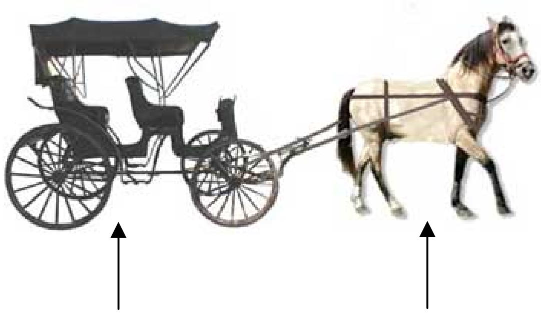
6.189 IAP 2007

Lecture 8

The StreamIt Language

Languages Have Not Kept Up

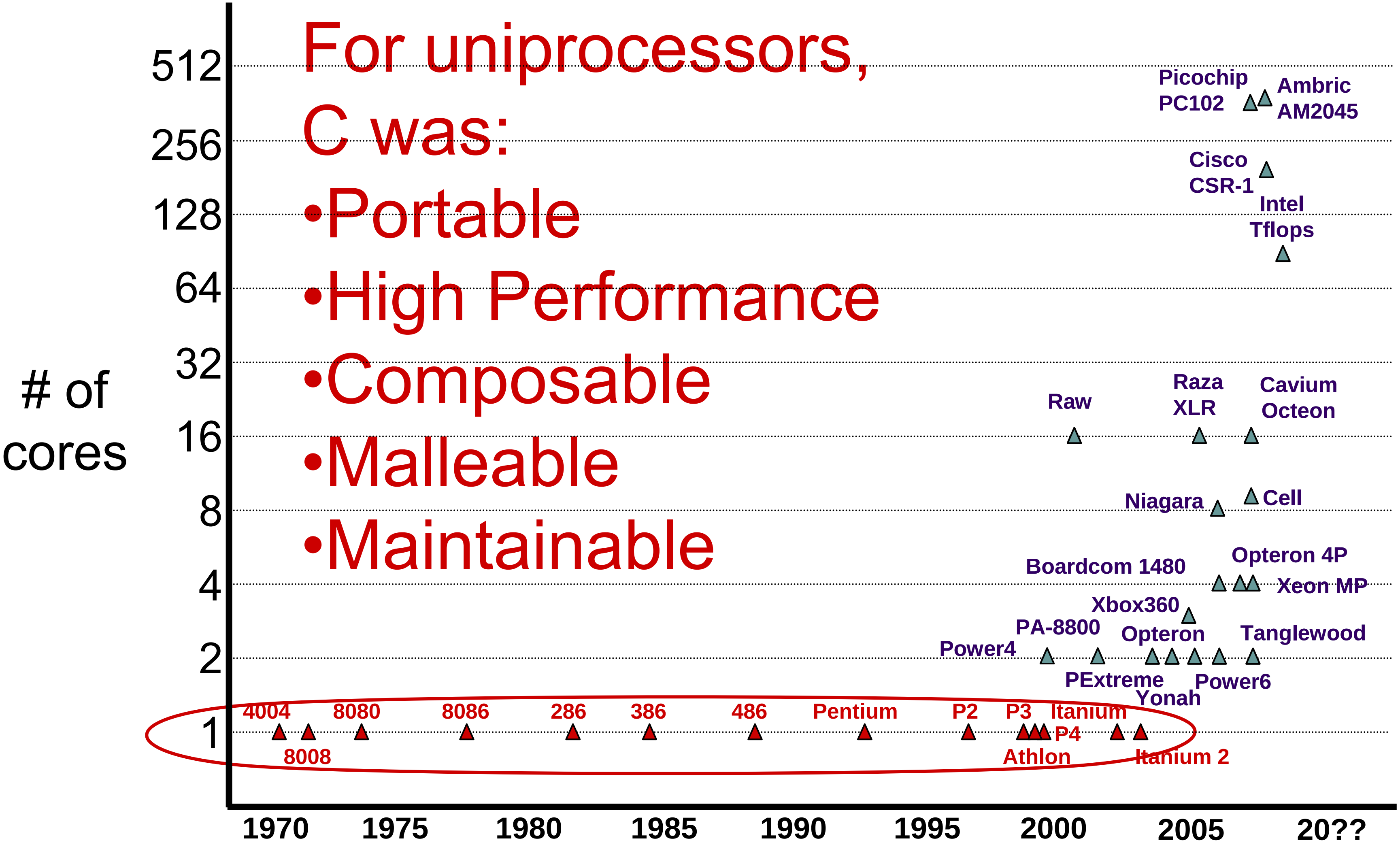


C ⇔ von-Neumann machine

Modern architecture

- Two choices:
  - Develop cool architecture with complicated, ad-hoc language
  - Bend over backwards to support old languages like C/C++

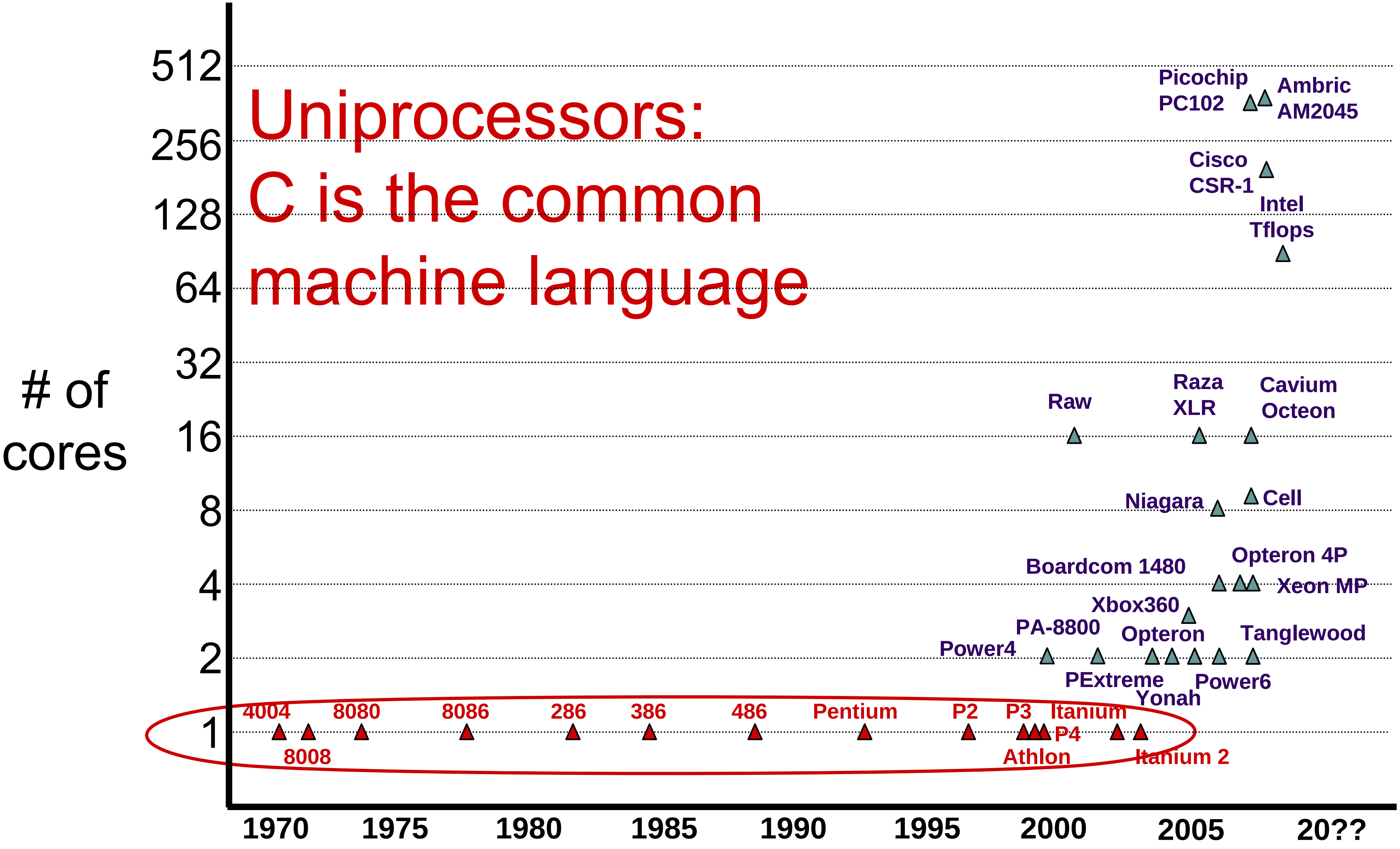
Why a New Language?



