Computational Process Networks

a model and framework for high-throughput signal processing

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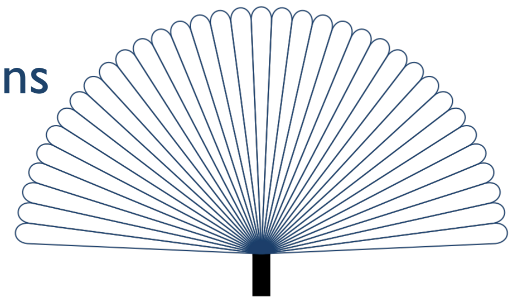
Outline

- Need for speed
- Dataflow models
- Contributions
  - Dynamic Distributed Deadlock Detection & Resolution (D4R)
  - The Computational Process Network (CPN) model
  - CPN framework implementation & case studies
- Conclusion

Introduction

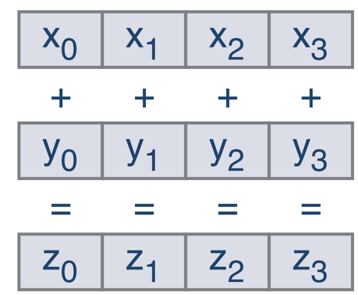
- High-throughput, high-performance applications
  - Sonar beamforming (100s of MB/s, 10s of GFLOPS)
  - Synthetic Aperture Radar (SAR) processing
- Traditional embedded concurrent implementations
  - Custom hardware
  - Custom integration of embedded processors



- Commercial workstations and clusters
  - Multi-core symmetric multiprocessing (SMP) computing
  - Distributed (cluster) computing, high-speed interconnect
  - Significant savings in design time

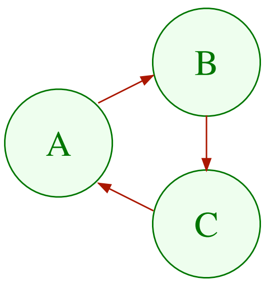
High Performance

- Single-task approaches
  - Single Instruction Multiple Data (SIMD) for data parallelism
  - Hand-optimized signal processing kernels and libraries
  - Memory latency hiding to reduce input/output bottleneck
  - Lock memory buffers to avoid swapping to disk
  - Fixed-priority real-time scheduling



- Executing tasks efficiently on parallel hardware
  - **Scalability:** more parallel hardware gives more performance
  - **Determinate:** always gets same answer (no race conditions)
  - **Locking:** prevent concurrent access to shared resources

Concurrent Programming



- Tension between scalability, determinism, and deadlock
  - Deadlock: processes waiting on each other in a cycle
  - Coarse-grained locks yield systems that do not scale well
  - Insufficient locking may cause non-determinate execution
- Industry approaches leave concurrency issues to programmer
  - Threads are "wildly nondeterministic" [Lee 2006]
  - Message Passing Interface compared to "assembly language"
- Formal models can handle complications of concurrency

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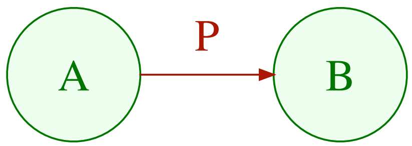
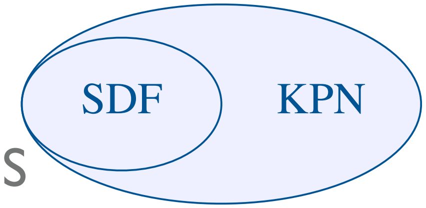
Dataflow Models

- Programs are modeled as directed graphs
  - Each node represents a computational unit
  - Each edge represents a one-way first-in first-out queue
  - Nodes may have any number of input or output edges
  - Nodes may communicate only via these edges

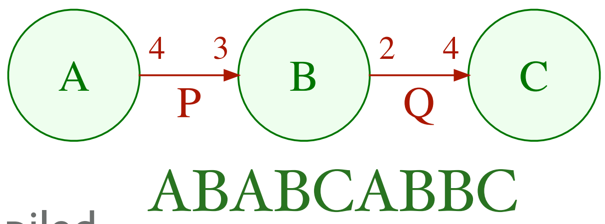


- Dataflow naturally models functional parallelism in systems
- Example dataflow models
  - Synchronous Dataflow (SDF), used in Agilent ADS
  - Kahn Process Networks (KPN), used in NI LabVIEW



Static Dataflow Models

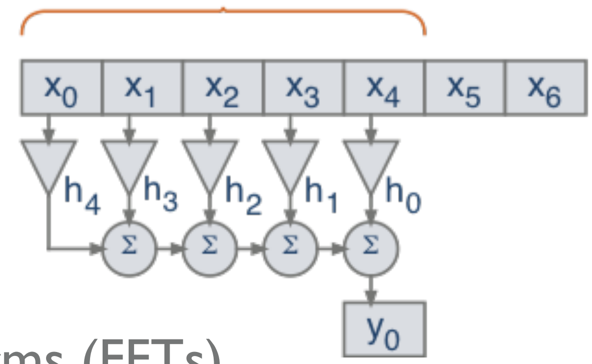
- Firing behavior of each node is known and static
  - Synchronous Dataflow (SDF) [Lee 1986]
  - Computation Graphs (CG) [Karp & Miller 1966]
- Termination & boundedness decidable
  - Flow of control and memory usage can be compiled
  - Schedule constructed once and repeatedly executed



- CG has parameters at each queue
  - U: number of tokens inserted by the producer at each firing
  - W: number of tokens removed by the consumer at each firing
  - T: (*firing threshold*) tokens present before consumer fires T≥W
- SDF is a special case of CG where T=W for all queues

Firing Thresholds

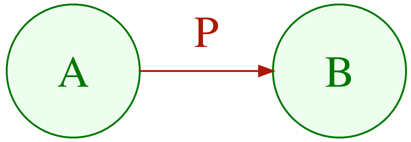
- A node can access more tokens than it will dequeue
- Model sliding window algorithms
  - Common in signal processing
  - Digital filters, y = x * h
  - Overlap-and-save fast Fourier transforms (FFTs)



- Queue maintains state and node becomes memoryless
  - Prevents node from having to make local copy of state
  - Enables optimizations for data management in queue

Kahn Process Networks

- A *networked set* of Turing machines, dynamically scheduled
- Determinate execution regardless of execution order
  - Sequential or concurrent execution
  - Mathematically proven model [Kahn 1974]
  - **Composable:** nodes can be clustered into a hierarchy to create larger, more complex systems



- Dynamic firing rules at each node
  - *Blocking reads:* suspend execution when attempting to read from an empty queue (necessary for determinism)
  - *Non-blocking writes:* never suspend a node for producing
- Possibly **unbounded:** may require infinite memory
- Termination and boundedness are undecidable in finite time

Dataflow Model Properties

	Model of Computation		
Property	SDF	CG	KPN
Determinism	✔	✔	✔
Boundedness	✔	✔	
Scalability			✔
Composability			✔
Firing Thresholds		✔	

SDF: Synchronous Dataflow
CG: Computation Graphs
KPN: Kahn Process Networks

Contributions

- Distributed Dynamic Deadlock Detection and Resolution (D4R)
  - For execution of KPN and CPN in bounded memory
- New model: Computational Process Networks
  - Built on formal underpinnings of KPN
  - Add firing thresholds and maintain scalability and composability
  - Bounded scheduling and enhancements for efficient implementation
- CPN Implementation and Case Studies
  - High-performance, scalable, distributed, and low overhead
  - Open-source implementation framework on POSIX (Unix) systems

CPN preserves the formal properties of KPN and reduces operations to implement common signal processing algorithms.

