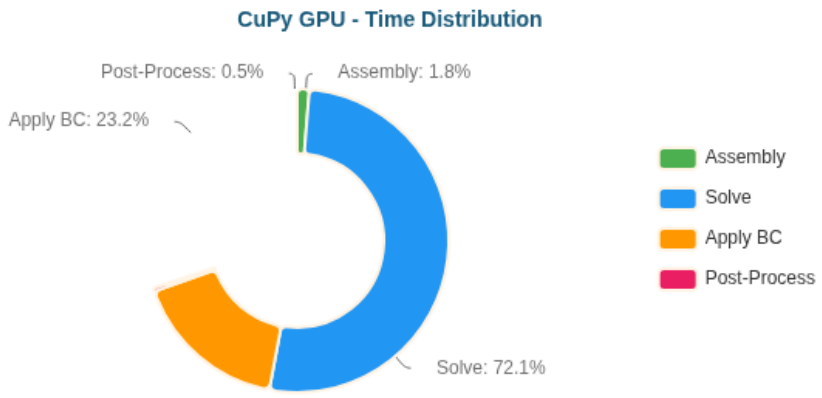
Backward-Facing Step (XS) - 287 nodes

Implementation	Primary Bottleneck	Secondary Bottleneck
CPU Baseline	Assembly (68%)	Post-Proc (20%)
CPU Threaded	Assembly (51%)	Post-Proc (25%)
CPU Multiprocess	Assembly (50%)	Post-Proc (49%)
Numba CPU	Solve (55%)	BC (16%)
Numba CUDA	Solve (88%)	Assembly (6%)
CuPy GPU	Solve (72%)	BC (23%)

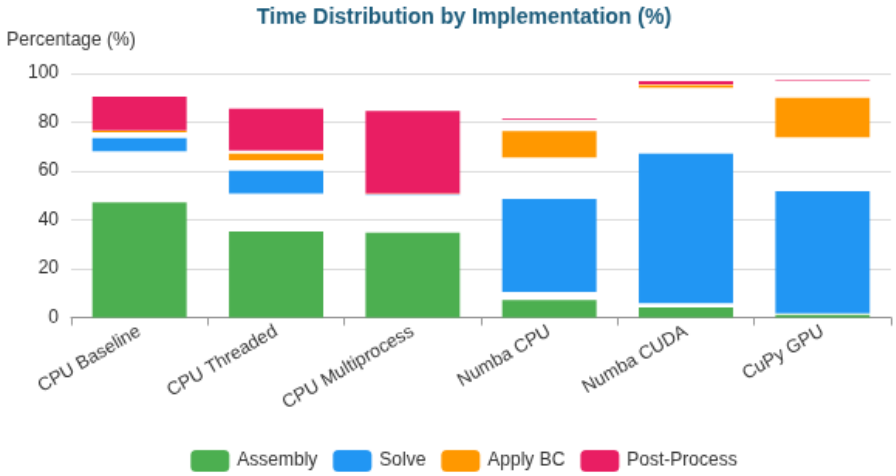
Time Distribution:



CPU Baseline - Time Distribution



CuPy GPU - Time Distribution

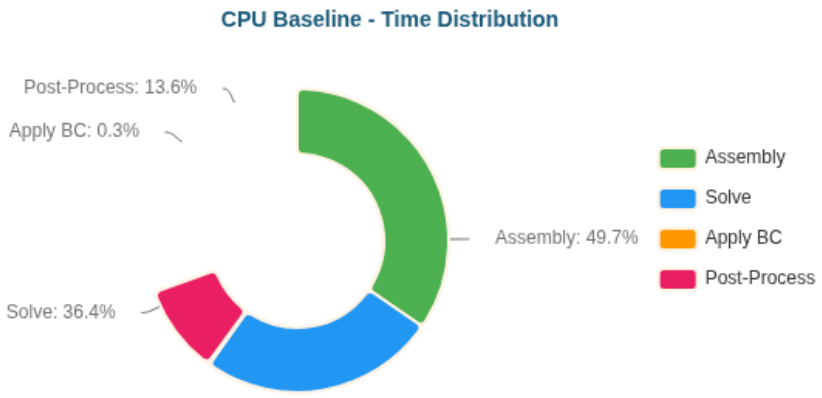


Time Distribution by Implementation (%)

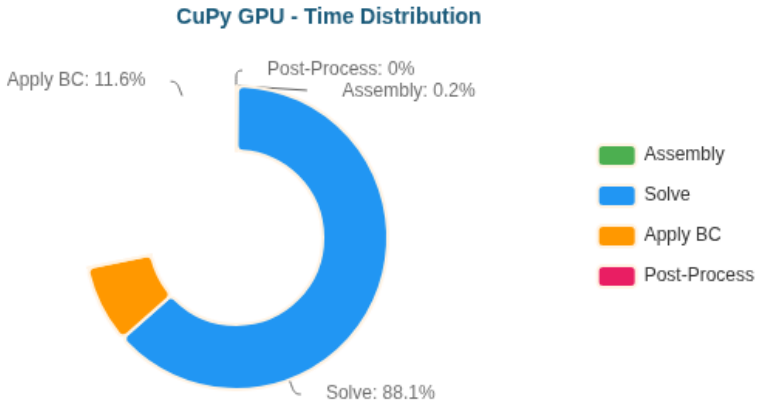
Backward-Facing Step (M) - 195,362 nodes

Implementation	Primary Bottleneck	Secondary Bottleneck
CPU Baseline	Assembly (50%)	Solve (36%)
CPU Threaded	Solve (56%)	Assembly (28%)
CPU Multiprocess	Solve (78%)	Assembly (12%)
Numba CPU	Solve (94%)	BC (4%)
Numba CUDA	Solve (50%)	Assembly (27%)
CuPy GPU	Solve (88%)	BC (12%)

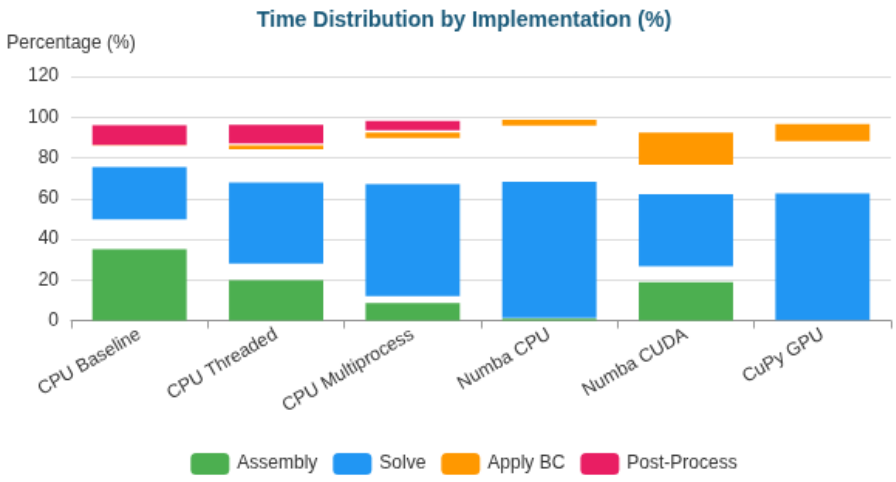
Time Distribution:



CPU Baseline - Time Distribution



CuPy GPU - Time Distribution



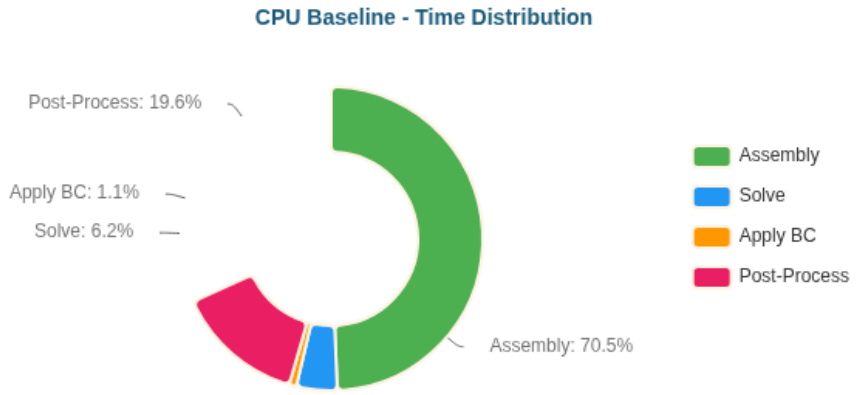
Time Distribution by Implementation (%)

Elbow 90° (XS) - 411 nodes

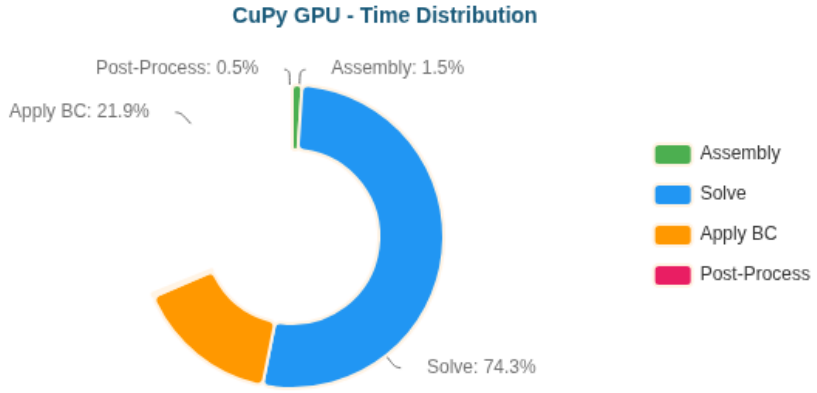
Implementation	Primary Bottleneck	Secondary Bottleneck
CPU Baseline	Assembly (71%)	Post-Proc (20%)
CPU Threaded	Assembly (59%)	Post-Proc (24%)
CPU Multiprocess	Assembly (50%)	Post-Proc (49%)

Implementation	Primary Bottleneck	Secondary Bottleneck
Numba CPU	Solve (53%)	BC (22%)
Numba CUDA	Solve (87%)	Assembly (6%)
CuPy GPU	Solve (74%)	BC (22%)

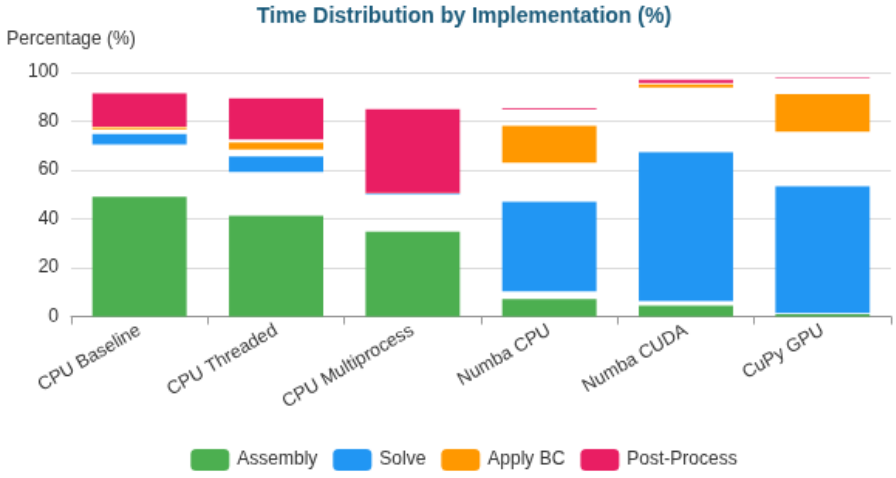
Time Distribution:



CPU Baseline - Time Distribution



CuPy GPU - Time Distribution

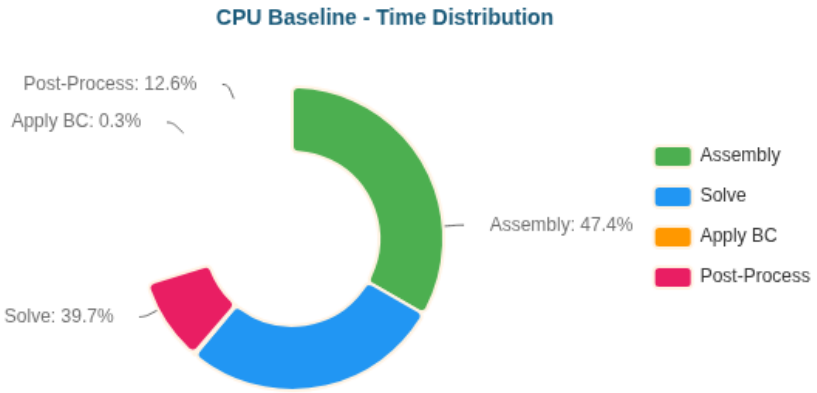


Time Distribution by Implementation (%)

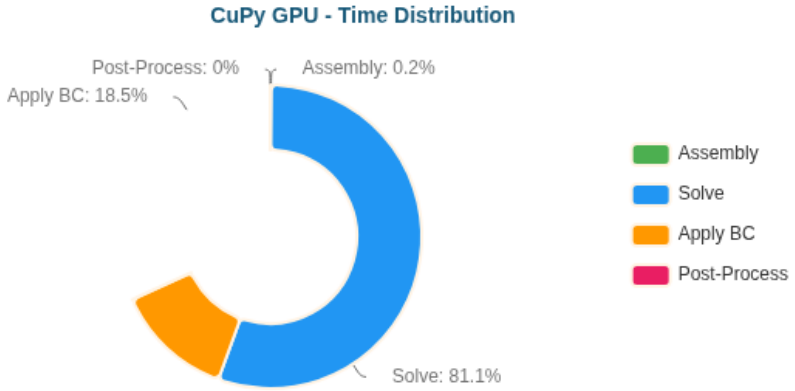
Elbow 90° (M) - 161,984 nodes

Implementation	Primary Bottleneck	Secondary Bottleneck
CPU Baseline	Assembly (47%)	Solve (40%)
CPU Threaded	Solve (51%)	Assembly (31%)
CPU Multiprocess	Solve (73%)	Assembly (15%)
Numba CPU	Solve (94%)	BC (4%)
Numba CUDA	Solve (48%)	Assembly (28%)
CuPy GPU	Solve (81%)	BC (19%)