For uniprocessors, C was:

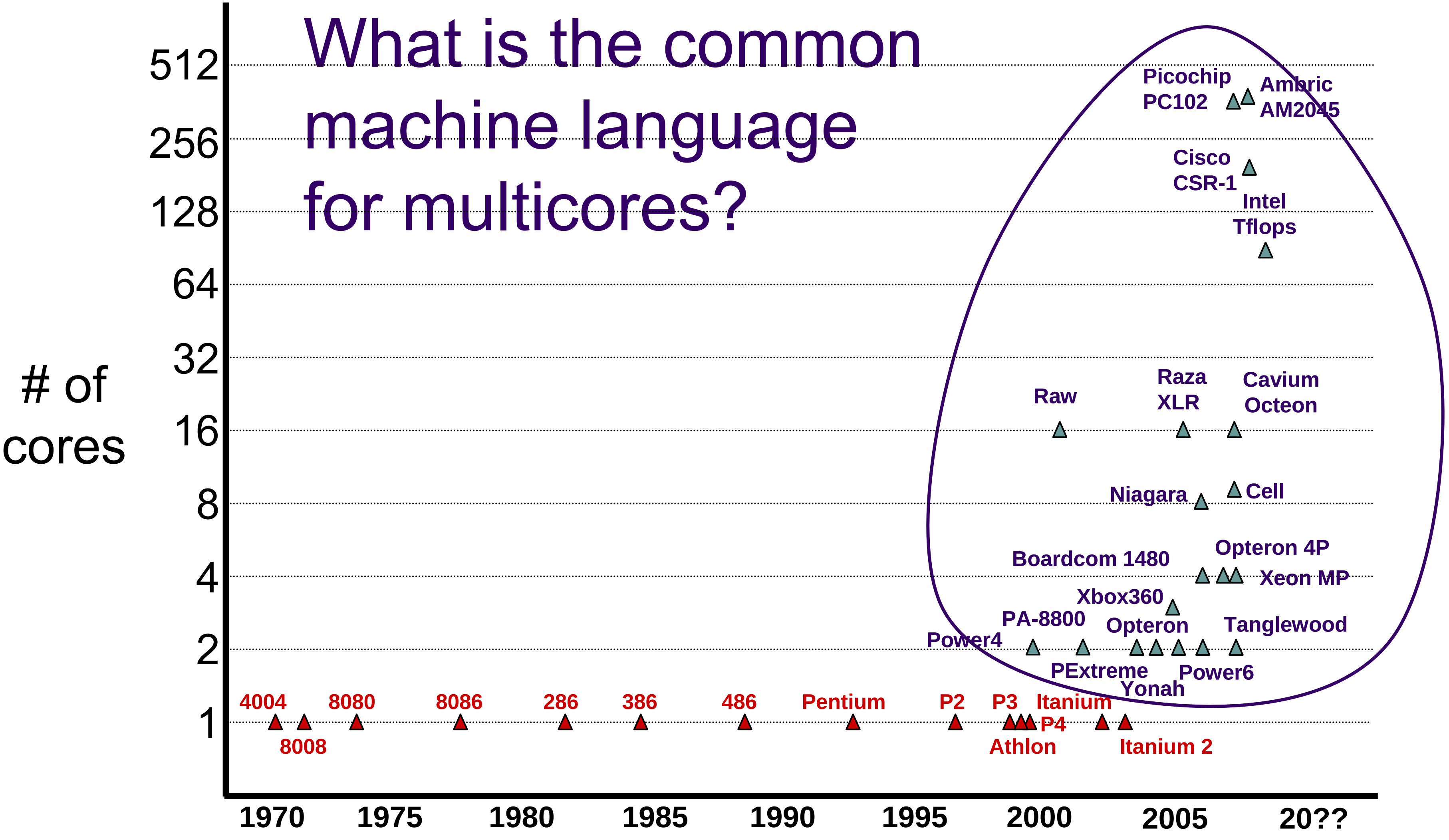
- Portable
- High Performance
- Composable
- Malleable
- Maintainable

Why a New Language?



Uniprocessors:
C is the common machine language

Why a New Language?



Common Machine Languages

Uniprocessors:

Common Properties
Single flow of control
Single memory image

Differences:
Register File
ISA
Functional Units

von-Neumann languages represent the common properties and abstract away the differences

Multicores:

Common Properties
Multiple flows of control
Multiple local memories

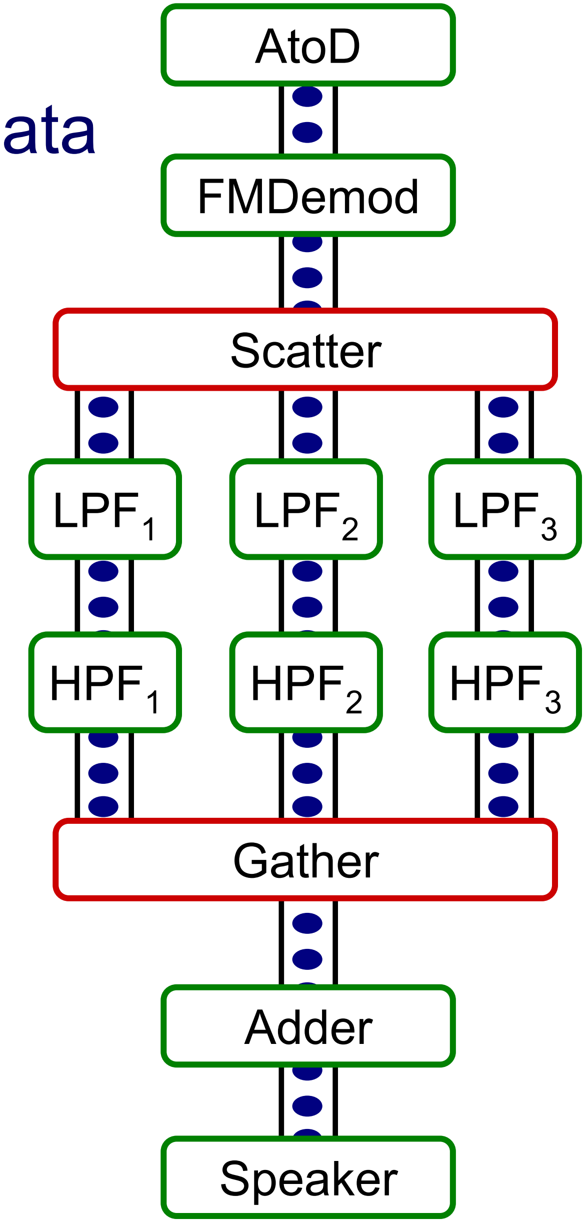
Differences:
Number and capabilities of cores
Communication Model
Synchronization Model

Need common machine language(s) for multicores

Streaming as a Common Machine Language

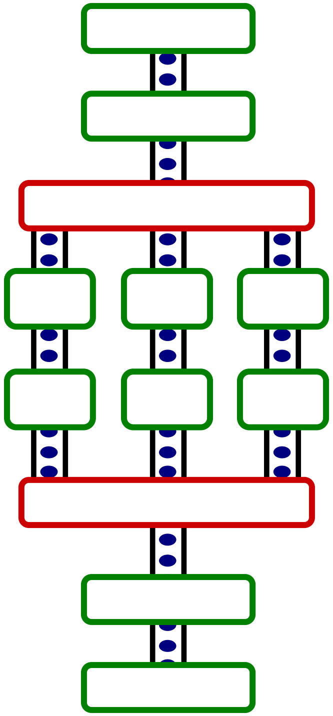
- For programs based on streams of data
  - Audio, video, DSP, networking, and cryptographic processing kernels
  - Examples: HDTV editing, radar tracking, microphone arrays, cell phone base stations, graphics

- Several attractive properties
  - Regular and repeating computation
  - Independent filters
    with explicit communication
  - Task, data, and pipeline parallelism



Streaming Models of Computation

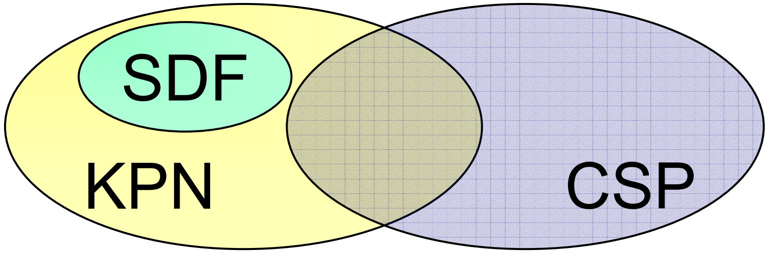
- Many different ways to represent streaming
  - Do senders/receivers block?
  - How much buffering is allowed on channels?
  - Is computation deterministic?
  - Can you avoid deadlock?