KPN Bounded Scheduling

- Execute KPN in bounded memory, if possible [Parks 95]
  - Place bounds on queue sizes and use blocking writes
  - Queue bounds may introduce *artificial deadlock*
  - Requires dynamic detection & resolution of deadlocks
  - Lengthen shortest deadlocked full queue to resolve
- Effective: all tokens produced are eventually consumed
- Fair: nodes cannot indefinitely ignore any input or output

	Parks 95	Geilen & Basten 03	D4R
Deadlock type specified	Global	Local	Local
Complete execution	No	Yes, if *effective* KPN	Yes, if *fair* KPN

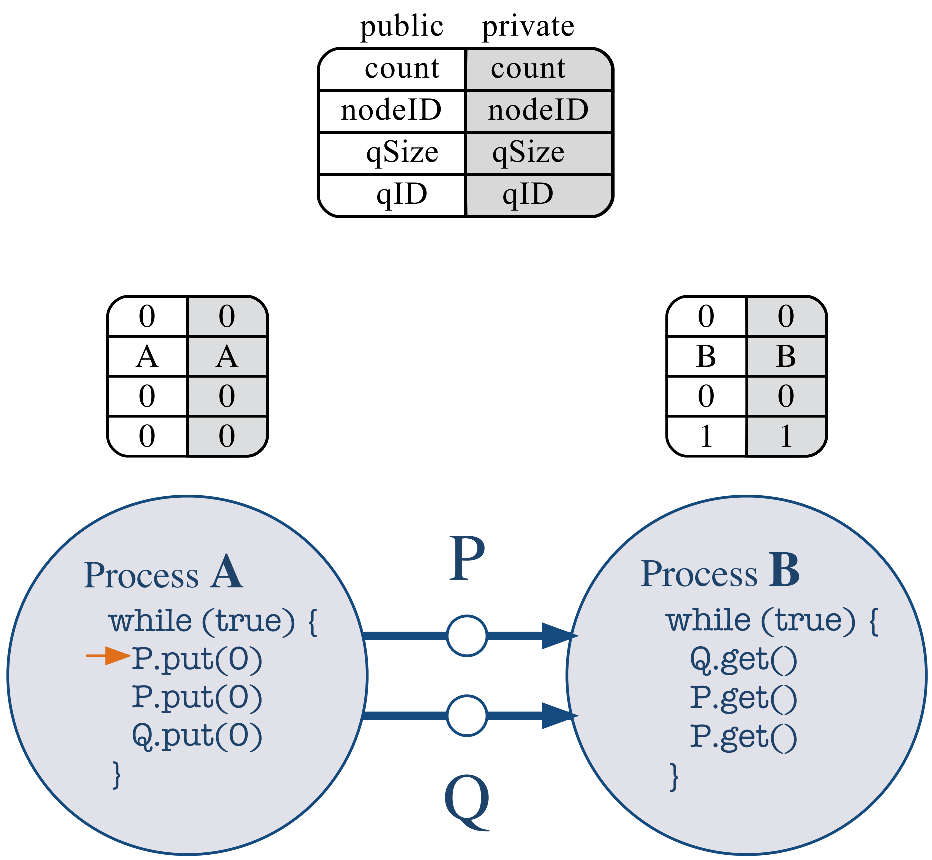
- Distributed algorithm by [Mitchell & Merritt 84] can detect local deadlocks in KPN [Olson & Evans 05]

Contribution #1: D4R

- D4R algorithm for KPN and CPN [Allen & Evans 07]
  - Based on a different priority-based distributed algorithm [M&M 84]
  - Detects whether deadlock is present
  - Determines whether a detected deadlock is real or artificial
  - If artificial, identifies the node blocked on culpable queue
  - Artificial deadlock is resolved by enlarging the culpable queue

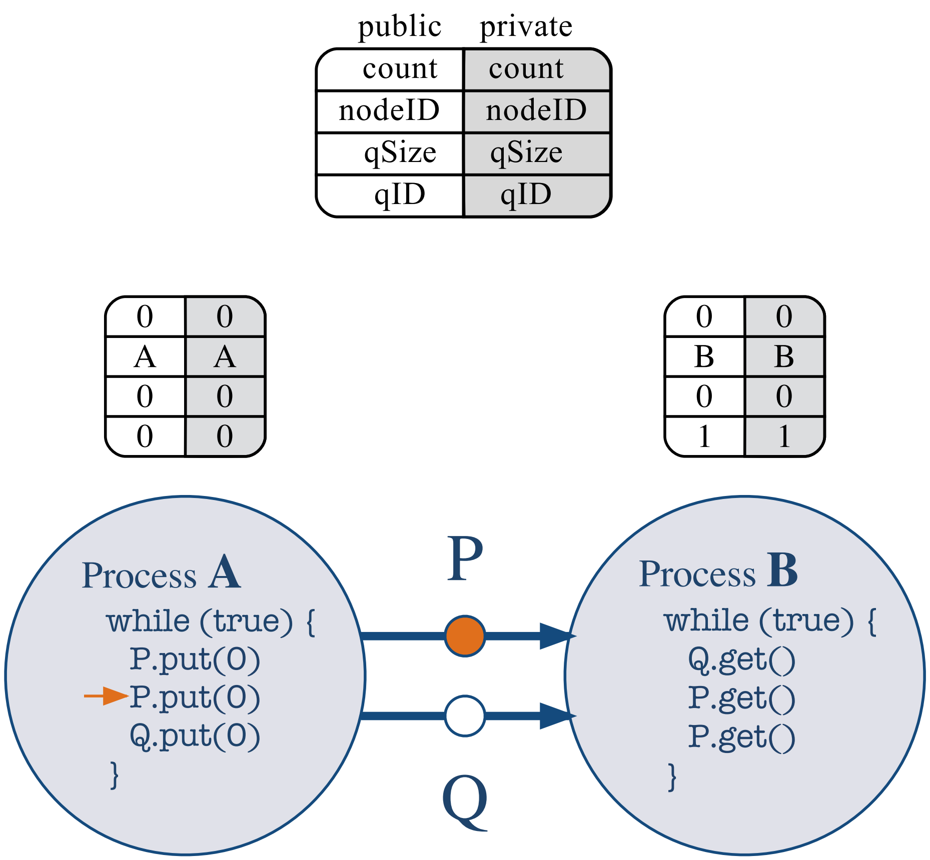
- Distributed and scalable
  - Each process contains D4R state variables
  - D4R state transactions occur between interacting processes