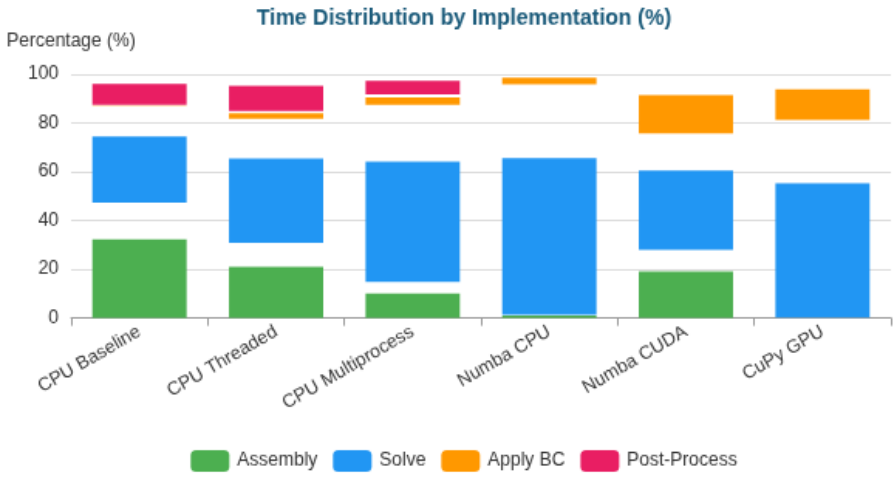
Time Distribution:



CPU Baseline - Time Distribution



CuPy GPU - Time Distribution

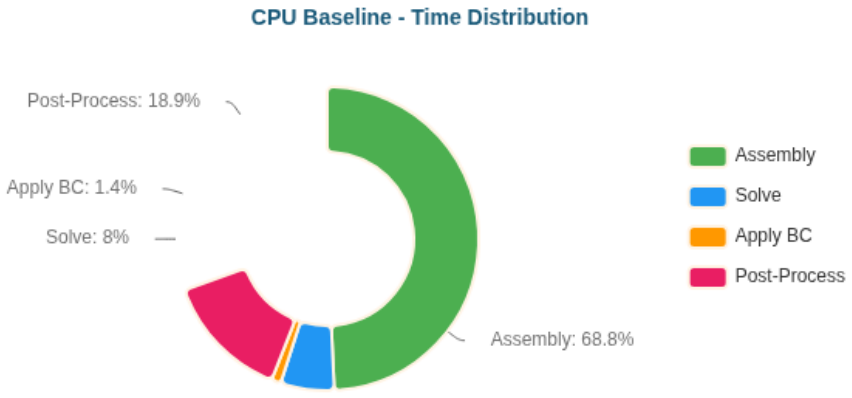


Time Distribution by Implementation (%)

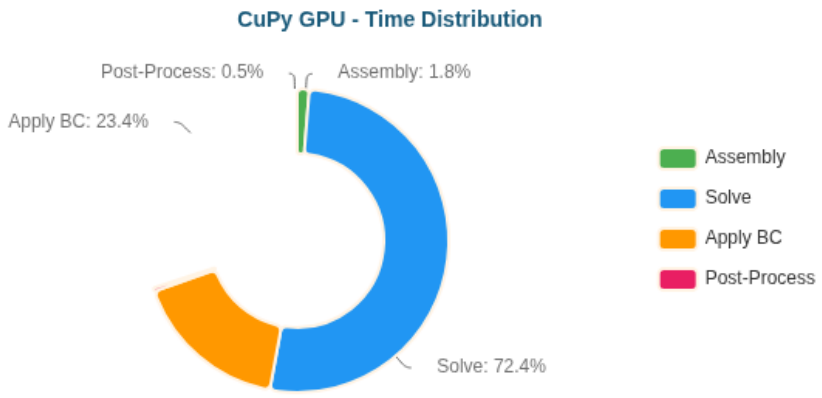
S-Bend (XS) - 387 nodes

Implementation	Primary Bottleneck	Secondary Bottleneck
CPU Baseline	Assembly (69%)	Post-Proc (19%)
CPU Threaded	Assembly (50%)	Post-Proc (20%)
CPU Multiprocess	Assembly (50%)	Post-Proc (49%)
Numba CPU	Solve (52%)	BC (21%)
Numba CUDA	Solve (89%)	Assembly (5%)
CuPy GPU	Solve (72%)	BC (23%)

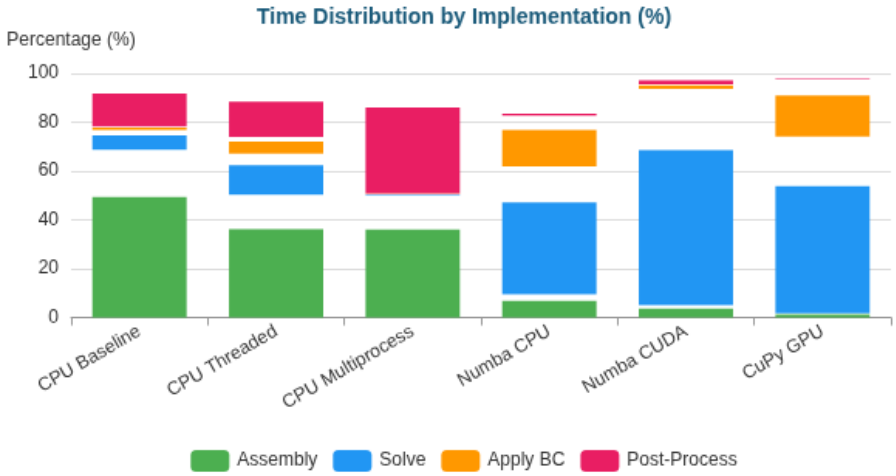
Time Distribution:



CPU Baseline - Time Distribution



CuPy GPU - Time Distribution

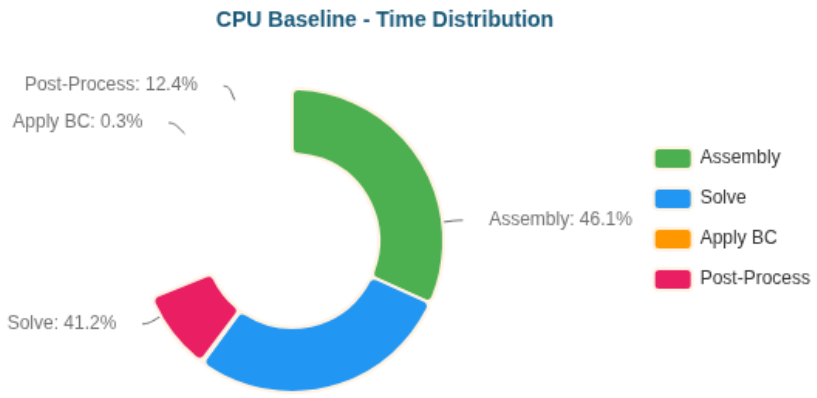


Time Distribution by Implementation (%)

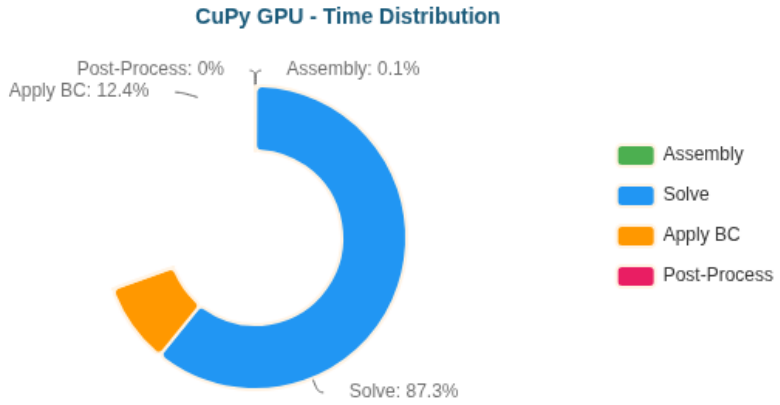
S-Bend (M) - 196,078 nodes

Implementation	Primary Bottleneck	Secondary Bottleneck
CPU Baseline	Assembly (46%)	Solve (41%)
CPU Threaded	Solve (58%)	Assembly (26%)
CPU Multiprocess	Solve (80%)	Assembly (11%)
Numba CPU	Solve (95%)	BC (4%)
Numba CUDA	Solve (52%)	Assembly (26%)
CuPy GPU	Solve (87%)	BC (12%)