- Three common models:
  1. Kahn Process Networks
  2. Synchronous Dataflow
  3. Communicating Sequential Processes

Streaming Models of Computation

	Communication Pattern	**Buffering**	**Notes**
Kahn process networks (KPN)	Data-dependent, but deterministic	Conceptually unbounded	- UNIX pipes - Ambric (startup)
Synchronous dataflow (SDF)	Static	Fixed by compiler	- Static scheduling - Deadlock freedom
Communicating Sequential Processes (CSP)	Data-dependent, allows non-determinism	None (Rendesvouz)	- Rich synchronization primitives - Occam language



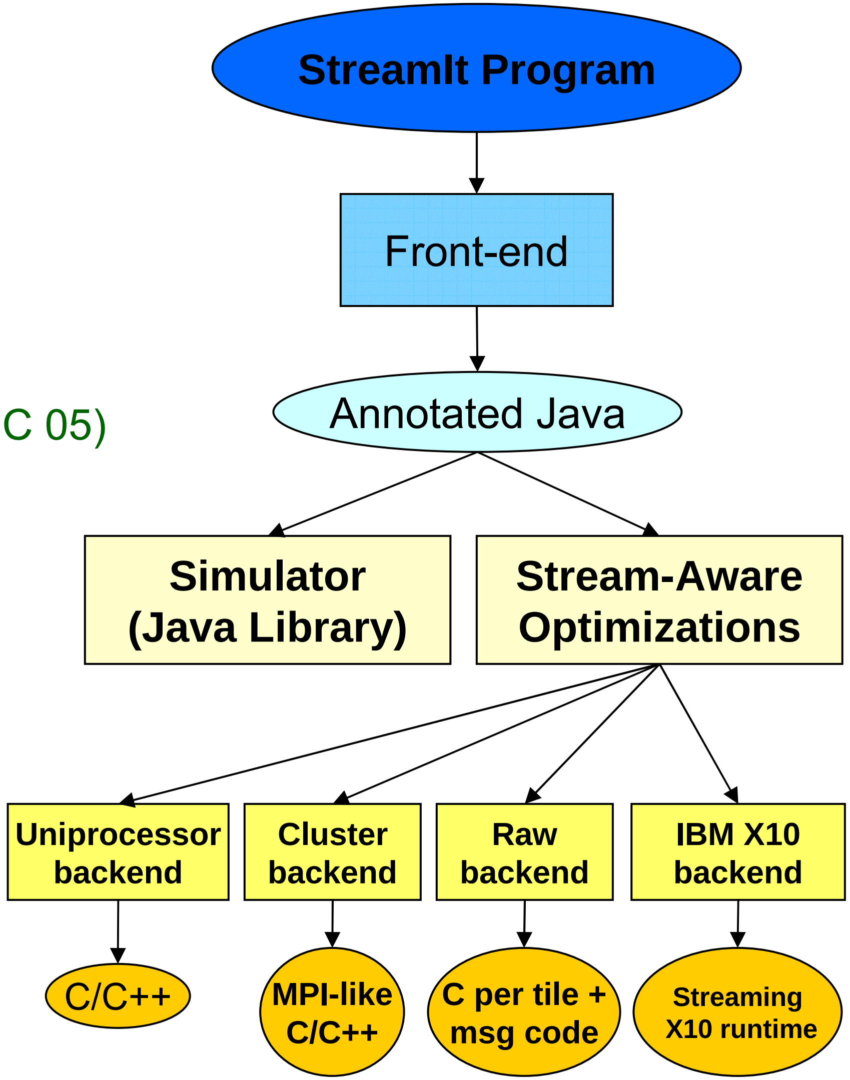
space of program behaviors

The StreamIt Language

- A high-level, architecture-independent language for streaming applications
  - Improves programmer productivity (vs. Java, C)
  - Offers scalable performance on multicores
- Based on synchronous dataflow, with dynamic extensions
  - Compiler determines execution order of filters
  - Many aggressive optimizations possible

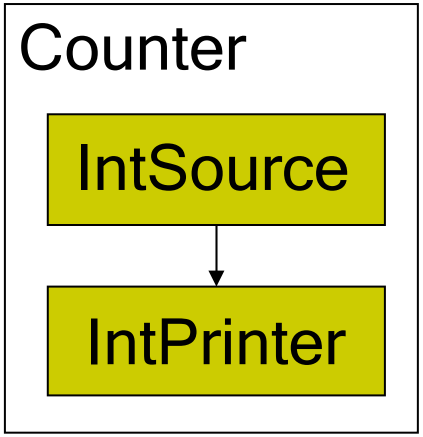
The StreamIt Project

- **Applications**
  - DES and Serpent [PLDI 05]
  - MPEG-2 [IPDPS 06]
  - SAR, DSP benchmarks, JPEG, …
- **Programmability**
  - StreamIt Language (CC 02)
  - Teleport Messaging (PPOPP 05)
  - Programming Environment in Eclipse (P-PHEC 05)
- **Domain Specific Optimizations**
  - Linear Analysis and Optimization (PLDI 03)
  - Optimizations for bit streaming (PLDI 05)
  - Linear State Space Analysis (CASES 05)
- **Architecture Specific Optimizations**
  - Compiling for Communication-Exposed Architectures (ASPLOS 02)
  - Phased Scheduling (LCTES 03)
  - Cache Aware Optimization (LCTES 05)
  - Load-Balanced Rendering (Graphics Hardware 05)



Example: A Simple Counter

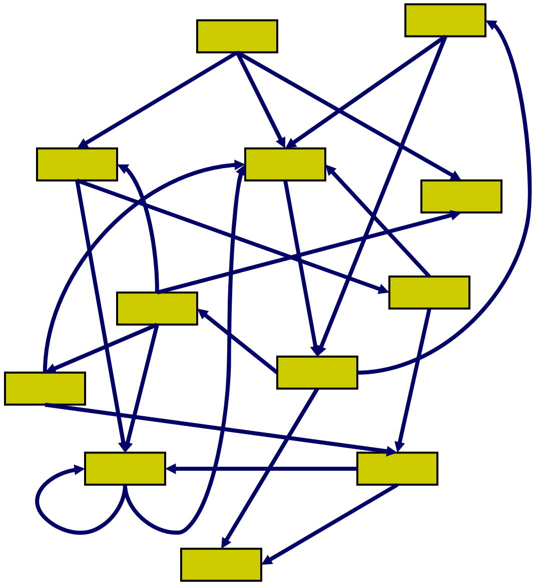
```
void->void pipeline Counter() {
    add IntSource();
    add IntPrinter();
}
void->int filter IntSource() {
    int x;
    init { x = 0; }
    work push 1 { push (x++); }
}
int->void filter IntPrinter() {
    work pop 1 { print(pop()); }
}
```



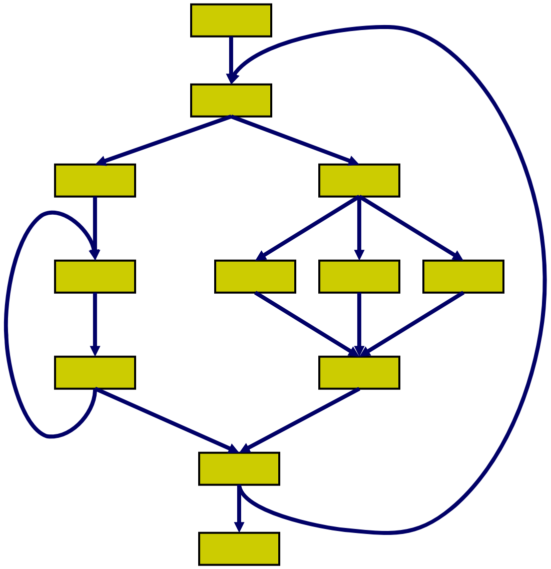
```
% strc Counter.str -o counter
% ./counter -i 4
0
1
2
3
```

Representing Streams

- Conventional wisdom: streams are graphs
  - Graphs have no simple textual representation
  - Graphs are difficult to analyze and optimize
- Insight: stream programs have structure