Example: Artificial Deadlock Detection & Resolution with D4R



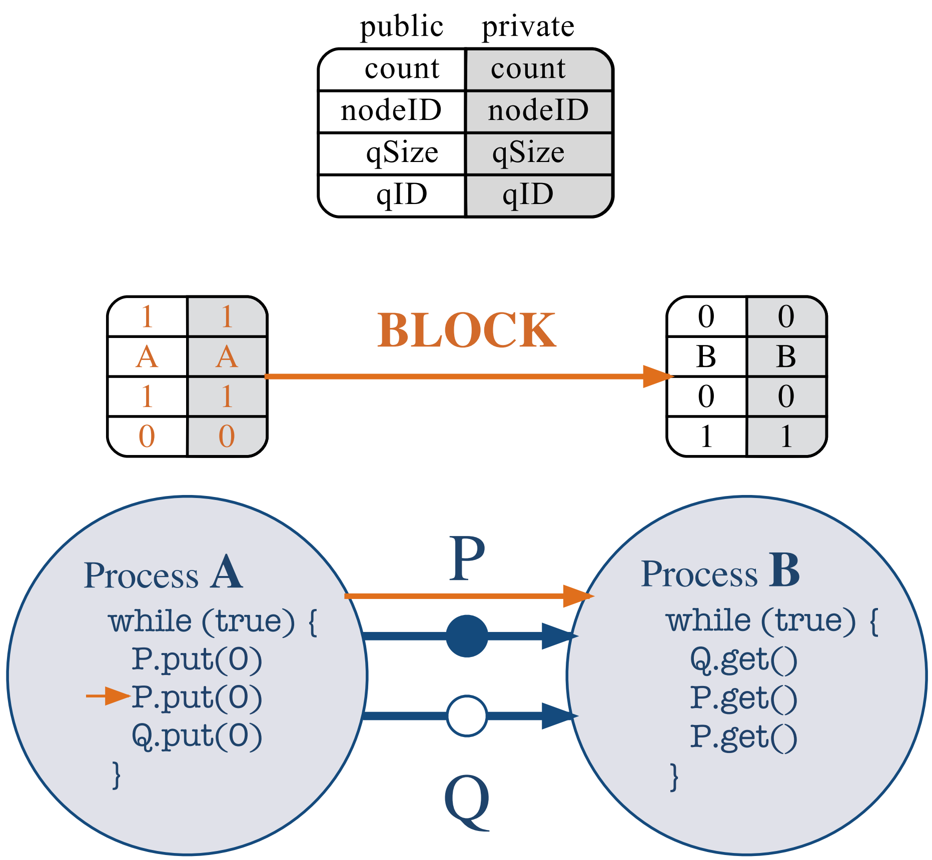
- Each node is an independent process
- Each node contains D4R state variables
  - Four state variables
  - Public and private sets
- Four state transitions
- Nodes directly interact
- Example is feed-forward
- One of several possible orders of execution

Example: Artificial Deadlock Detection & Resolution with D4R



1. **A** writes to **P**

Example: Artificial Deadlock Detection & Resolution with D4R



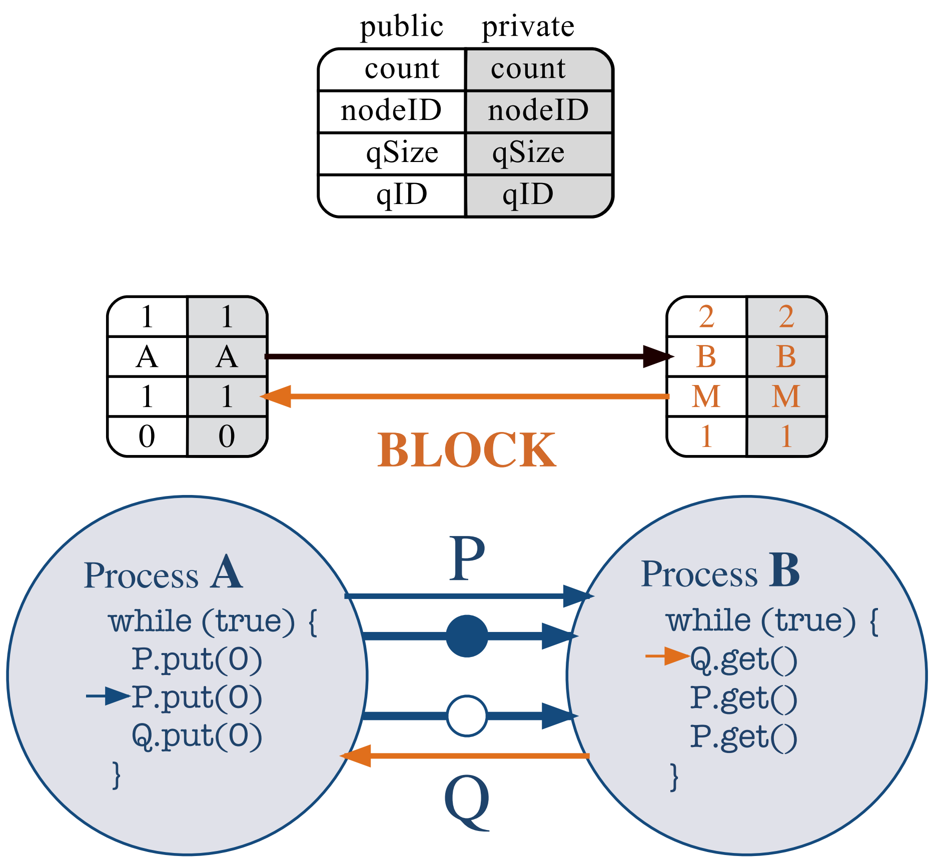
1. **A** writes to **P**
2. **A** *blocks* writing to **P**

   D4R state updated for ***A****:*

   count incremented and

   qSize set to size of ***P***

Example: Artificial Deadlock Detection & Resolution with D4R



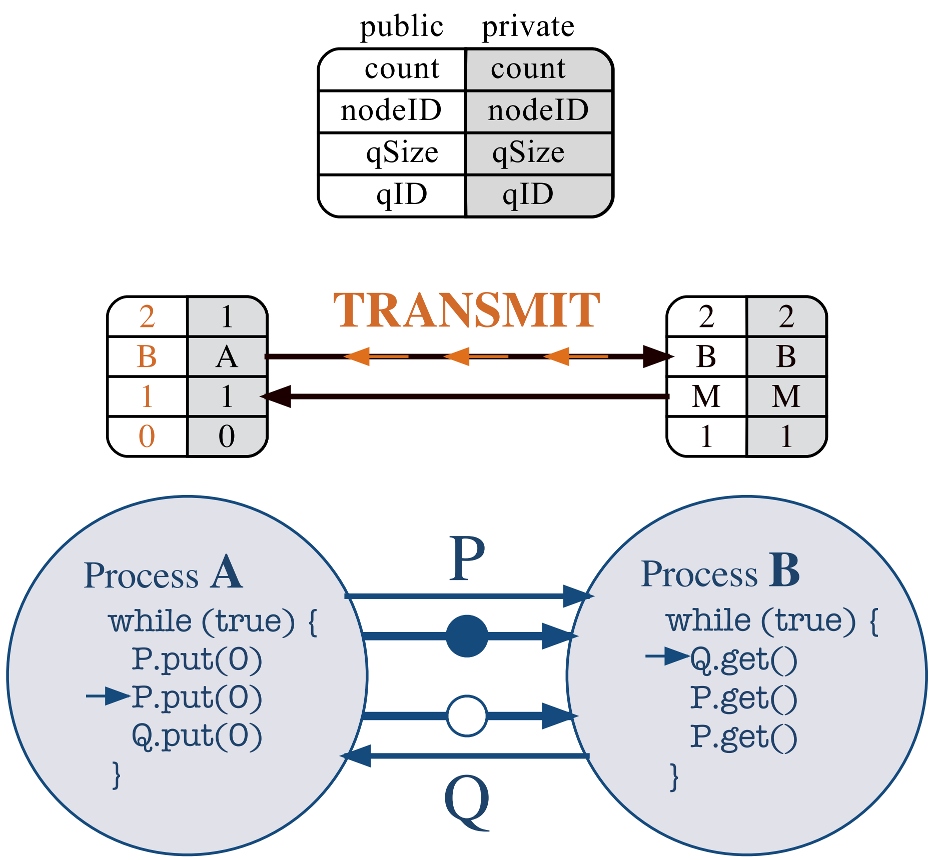
1. **A** writes to **P**
2. **A** *blocks* writing to **P**
3. **B** *blocks* reading from **Q**