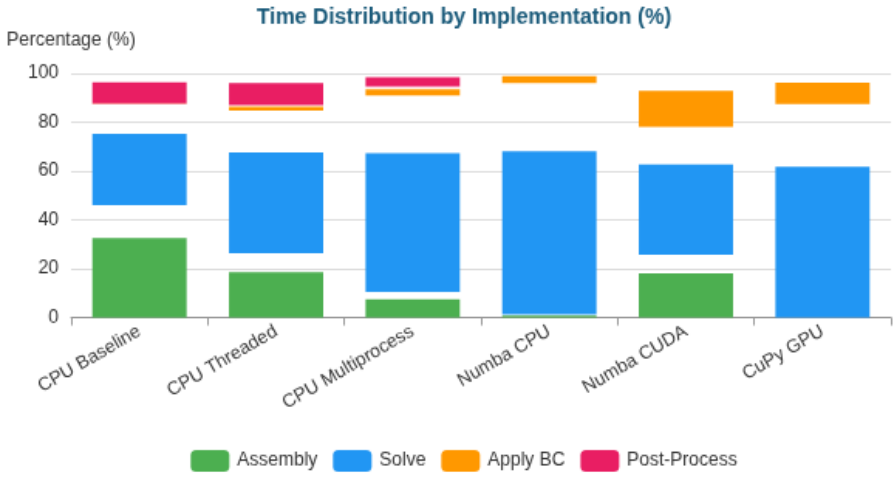
Time Distribution:



CPU Baseline - Time Distribution



CuPy GPU - Time Distribution

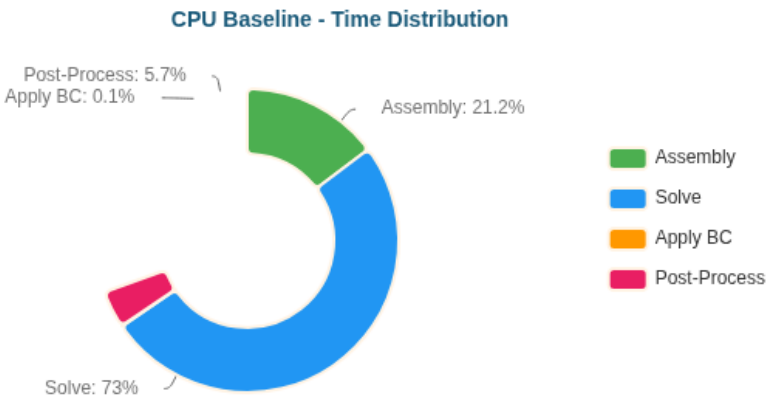


Time Distribution by Implementation (%)

S-Bend (L) - 765,441 nodes

Implementation	Primary Bottleneck	Secondary Bottleneck
CPU Baseline	Solve (73%)	Assembly (21%)

Time Distribution:

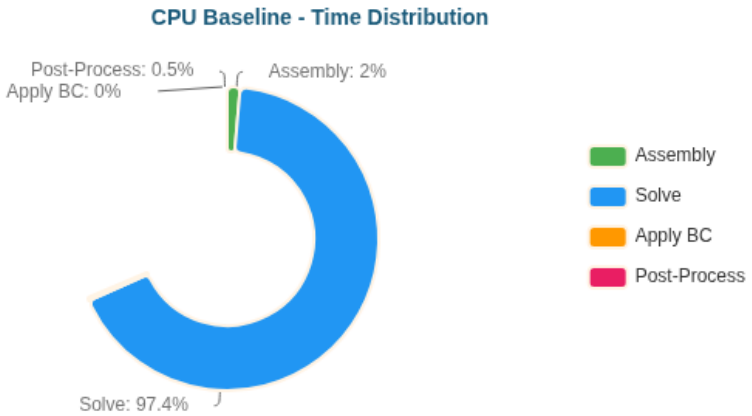


CPU Baseline - Time Distribution

S-Bend (XL) - 1,286,039 nodes

Implementation	Primary Bottleneck	Secondary Bottleneck
CPU Baseline	Solve (97%)	Assembly (2%)

Time Distribution:

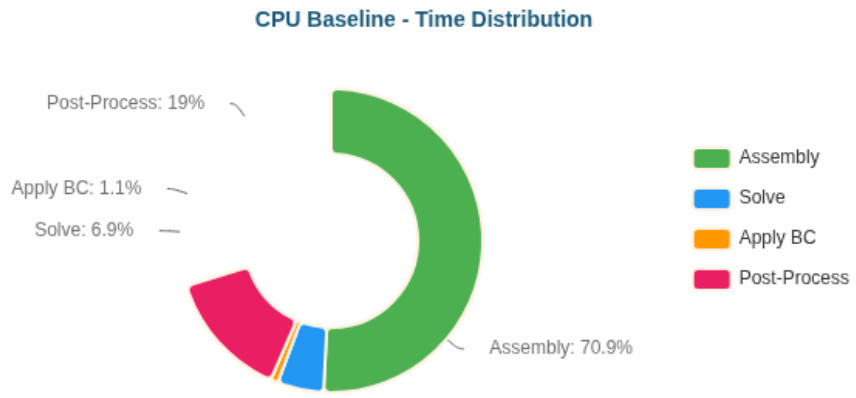


CPU Baseline - Time Distribution

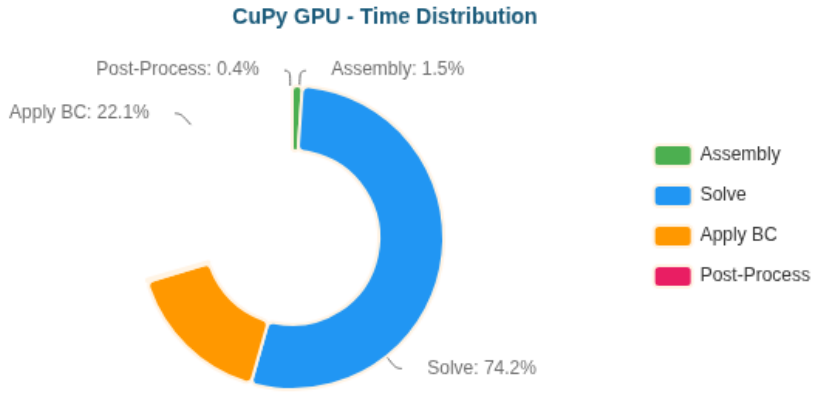
T-Junction (XS) - 393 nodes

Implementation	Primary Bottleneck	Secondary Bottleneck
CPU Baseline	Assembly (71%)	Post-Proc (19%)
CPU Threaded	Assembly (53%)	Post-Proc (24%)
CPU Multiprocess	Assembly (51%)	Post-Proc (48%)
Numba CPU	Solve (59%)	BC (17%)
Numba CUDA	Solve (88%)	Assembly (6%)
CuPy GPU	Solve (74%)	BC (22%)