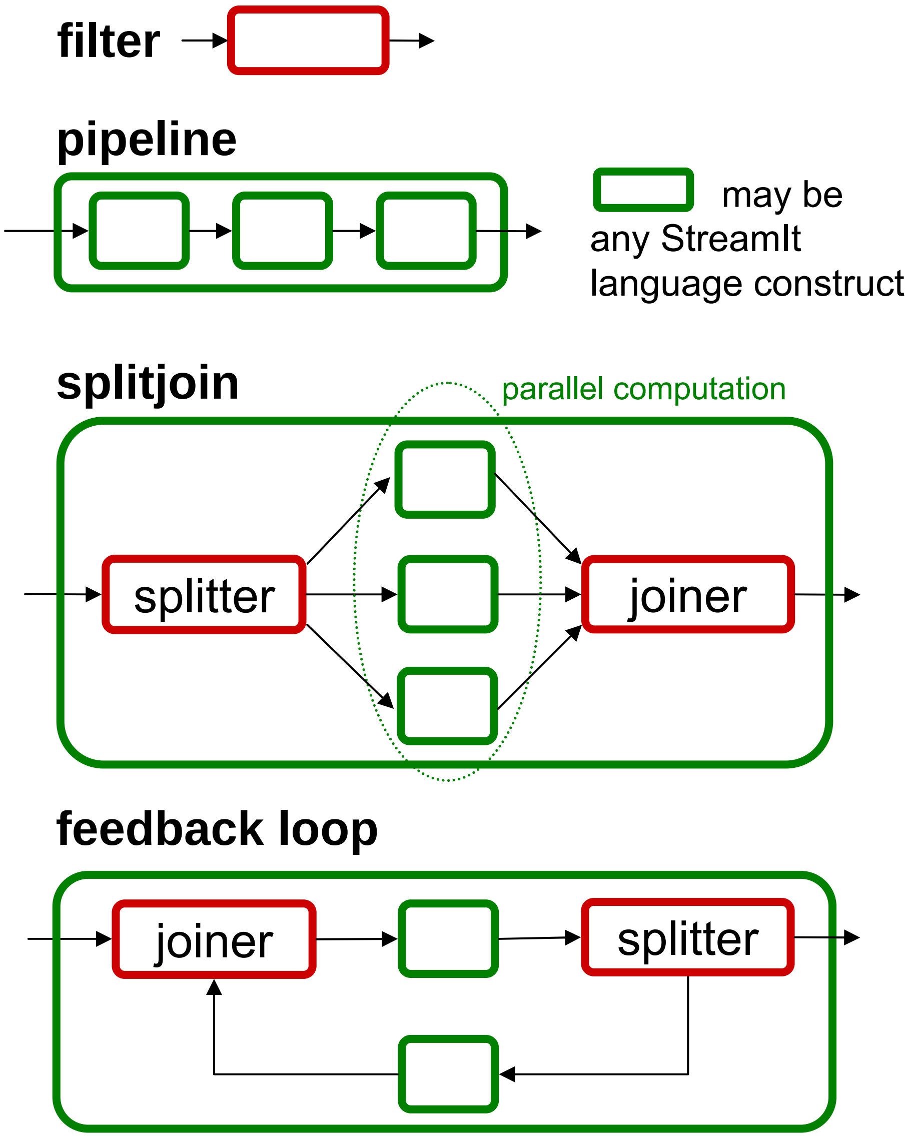


unstructured



structured

Structured Streams



filter

pipeline

may be any StreamIt language construct

splitjoin

parallel computation

splitter

joiner

feedback loop

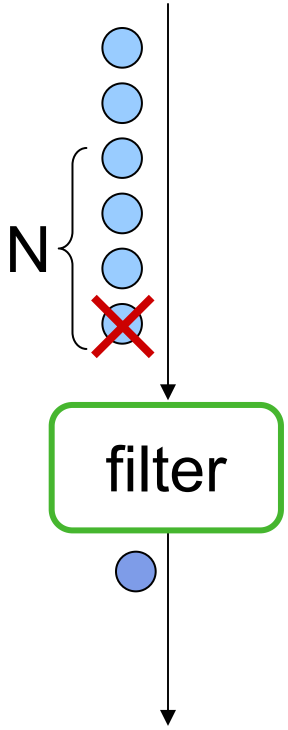
joiner

splitter

- Each structure is single-input, single-output
- Hierarchical and composable

Filter Example: Low Pass Filter

```
float->float filter LowPassFilter (int N, float freq) {
    float[N] weights;

    init {
        weights = calcWeights(freq);
    }

    work peek N push 1 pop 1 {
        float result = 0;
        for (int i=0; i<weights.length; i++) {
            result += weights[i] * peek(i);
        }
        push(result);
        pop();
    }
}
```



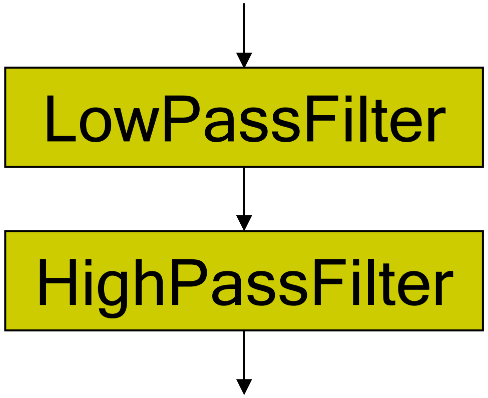
Low Pass Filter in C

```c
void FIR(
  int* src,
  int* dest,
  int* srcIndex,
  int* destIndex,
  int srcBufferSize,
  int destBufferSize,
  int N) {

  float result = 0.0;
  for (int i = 0; i < N; i++) {
    result += weights[i] * src[(*srcIndex + i) % srcBufferSize];
  }
  dest[*destIndex] = result;
  *srcIndex = (*srcIndex + 1) % srcBufferSize;
  *destIndex = (*destIndex + 1) % destBufferSize;
}
```

- FIR functionality obscured by buffer management details
- Programmer must commit to a particular buffer implementation strategy

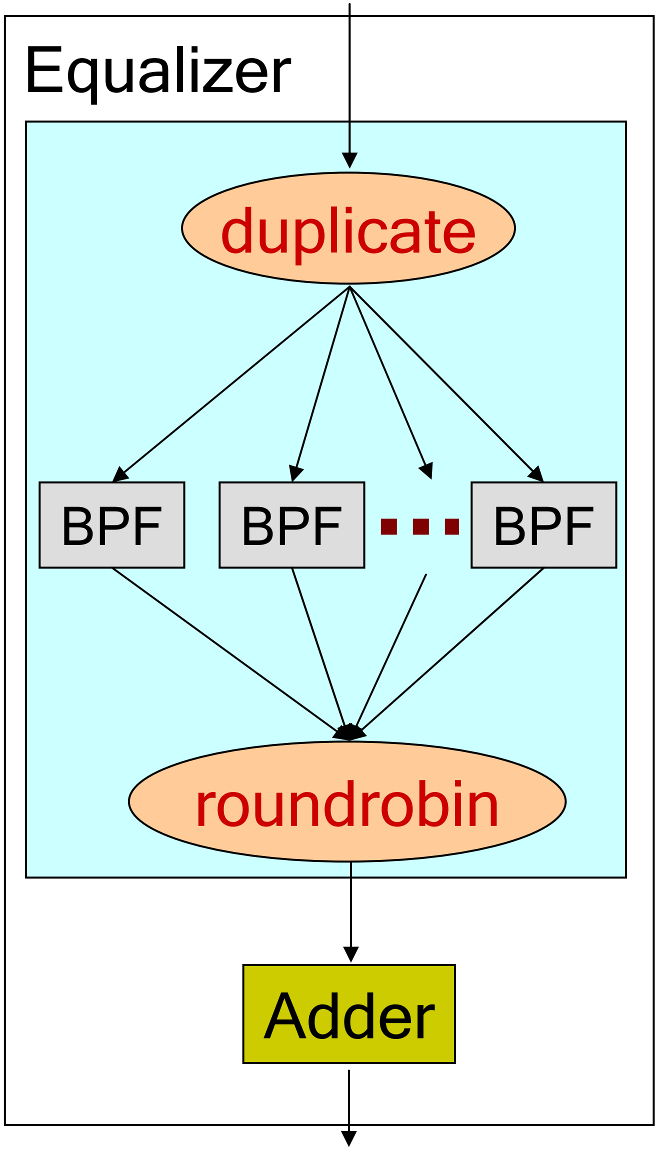
Pipeline Example: Band Pass Filter

```
float→float pipeline BandPassFilter (int N,
                                     float low,
                                     float high) {
    add LowPassFilter(N, low);
    add HighPassFilter(N, high);
}
```