   D4R state updated for ***B****:*

   count incremented and

   qSize set to MAX_UINT

Example: Artificial Deadlock Detection & Resolution with D4R



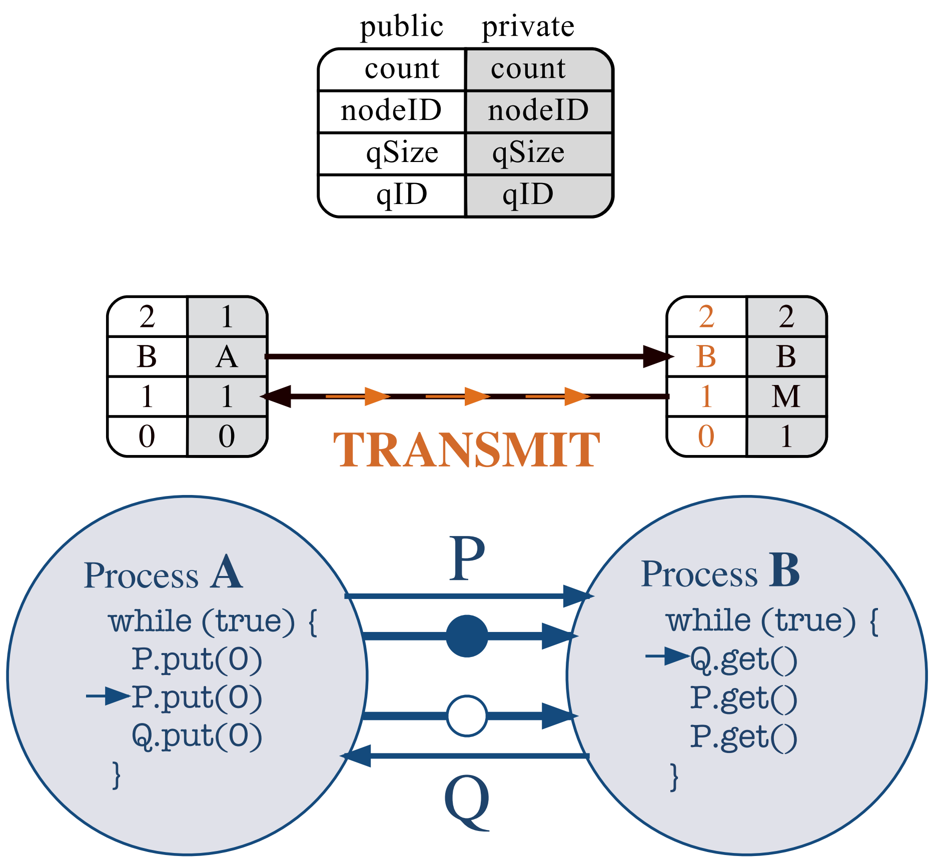
1. **A** writes to **P**
2. **A** *blocks* writing to **P**
3. **B** *blocks* reading from **Q**
4. **B** *transmits* to **A**

   *D4R state updated for **A**:*

   keep larger count:nodeID

   and smaller qSize:qID

Example: Artificial Deadlock Detection & Resolution with D4R



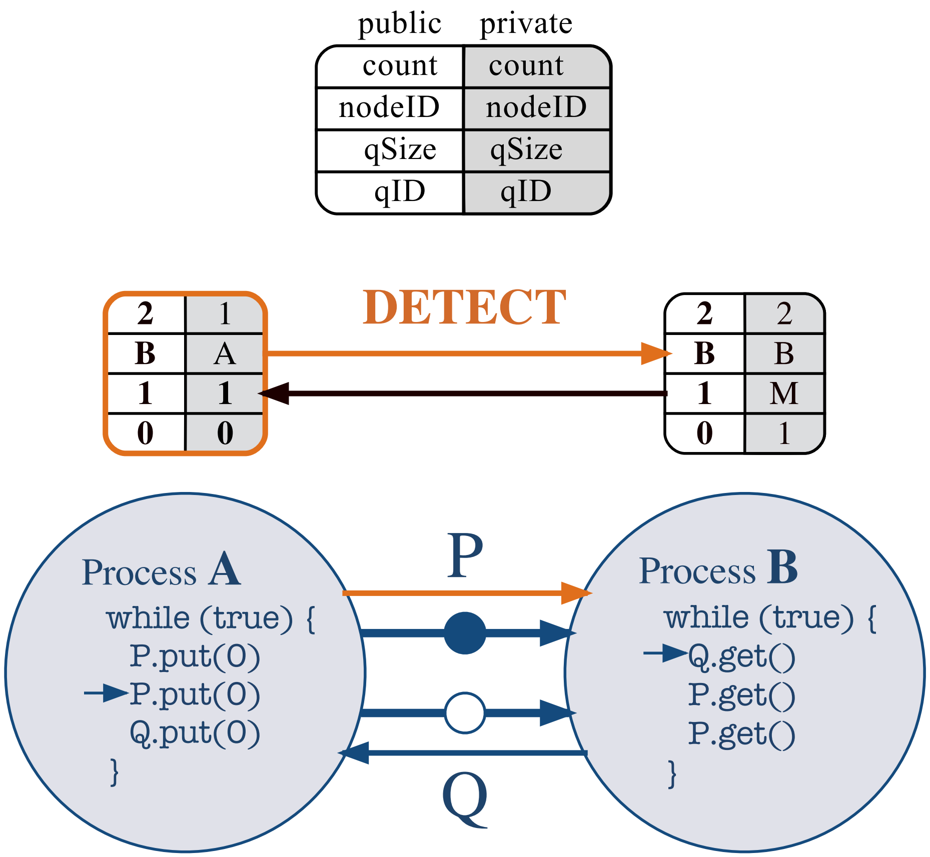
1. **A** writes to **P**
2. **A** *blocks* writing to **P**
3. **B** *blocks* reading from **Q**
4. **B** *transmits* to **A**
5. **A** *transmits* to **B**

   D4R state updated for ***B****:*

   keep larger count:nodeID

   and smaller qSize:qID

Example: Artificial Deadlock Detection & Resolution with D4R



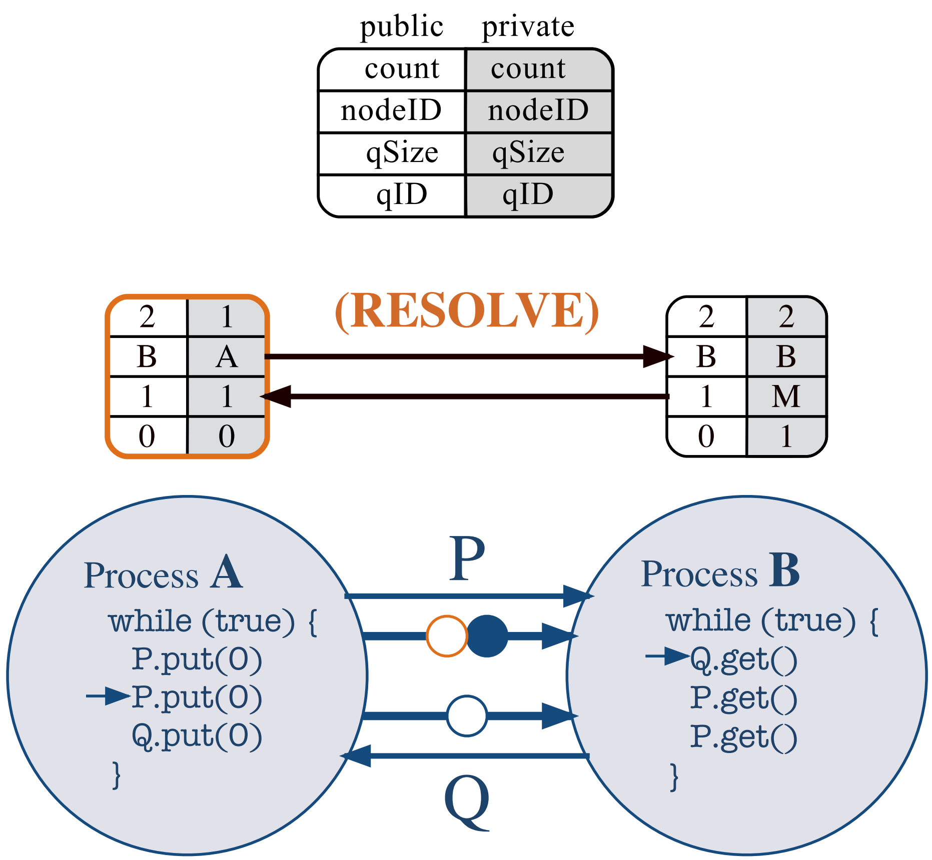
1. **A** writes to **P**
2. **A** *blocks* writing to **P**
3. **B** *blocks* reading from **Q**
4. **B** *transmits* to **A**
5. **A** *transmits* to **B**
6. **A** *detects* deadlock