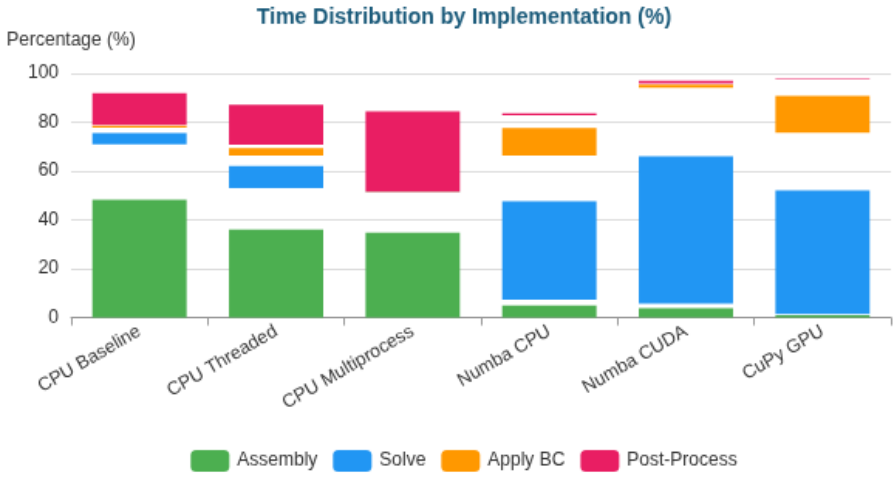
Time Distribution:



CPU Baseline - Time Distribution



CuPy GPU - Time Distribution



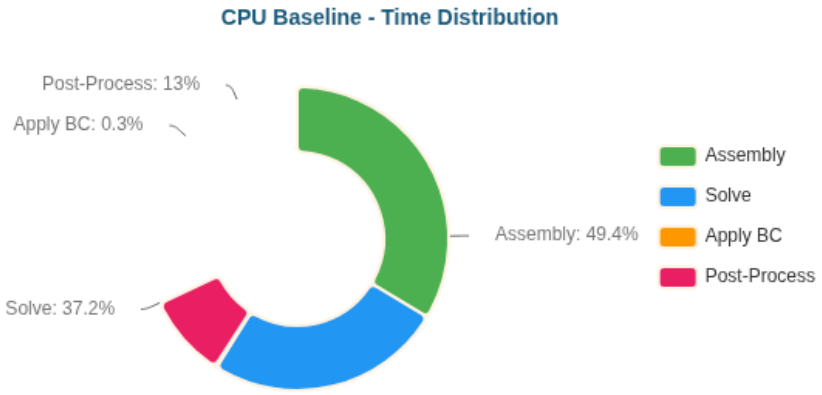
Time Distribution by Implementation (%)

T-Junction (M) - 196,420 nodes

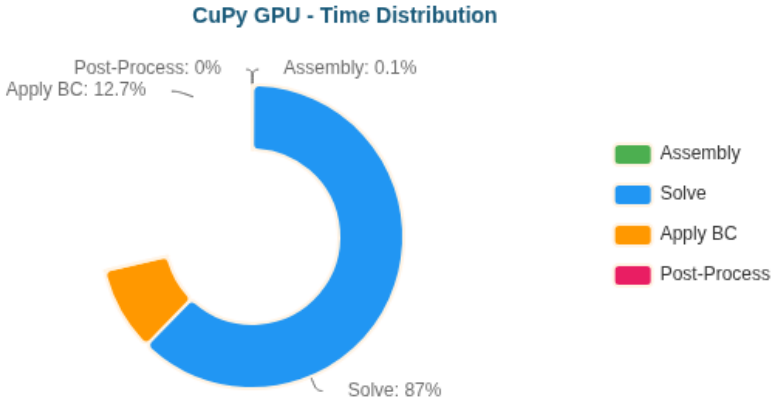
Implementation	Primary Bottleneck	Secondary Bottleneck
CPU Baseline	Assembly (49%)	Solve (37%)
CPU Threaded	Solve (57%)	Assembly (28%)
CPU Multiprocess	Solve (79%)	Assembly (11%)

Implementation	Primary Bottleneck	Secondary Bottleneck
Numba CPU	Solve (95%)	BC (4%)
Numba CUDA	Solve (51%)	Assembly (27%)
CuPy GPU	Solve (87%)	BC (13%)

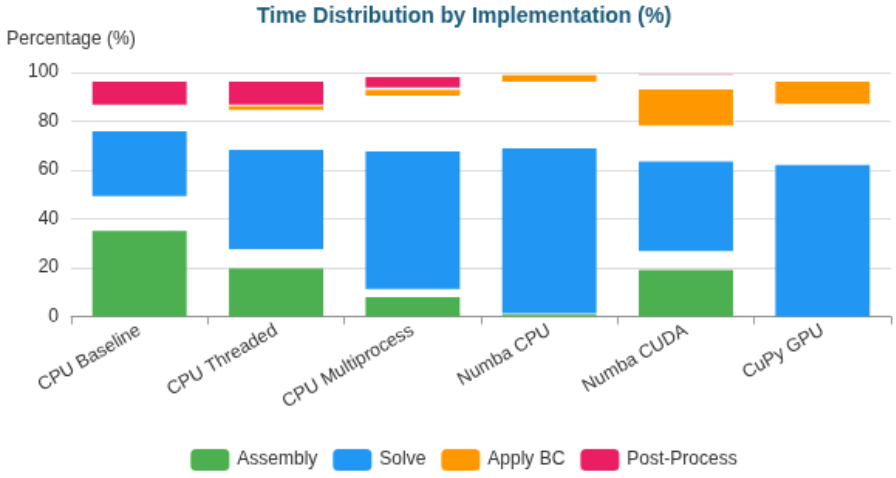
Time Distribution:



CPU Baseline - Time Distribution



CuPy GPU - Time Distribution

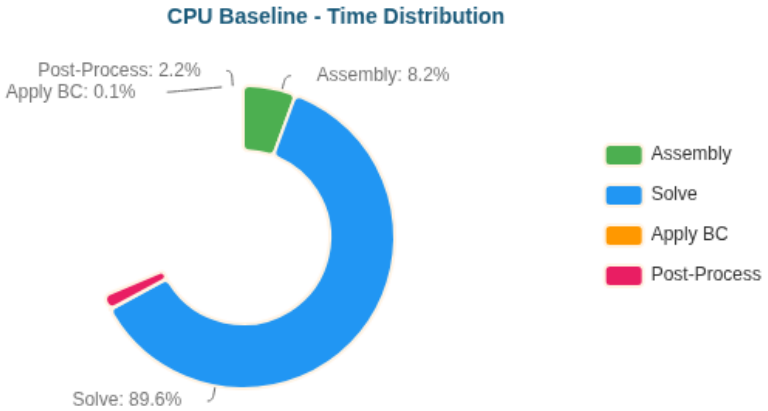


Time Distribution by Implementation (%)

T-Junction (L) - 768,898 nodes

Implementation	Primary Bottleneck	Secondary Bottleneck
CPU Baseline	Solve (90%)	Assembly (8%)

Time Distribution:

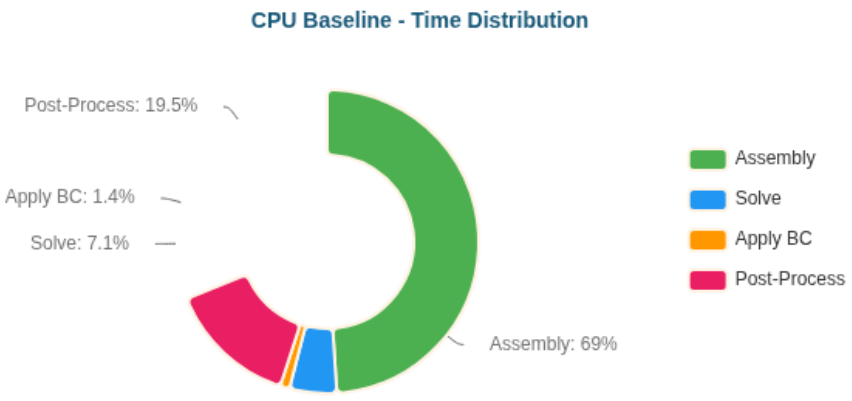


CPU Baseline - Time Distribution

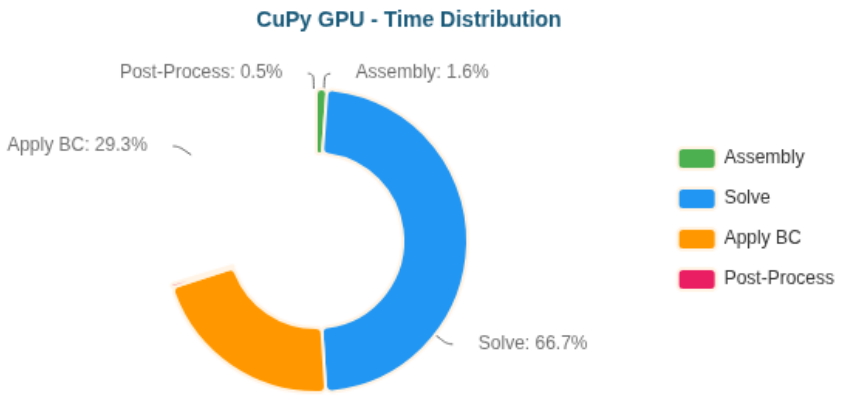
Venturi (XS) - 341 nodes

Implementation	Primary Bottleneck	Secondary Bottleneck
CPU Baseline	Assembly (69%)	Post-Proc (19%)
CPU Threaded	Assembly (51%)	Post-Proc (24%)
CPU Multiprocess	Assembly (50%)	Post-Proc (49%)
Numba CPU	Solve (49%)	BC (21%)
Numba CUDA	Solve (87%)	Assembly (6%)
CuPy GPU	Solve (67%)	BC (29%)

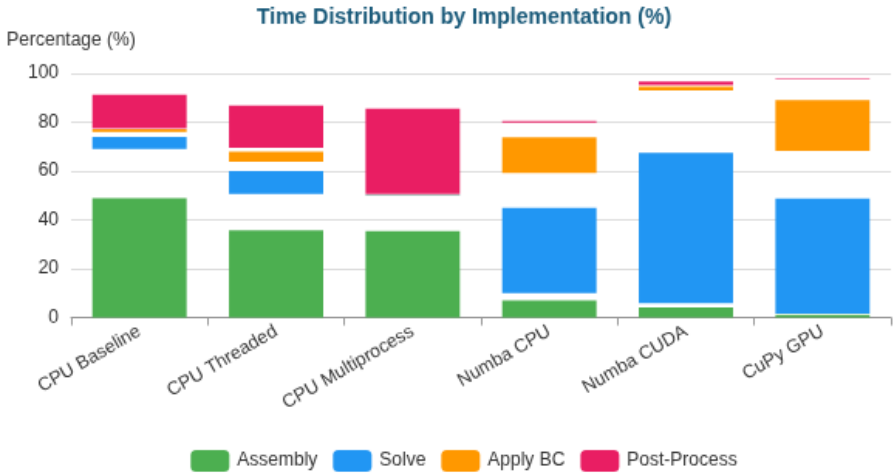
Time Distribution:



CPU Baseline - Time Distribution



CuPy GPU - Time Distribution

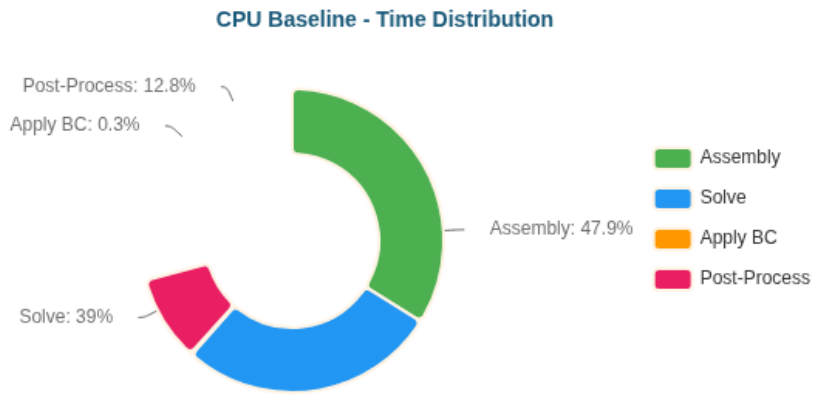


Time Distribution by Implementation (%)

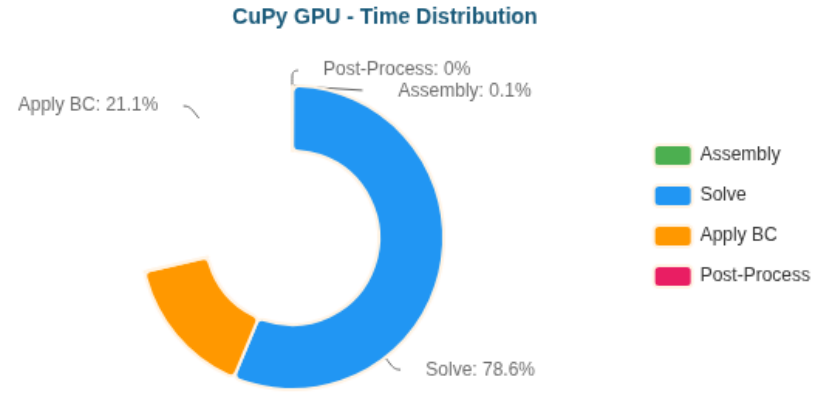
Venturi (M) - 194,325 nodes

Implementation	Primary Bottleneck	Secondary Bottleneck
CPU Baseline	Assembly (48%)	Solve (39%)
CPU Threaded	Solve (55%)	Assembly (29%)
CPU Multiprocess	Solve (78%)	Assembly (12%)
Numba CPU	Solve (94%)	BC (5%)
Numba CUDA	Solve (49%)	Assembly (28%)
CuPy GPU	Solve (79%)	BC (21%)

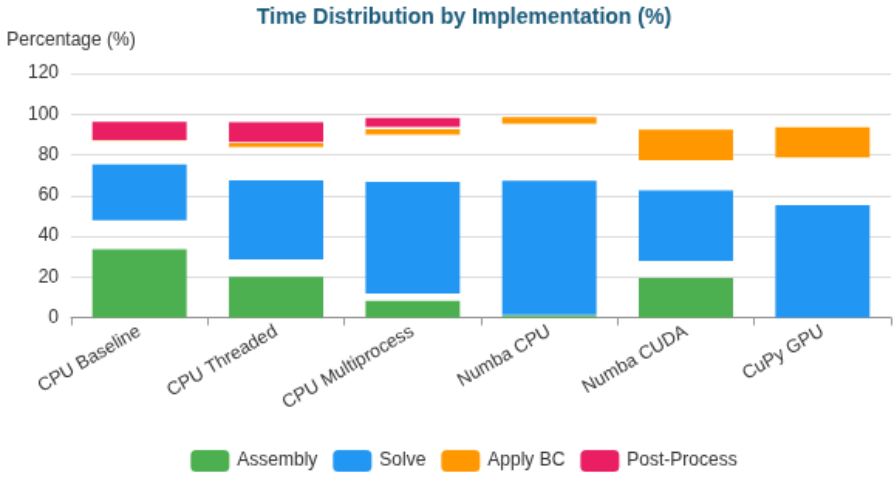
Time Distribution:



CPU Baseline - Time Distribution



CuPy GPU - Time Distribution

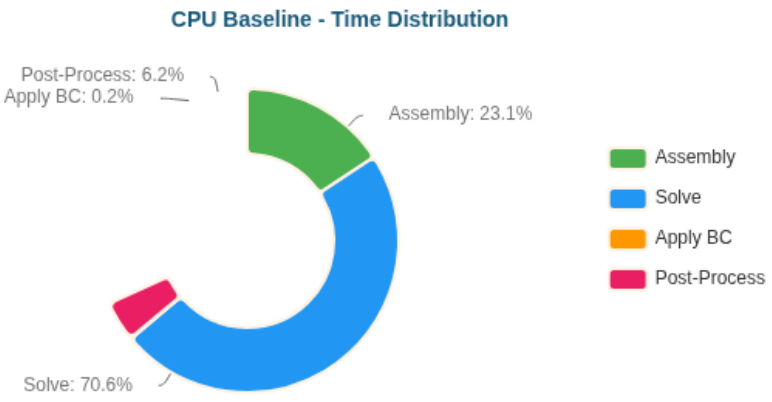


Time Distribution by Implementation (%)

Venturi (L) - 763,707 nodes

Implementation	Primary Bottleneck	Secondary Bottleneck
CPU Baseline	Solve (71%)	Assembly (23%)

Time Distribution:

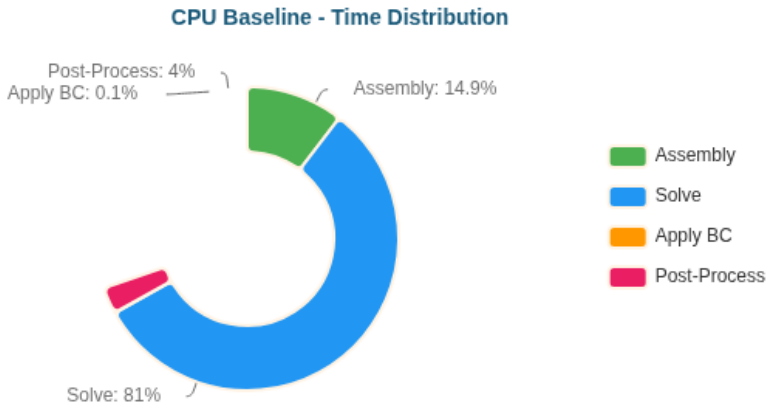


CPU Baseline - Time Distribution

Venturi (XL) - 1,284,412 nodes

Implementation	Primary Bottleneck	Secondary Bottleneck
CPU Baseline	Solve (81%)	Assembly (15%)

Time Distribution:

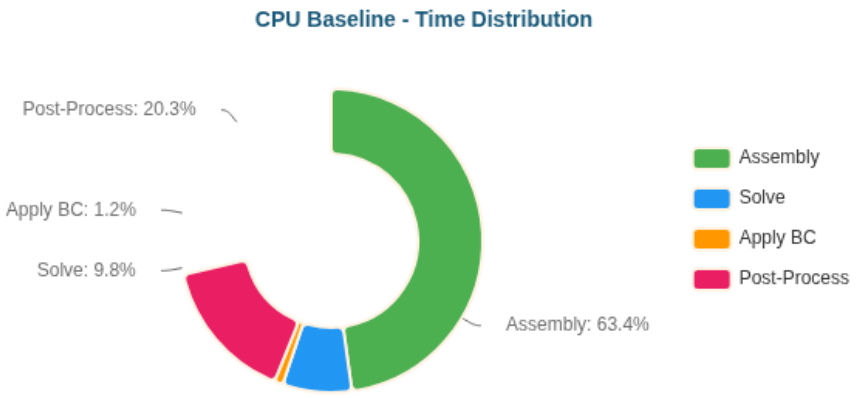


CPU Baseline - Time Distribution

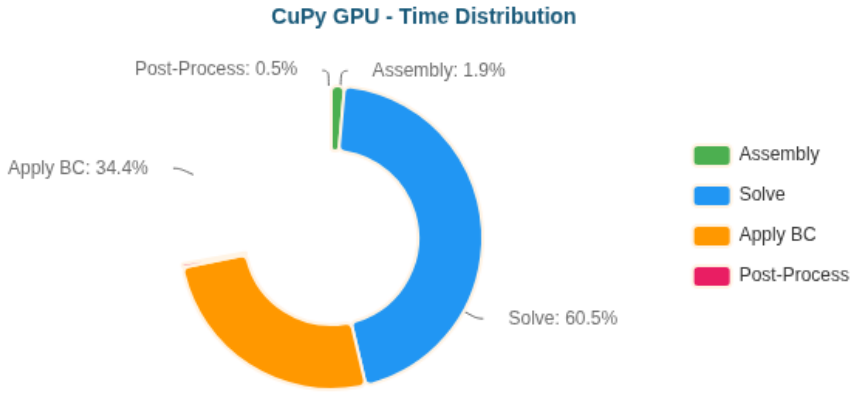
Y-Shaped (XS) - 201 nodes

Implementation	Primary Bottleneck	Secondary Bottleneck
CPU Baseline	Assembly (63%)	Post-Proc (20%)
CPU Threaded	Assembly (44%)	Post-Proc (26%)
CPU Multiprocess	Assembly (51%)	Post-Proc (49%)
Numba CPU	Solve (52%)	BC (15%)
Numba CUDA	Solve (86%)	Assembly (6%)
CuPy GPU	Solve (61%)	BC (34%)

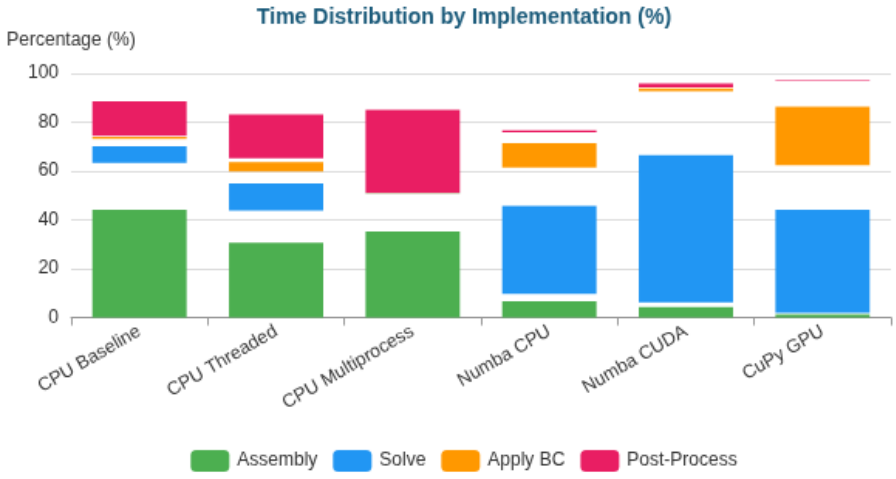
Time Distribution:



CPU Baseline - Time Distribution



CuPy GPU - Time Distribution



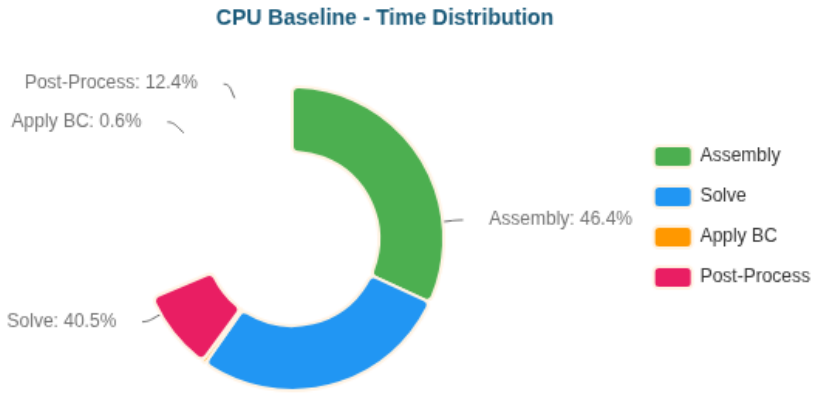
Time Distribution by Implementation (%)

Y-Shaped (M) - 195,853 nodes

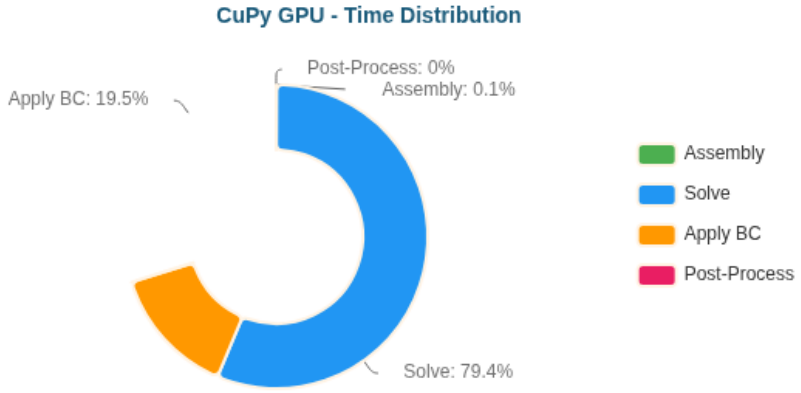
Implementation	Primary Bottleneck	Secondary Bottleneck
CPU Baseline	Assembly (46%)	Solve (41%)
CPU Threaded	Solve (59%)	Assembly (26%)
CPU Multiprocess	Solve (79%)	Assembly (10%)

Implementation	Primary Bottleneck	Secondary Bottleneck
Numba CPU	Solve (93%)	BC (6%)
Numba CUDA	Solve (48%)	BC (26%)
CuPy GPU	Solve (79%)	BC (20%)

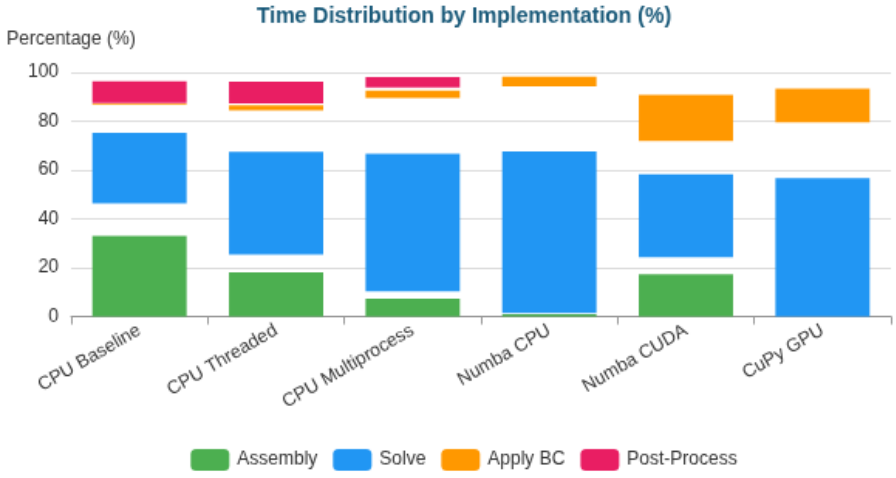
Time Distribution:



CPU Baseline - Time Distribution



CuPy GPU - Time Distribution

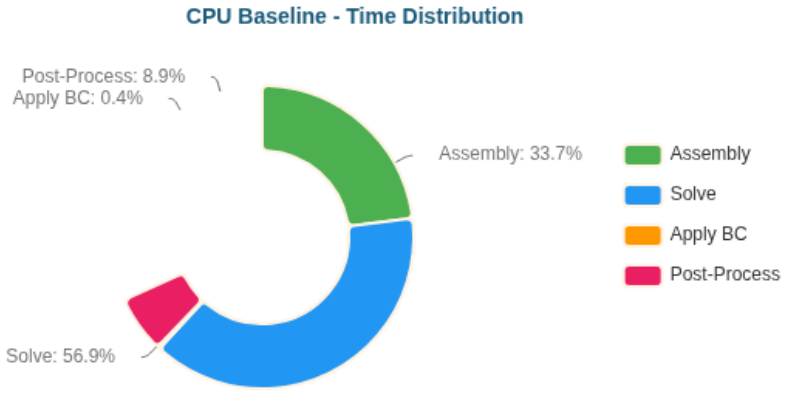


Time Distribution by Implementation (%)

Y-Shaped (L) - 772,069 nodes

Implementation	Primary Bottleneck	Secondary Bottleneck
CPU Baseline	Solve (57%)	Assembly (34%)

Time Distribution:

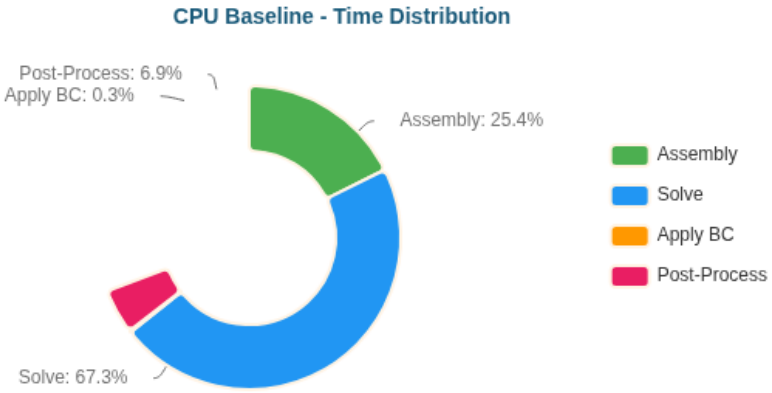


CPU Baseline - Time Distribution

Y-Shaped (XL) - 1,357,953 nodes

Implementation	Primary Bottleneck	Secondary Bottleneck
CPU Baseline	Solve (67%)	Assembly (25%)

Time Distribution:



CPU Baseline - Time Distribution

Why Each Optimization Helps

Transition	Reason
Baseline → Threaded	Limited by Python GIL; threads only help for I/O

Transition	Reason
Threaded → Multiprocess	Bypasses GIL via separate processes; IPC overhead limits gains
Multiprocess → Numba CPU	JIT compilation eliminates interpreter overhead; true parallel loops
Numba CPU → Numba CUDA	GPU parallelism: thousands of threads vs dozens of CPU cores
Numba CUDA → CuPy GPU	CUDA C kernels more optimized than Numba-generated PTX