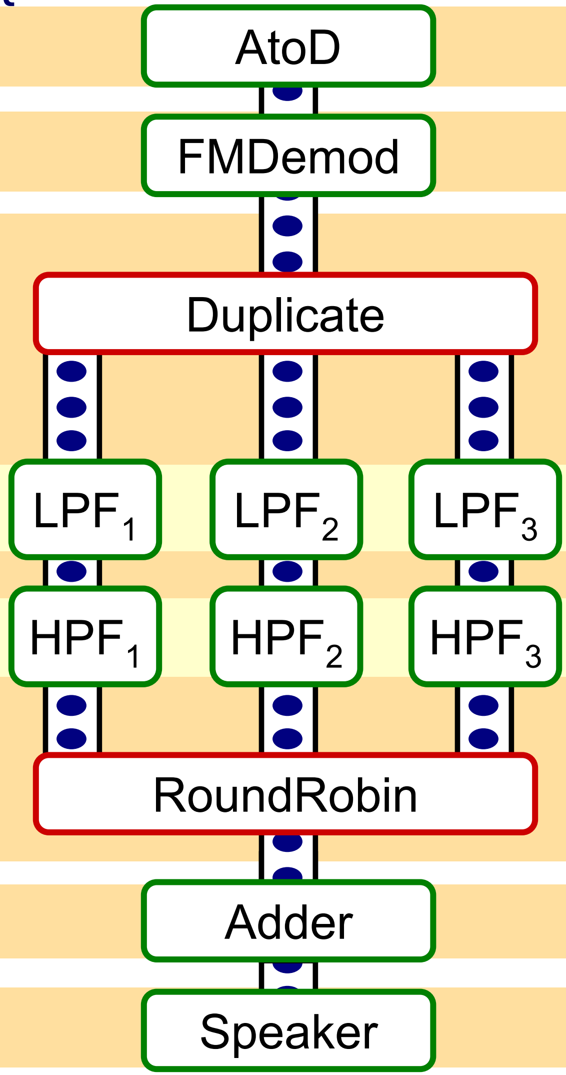
SplitJoin Example: Equalizer

```
float→float pipeline Equalizer (int N,
                                float lo,
                                float hi) {
  add splitjoin {
    split duplicate;
    for (int i=0; i<N; i++)
      add BandPassFilter(64, lo + i*(hi - lo)/N);
    join roundrobin(1);
  }
  add Adder(N);
}
```



Building Larger Programs: FMRadio

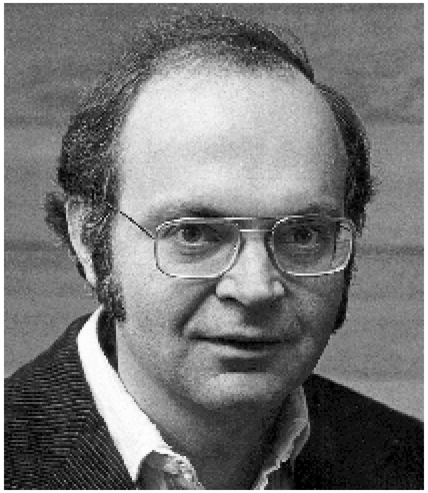
```
void->void pipeline FMRadio(int N, float lo, float hi) {
  add AtoD();

  add FMDemod();

  add splitjoin {
   split duplicate;
   for (int i=0; i<N; i++) {
      add pipeline {
         add LowPassFilter(lo + i*(hi - lo)/N);

         add HighPassFilter(lo + i*(hi - lo)/N);
      }
   }
   join roundrobin();
  }
  add Adder();

  add Speaker();
}
```



The Beauty of Streaming

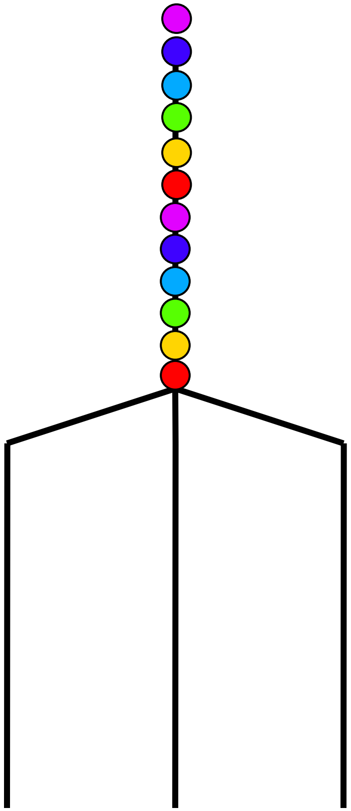
"Some programs are elegant, some are exquisite, some are sparkling. My claim is that it is possible to write *grand* programs, *noble* programs, truly *magnificient* ones!"

— Don Knuth, ACM Turing Award Lecture

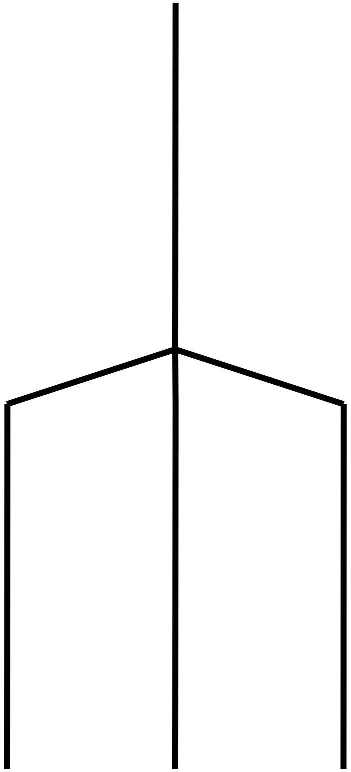


SplitJoins are Beautiful

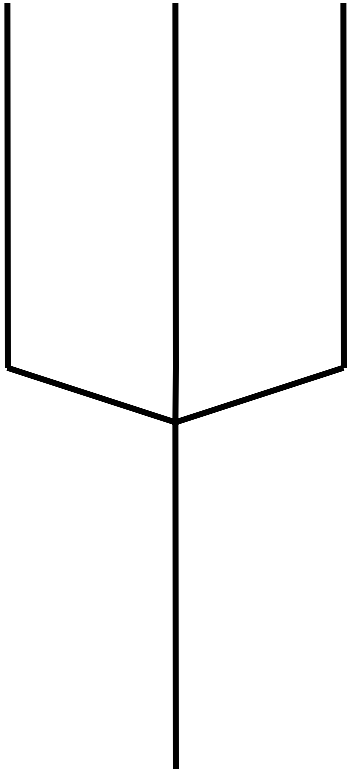
split duplicate



split roundrobin(N)

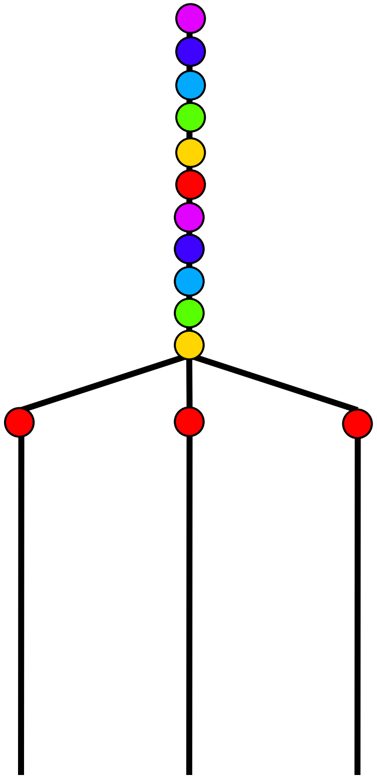


join roundrobin(N)

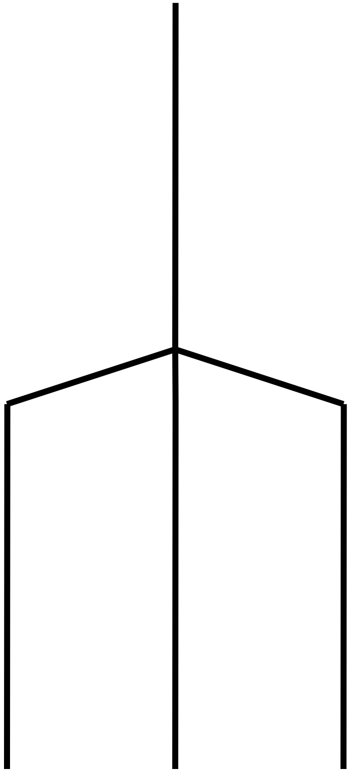


SplitJoins are Beautiful

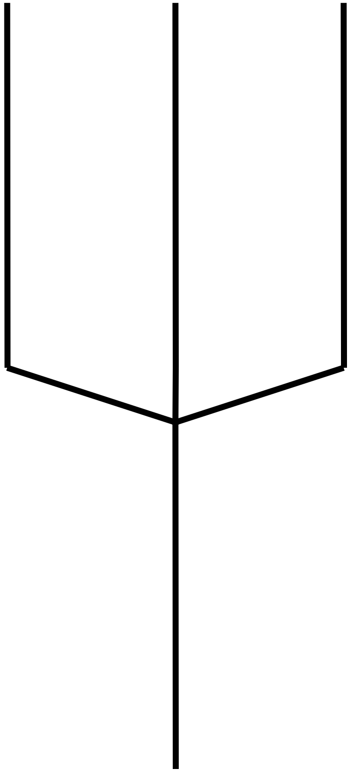
split duplicate



split roundrobin(N)