   if qSize != MAX_UINT,

   deadlock is artificial and

   ***A** blocked on culpable queue*

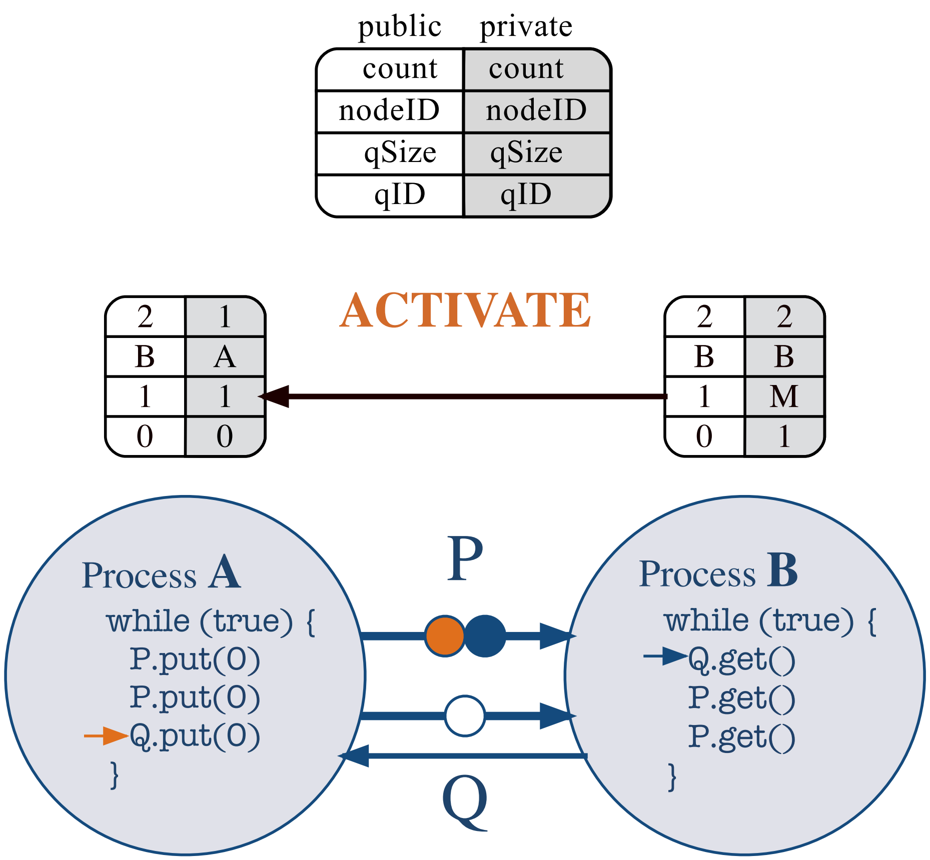
Example: Artificial Deadlock Detection & Resolution with D4R



1. **A** writes to **P**
2. **A** *blocks* writing to **P**
3. **B** *blocks* reading from **Q**
4. **B** *transmits* to **A**
5. **A** *transmits* to **B**
6. **A** *detects* deadlock
7. deadlock resolved

culpable queue grows

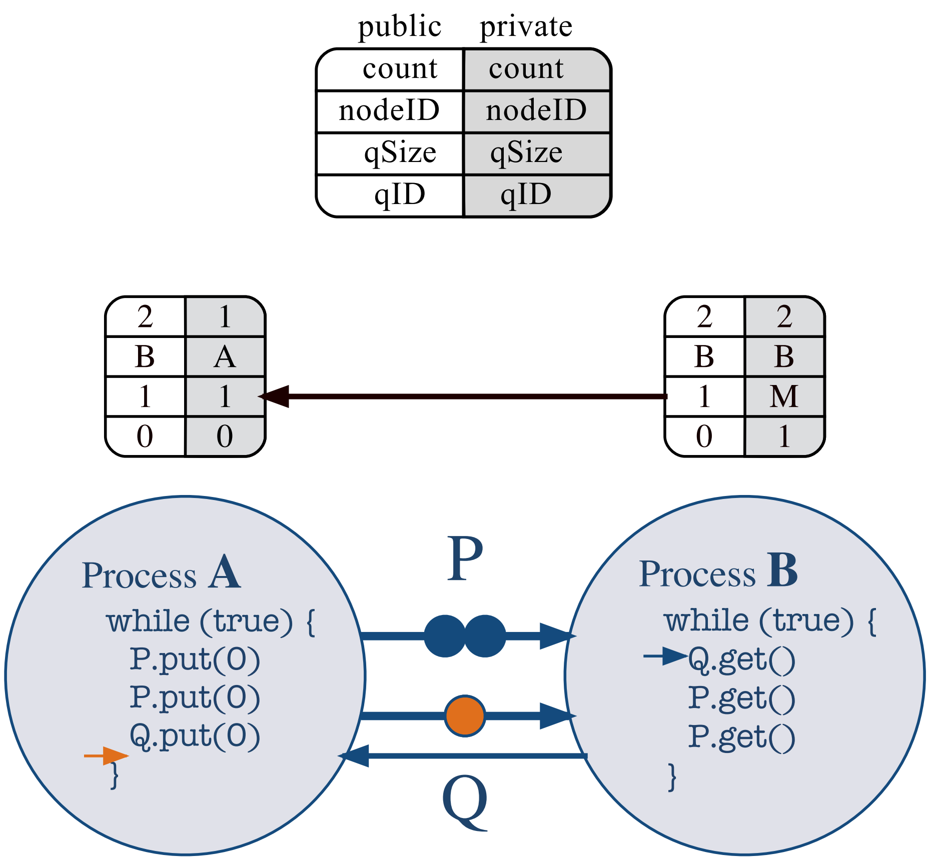
Example: Artificial Deadlock Detection & Resolution with D4R



1. **A** writes to **P**
2. **A** *blocks* writing to **P**
3. **B** *blocks* reading from **Q**
4. **B** *transmits* to **A**
5. **A** *transmits* to **B**
6. **A** *detects* deadlock
7. deadlock resolved
8. **A** activates, writes to **P**