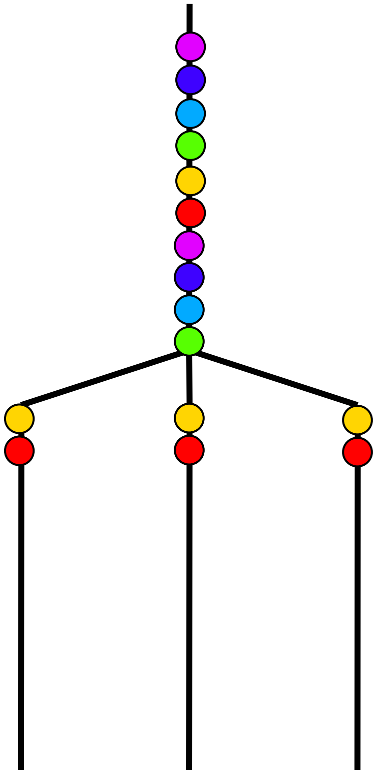


join roundrobin(N)

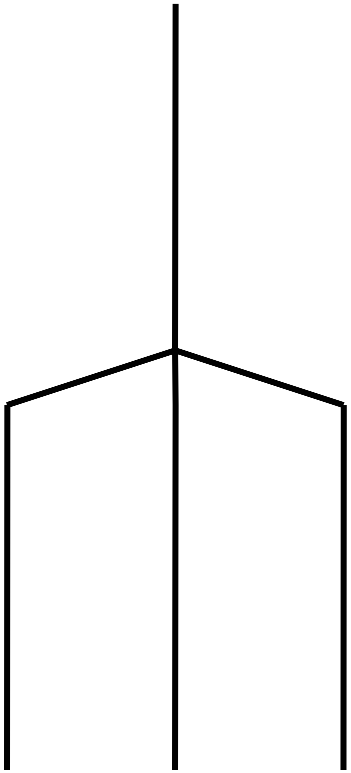


SplitJoins are Beautiful

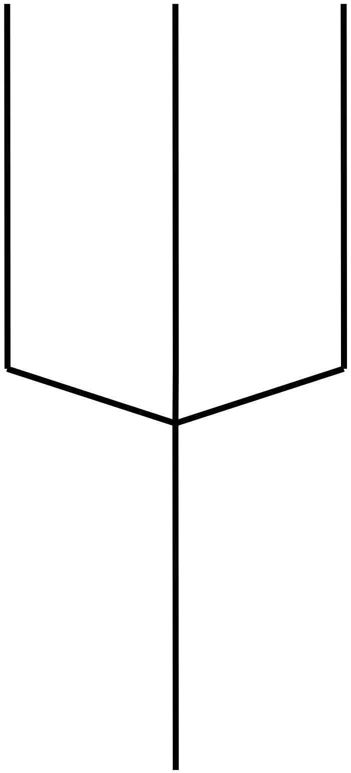
split duplicate



split roundrobin(N)

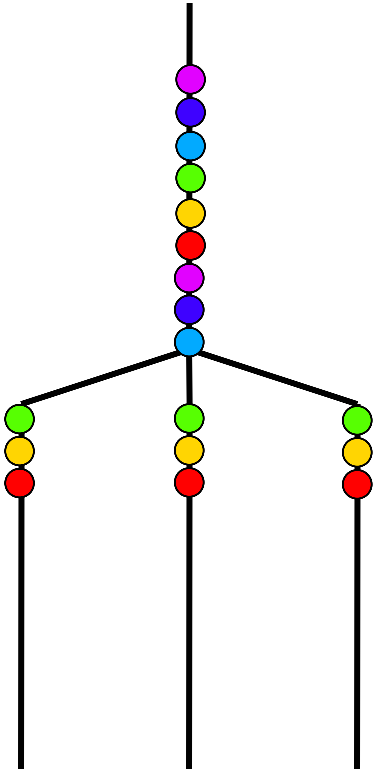


join roundrobin(N)

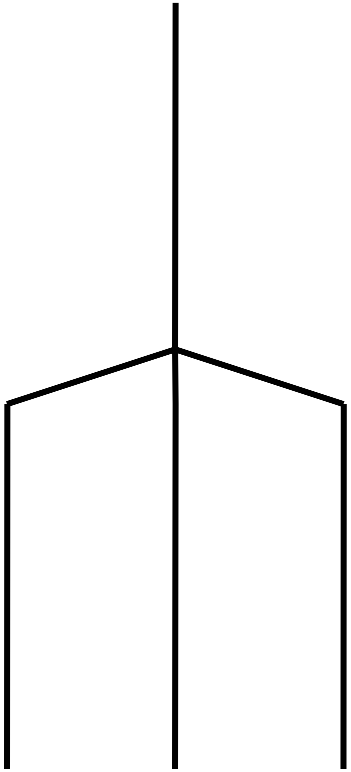


SplitJoins are Beautiful

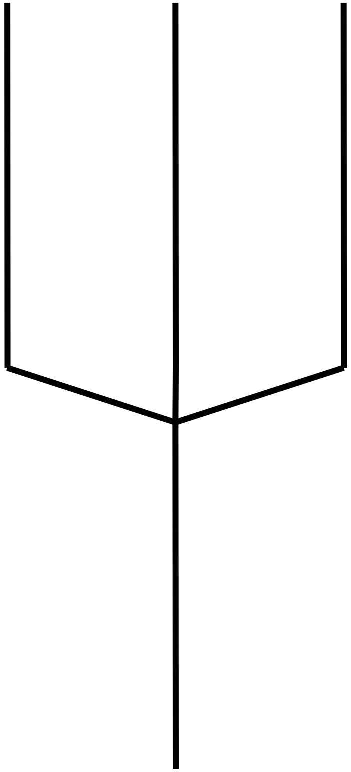
split duplicate



split roundrobin(N)

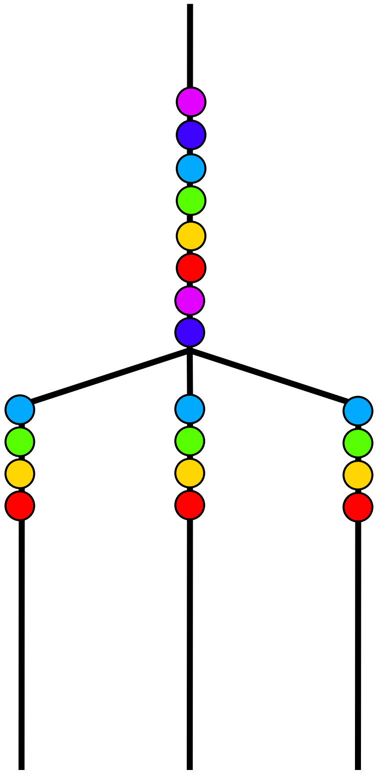


join roundrobin(N)

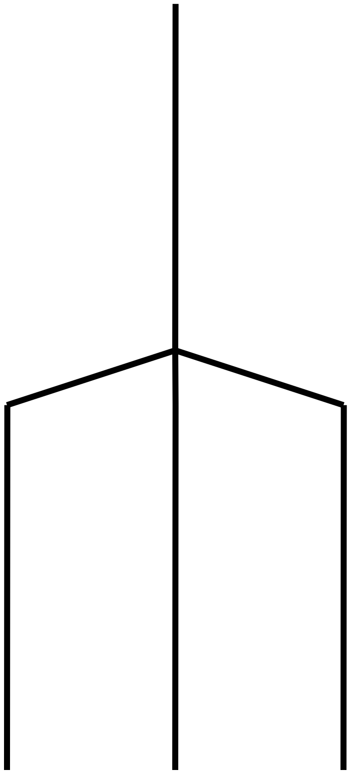


SplitJoins are Beautiful

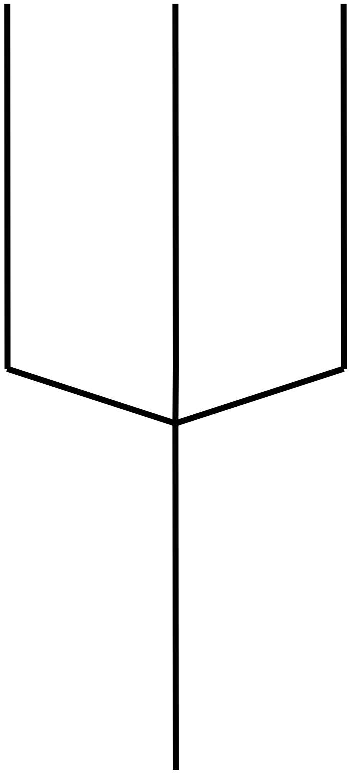
split duplicate



split roundrobin(N)