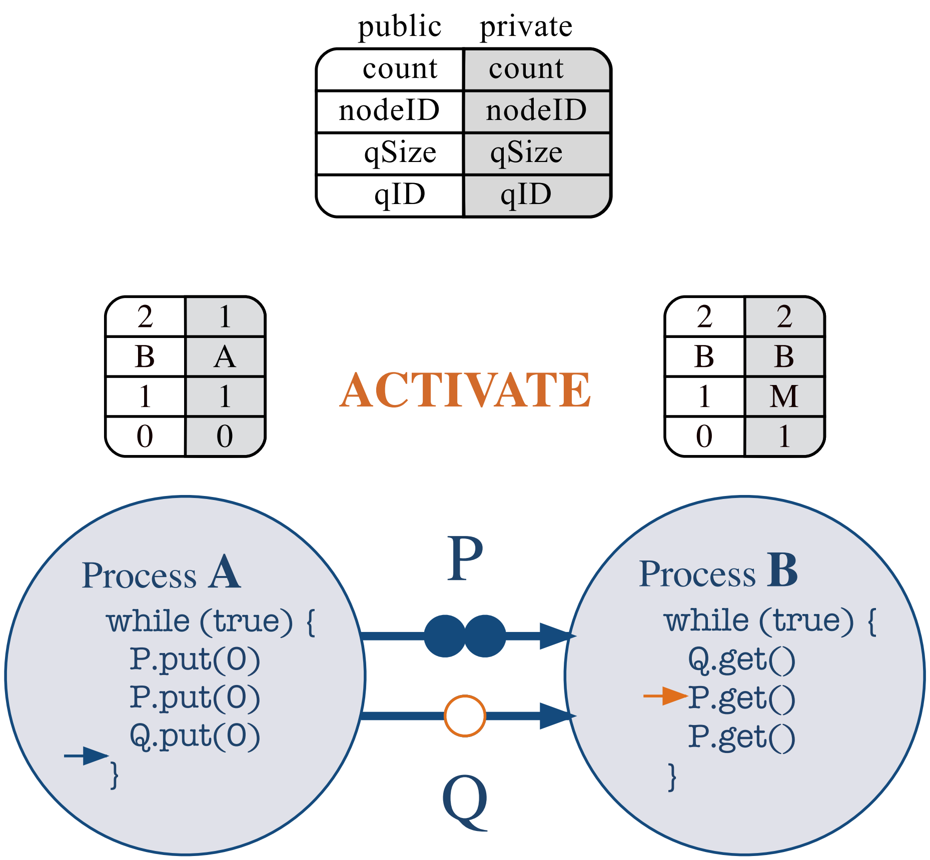
dependency removed

Example: Artificial Deadlock Detection & Resolution with D4R



1. **A** writes to **P**
2. **A** *blocks* writing to **P**
3. **B** *blocks* reading from **Q**
4. **B** *transmits* to **A**
5. **A** *transmits* to **B**
6. **A** *detects* deadlock
7. deadlock resolved
8. **A** activates, writes to **P**
9. **A** writes to **Q**

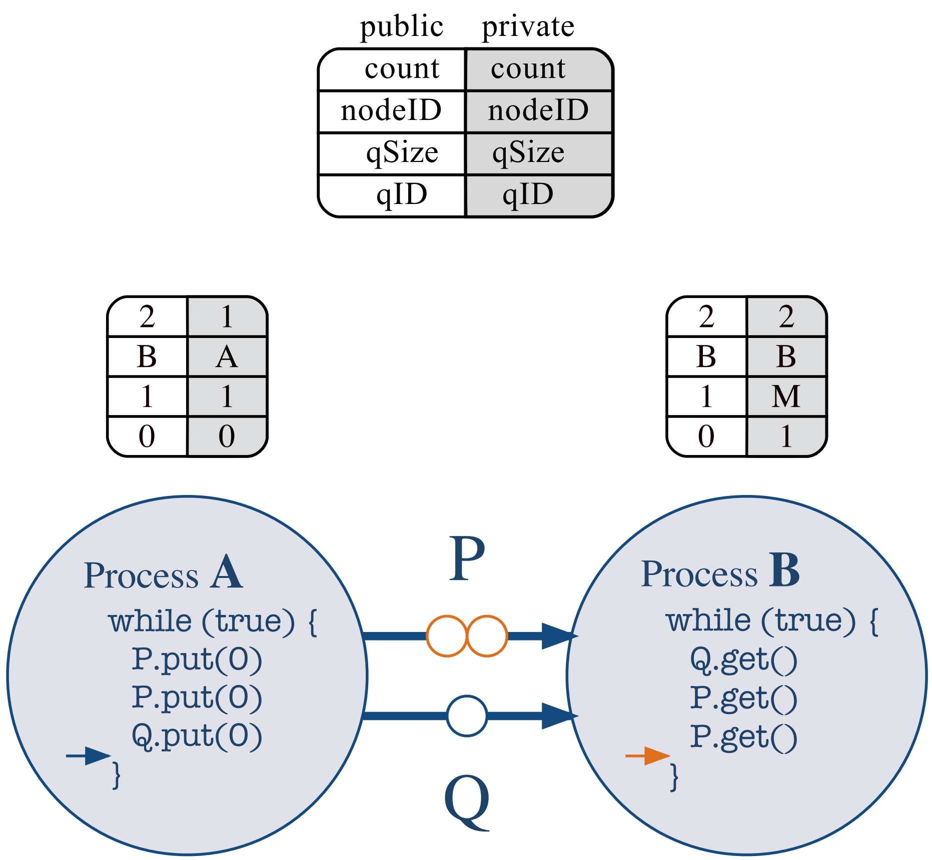
Example: Artificial Deadlock Detection & Resolution with D4R



1. **A** writes to **P**
2. **A** *blocks* writing to **P**
3. **B** *blocks* reading from **Q**
4. **B** *transmits* to **A**
5. **A** *transmits* to **B**
6. **A** *detects* deadlock
7. deadlock resolved
8. **A** activates, writes to **P**
9. **A** writes to **Q**
10. **B** activates, reads from **Q**

dependency removed

Example: Artificial Deadlock Detection & Resolution with D4R



1. **A** writes to **P**
2. **A** *blocks* writing to **P**
3. **B** *blocks* reading from **Q**
4. **B** *transmits* to **A**
5. **A** *transmits* to **B**
6. **A** *detects* deadlock
7. deadlock resolved
8. **A** activates, writes to **P**
9. **A** writes to **Q**
10. **B** activates, reads from **Q**
11. **B** reads (twice) from **P**

Contribution #2: CPN Model

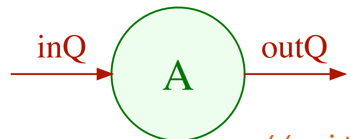
- Preserves KPN determinism, scalability, and composability
- Reduces operations for common signal processing algorithms
- Bounded memory when possible with D4R (Contribution #1)
- Enhancements for streaming data
  - Multi-token queue transactions to reduce overhead ← LabVIEW's "G" language traditionally used single-token transactions
  - Multi-channel queues for multi-dimensional synchronized data
  - Firing thresholds for both consumers and producers ← Computation Graphs have only consumer firing thresholds
  - Zero-copy queue transactions
- Enables high-throughput signal processing

CPN Queue Semantics

- Bounded queue sizes and blocking reads and writes
- Producer and consumer firing thresholds
- CPN semantics use two steps each for *read* or *write*
  - GetDequeuePtr(*threshold*, *channel*) blocks until sufficient tokens are readable in input queue, returns contiguous token array for consumption
  - Dequeue(*count*) dequeues tokens from head of input queue
  - GetEnqueuePtr(*threshold*, *channel*) blocks until sufficient free space is available in output queue, returns contiguous token array for writing
  - Enqueue(*count*) enqueues tokens from array head into output queue
- These semantics provide a zero-copy interface for queue I/O

CPN vs. KPN Semantics

FIR filter in the frequency domain using 50% overlap-and-save FFT




```
// with (extended) bounded KPN semantics
typedef complex<float> T;
const int nfft = 1024;
T filter[nfft];
T workBuf[nfft];
while (true) {
    // manage sliding window state
    memcpy(workBuf, workBuf+nfft/2, nfft/2*sizeof(T));
    // blocking call to copy in new data
    inQ.read(workBuf+nfft/2, nfft/2);

    // execute one step of filter
    fft(workBuf, workBuf, nfft);
    cpx_multiply(filter, workBuf, workBuf, nfft);
    ifft(workBuf, workBuf, nfft);

    // blocking call to copy out the results
    outQ.write(workBuf, nfft/2);
}
```

memory for overlap state

data copies

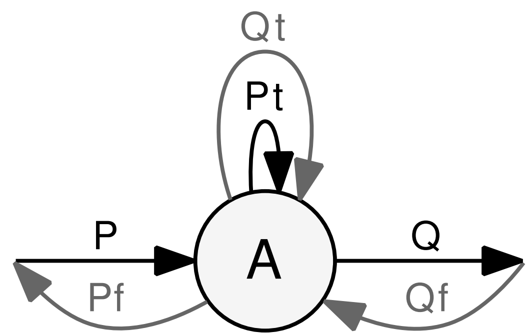
```
// with CPN semantics
typedef complex<float> T;
const int nfft = 1024;
T filter[nfft];

while (true) {
    // blocking calls for in/out buffer pointers
    const T* inPtr = inQ.GetDequeuePtr(nfft);
    T*       outPtr = outQ.GetEnqueuePtr(nfft);

    // execute one step of filter
    fft(inPtr, outPtr, nfft);
    cpx_multiply(filter, outPtr, outPtr, nfft);
    ifft(outPtr, outPtr, nfft);

    // complete the queue transactions
    inQ.Dequeue(nfft/2);
    outQ.Enqueue(nfft/2);
}
```