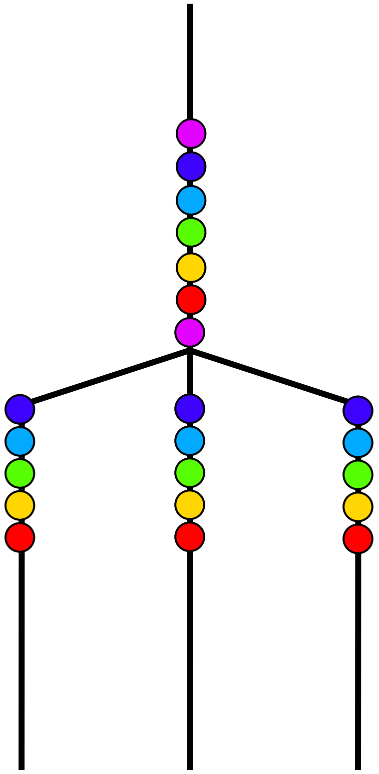


join roundrobin(N)

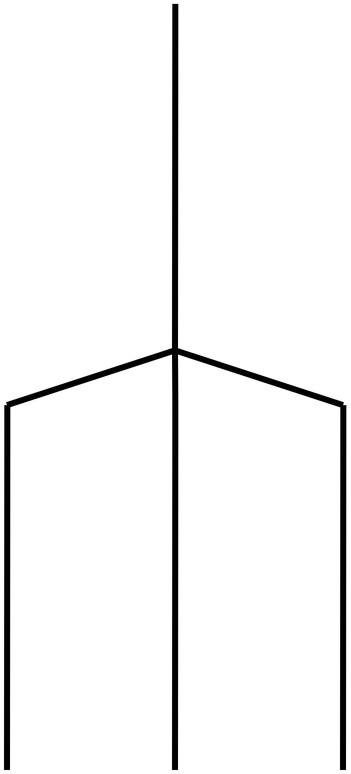


SplitJoins are Beautiful

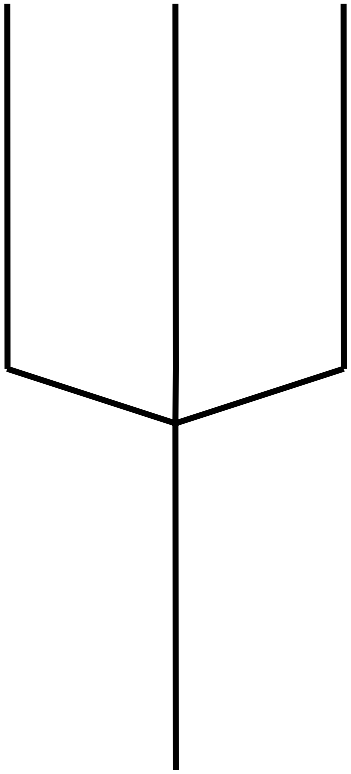
split duplicate



split roundrobin(N)

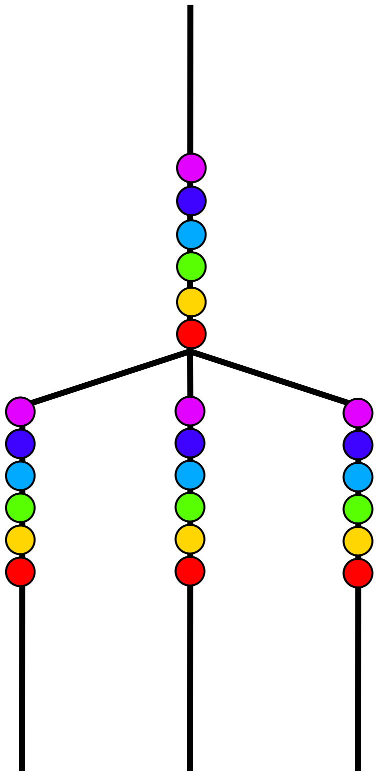


join roundrobin(N)

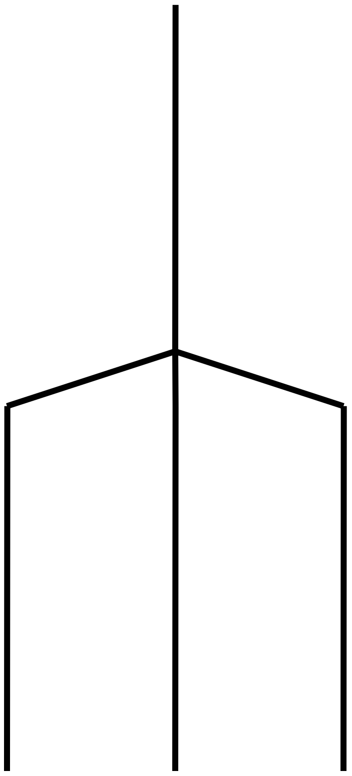


SplitJoins are Beautiful

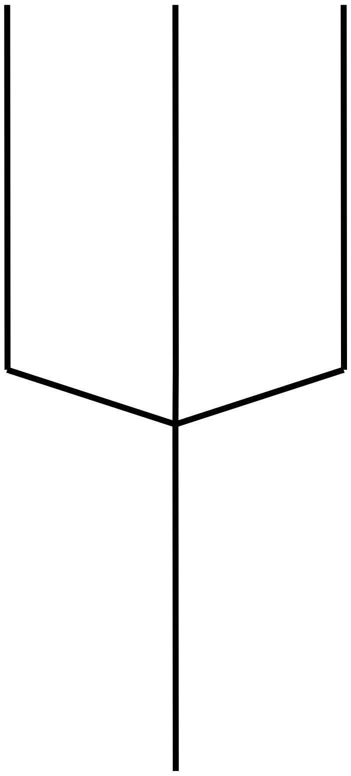
split duplicate



split roundrobin(N)

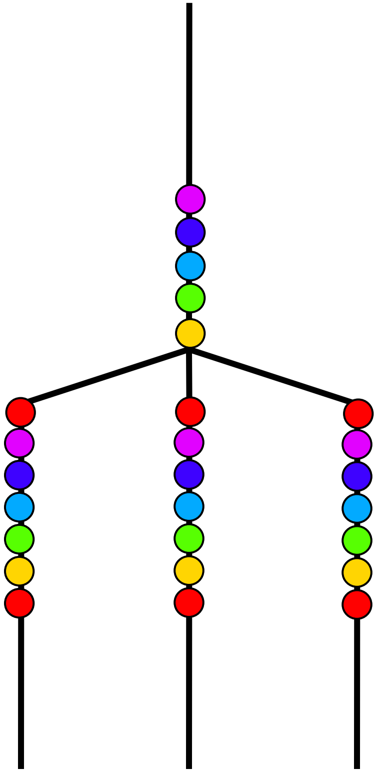


join roundrobin(N)

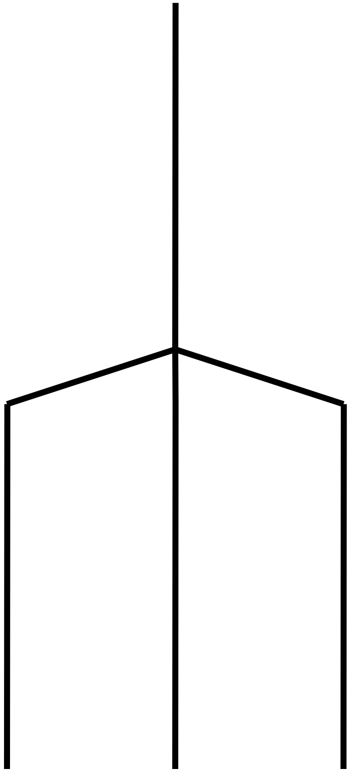


SplitJoins are Beautiful

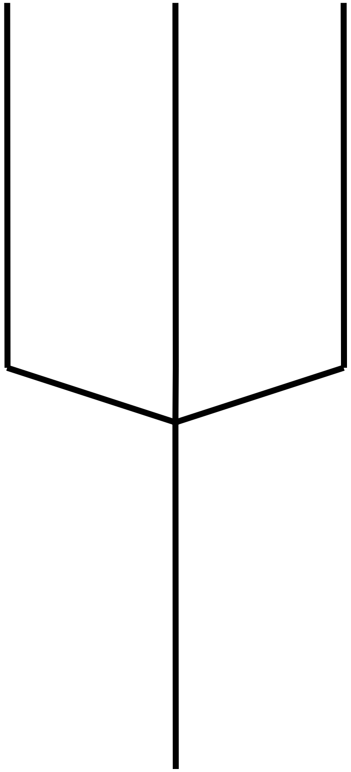
split duplicate



split roundrobin(N)