Preserving KPN's Properties



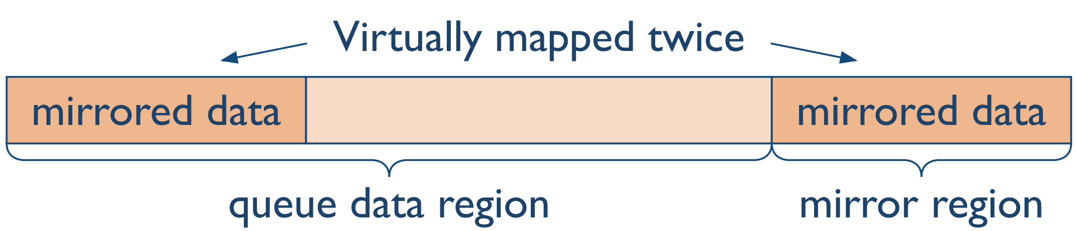
- Any CPN program can be transformed to KPN
  - Adding queues and modifying each node
  - Feedback queues (P_f and Q_f) are for boundedness
  - Self-loop queues (P_t and Q_t) are for managing firing thresholds
  - Grayed queues carry placeholder feedback tokens (value is unimportant)
- All tokens entering a process pass through self-loop queue
  - *GetDequeuePtr* ensures self-loop contains at least threshold number of tokens
  - *Dequeue* discards requested number of tokens from self-loop queue
  - *GetEnqueuePtr* and *Enqueue* behave similarly but with feedback tokens
- Same mathematical representation, formal properties preserved

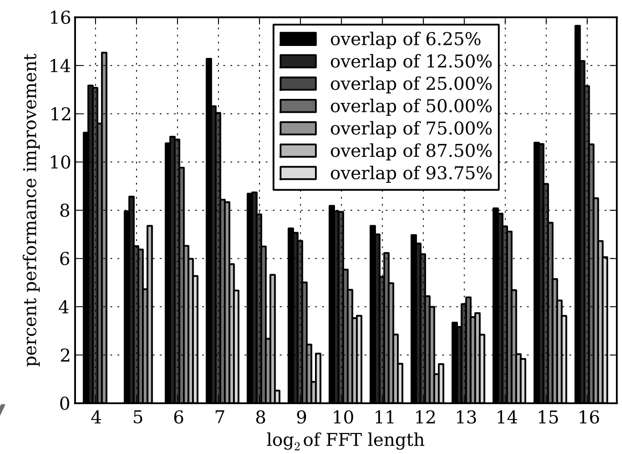
Contribution #3: CPN Framework

- High-performance implementation of the CPN model
- Scalable framework in C++, targeting POSIX (Unix) systems
  - Released as an open source library under the GNU LGPL license
  - More than 4 work-years of development effort, 26K lines of code
  - D4R algorithm for bounded scheduling
  - Unit tests and 72 hour tests for robustness and stability
- Developers can build high-throughput distributed systems from deterministic, composable components
- Case studies on both multi-core and distributed platforms

CPN Nodes and Queues

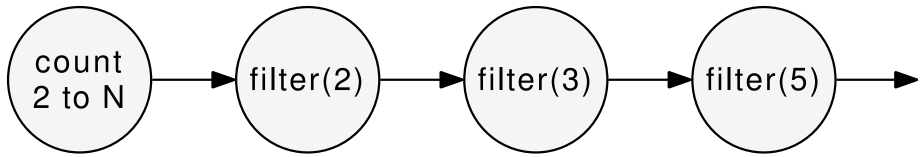
- Each CPN Node maps onto a single POSIX thread (Pthread)
- CPN Queues have firing thresholds and zero-copy interface
  - Nodes operate directly on queue memory to avoid unnecessary copies
- CPN Queues use mirroring for contiguous data [Allen *et al.* 2006]



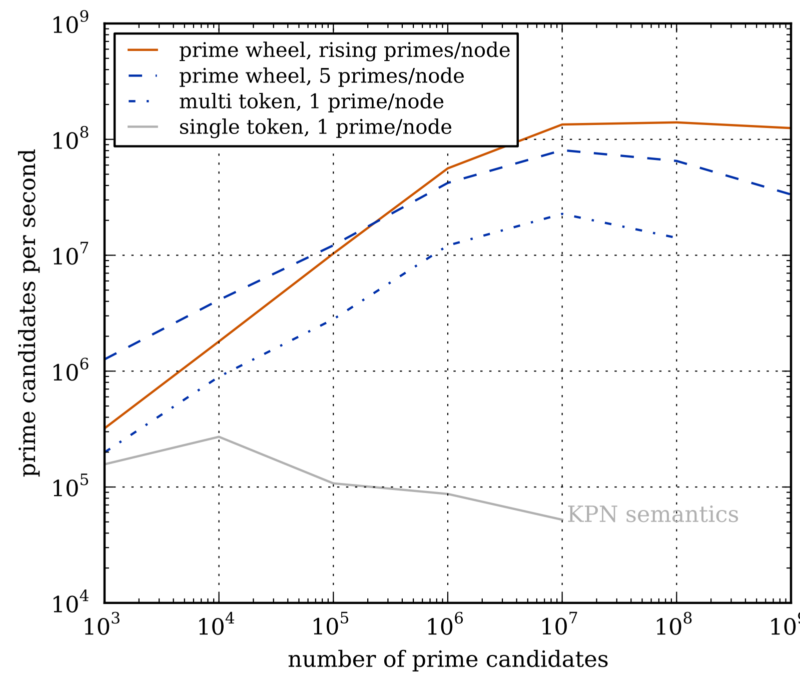


  - Circular buffers similar to modulo addressing
  - Virtual memory manager maintains data circularity
- OS dynamically schedules and load balances nodes (threads)

Prime Sieve Case Study

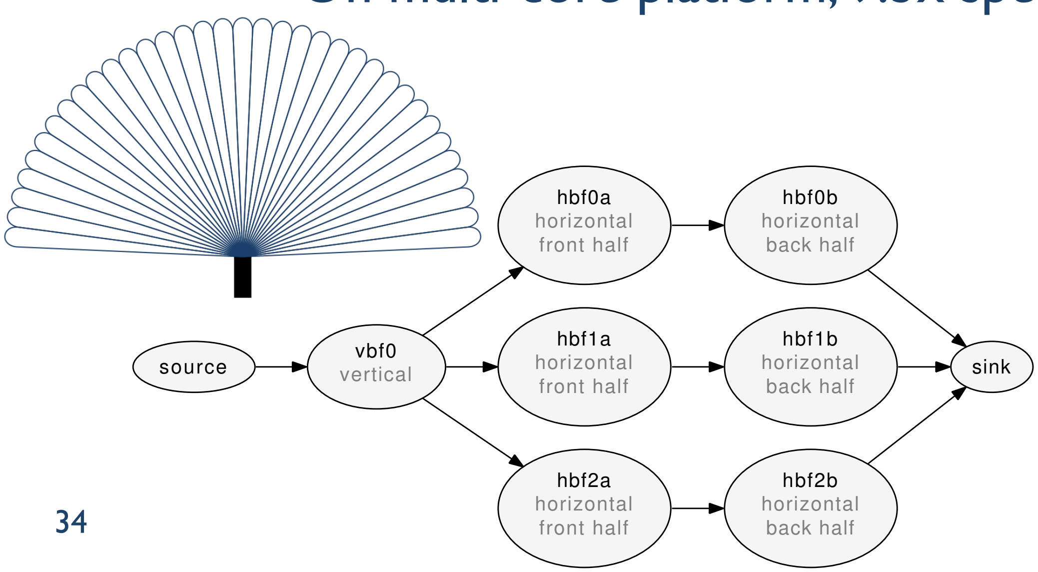


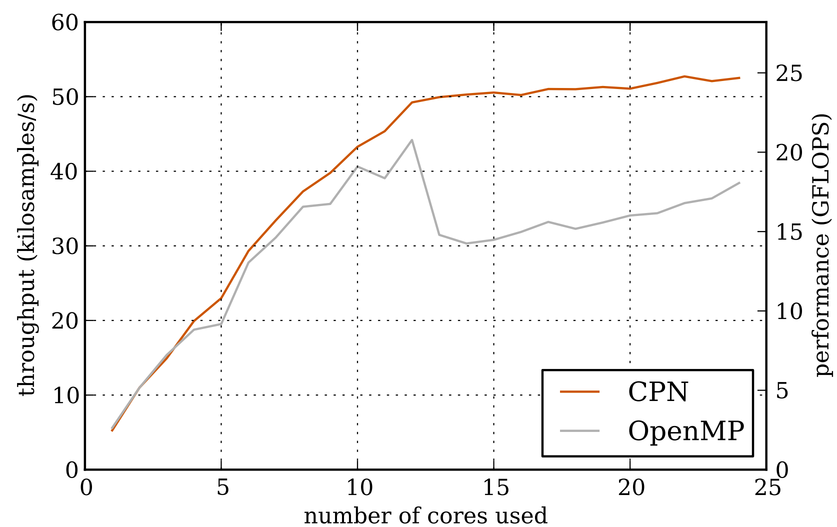
- Simple algorithm for finding prime numbers [Eratosthenes 250BCE]
  - First real example for KPN, requires dynamic creation & recursion
- Multi-core platform: 12x 2.66 GHz Intel Xeon with Hyper-Threads
- Guidelines for high performance
  - Multi-token firings reduce overhead
  - Node granularity vs. context switch
  - Load balancing of nodes
- 2500x speedup for 10^7 candidates



Beamformer Case Study

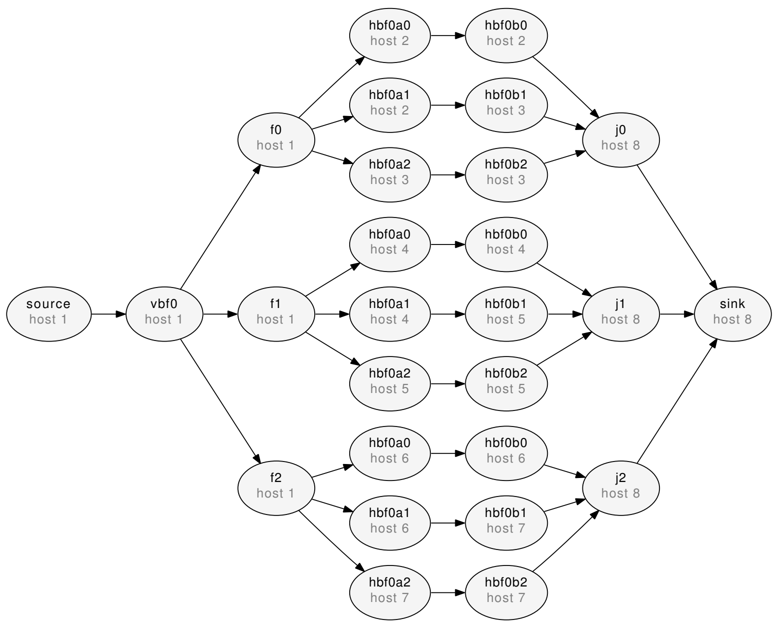
- Multiple beams formed from cylindrical sensor array outputs
  - Decomposed into horizontal and vertical components
  - Optimized kernels use SIMD and OpenMP loop parallelism
  - Horizontal beamformer uses FFTs and performs matched filtering
- At 50 ks/s target: 614 MB/s in, 672 MB/s out, 24 GFLOPS
- On multi-core platform, 9.3x speedup at 12 cores

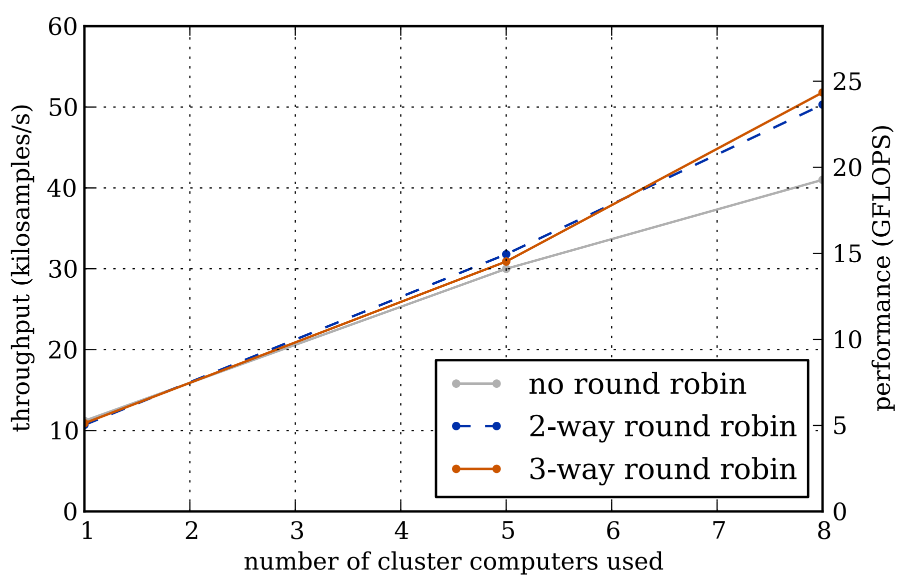




Beamformer Case Study

- On 8-host cluster connected by 8 Gigabit Infiniband network
  - Each host with four 2.33 GHz Intel Xeon processors
- Mapping file to distribute and load balance CPN program
- Increase data parallelism of horizontal with time multiplexing
- 4.6x speedup on 8 hosts w/ Infiniband output at 70% of peak





Conclusion

	Dataflow Model			
Property	SDF	CG	KPN	**CPN**
Determinism	✔	✔	✔	✔
Boundedness	✔	✔	*	*
Scalability			✔	✔
Composability			✔	✔
Firing Thresholds		✔		✔
Zero-copy Semantics				✔

* Execution of *fair* KPN and CPN in bounded memory with D4R

CPN preserves the formal properties of KPN and reduces operations to implement common signal processing algorithms.

Future Work

- Improve D4R algorithm
  - Artificial deadlocks can occur without cycles [Basten&Hoogerbrugge 2001]
  - A similar edge-chasing algorithm could detect these deadlocks
- CPN Node migration and distributed scheduling
  - Automated load balancing on cluster computers
- CPN Queues with Remote Direct Memory Access (RDMA)
  - Higher throughput, reduced overhead on cluster systems
- Integrate into design automation tools (graphical programming)
- Additional targets and applications