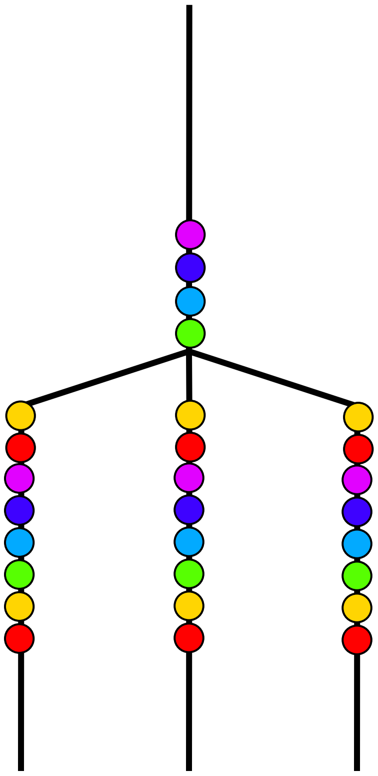


join roundrobin(N)

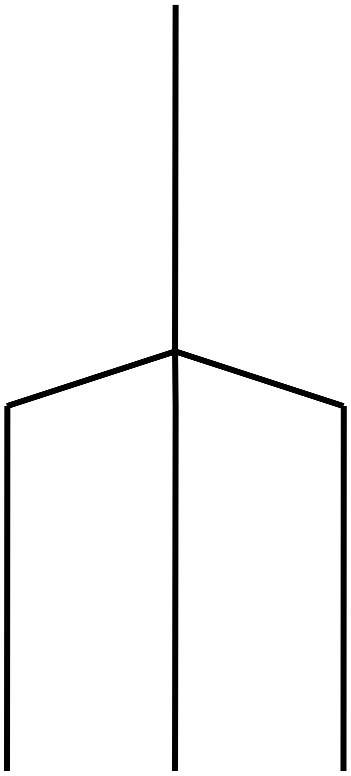


SplitJoins are Beautiful

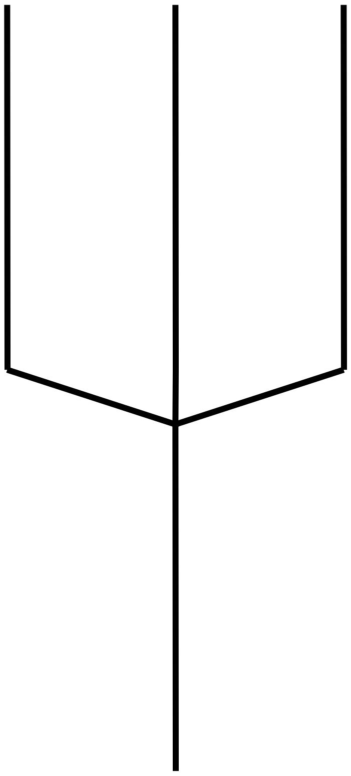
split duplicate



split roundrobin(N)

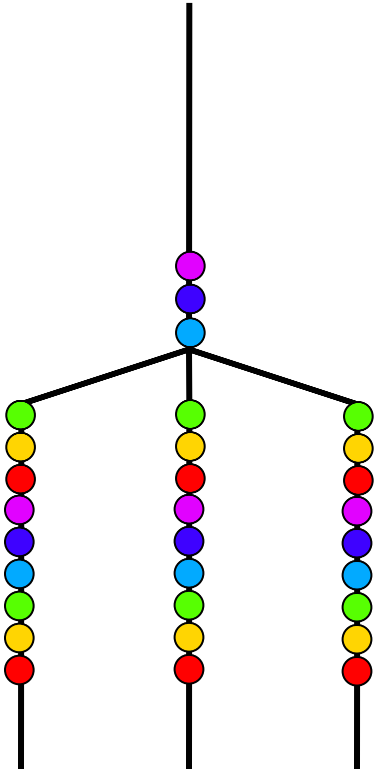


join roundrobin(N)

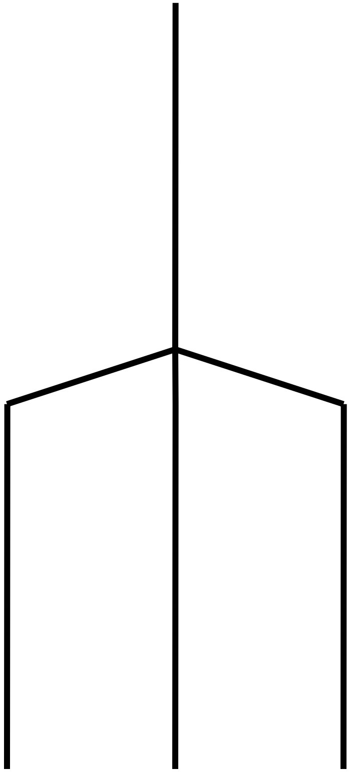


SplitJoins are Beautiful

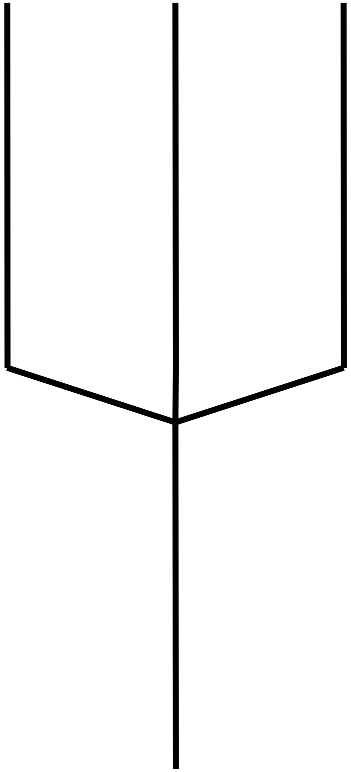
split duplicate



split roundrobin(N)

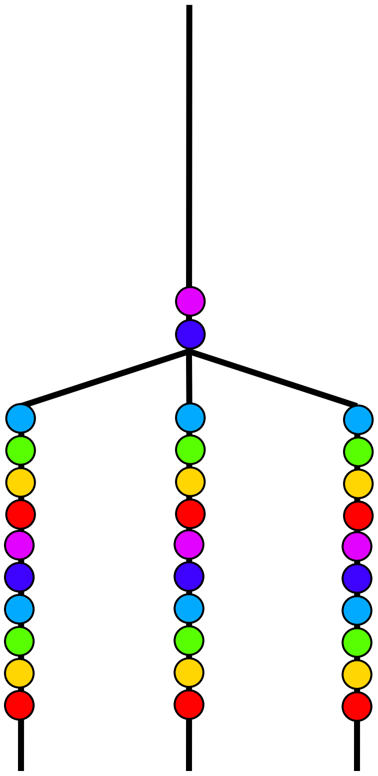


join roundrobin(N)

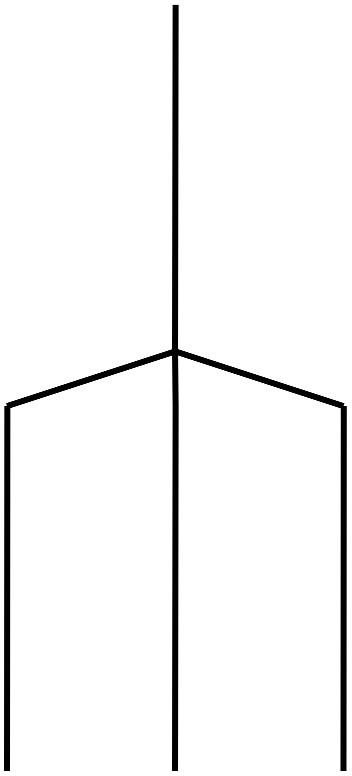


SplitJoins are Beautiful

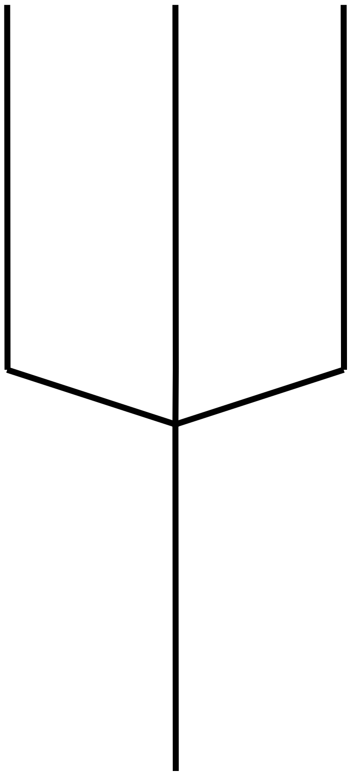
split duplicate



split roundrobin(N)

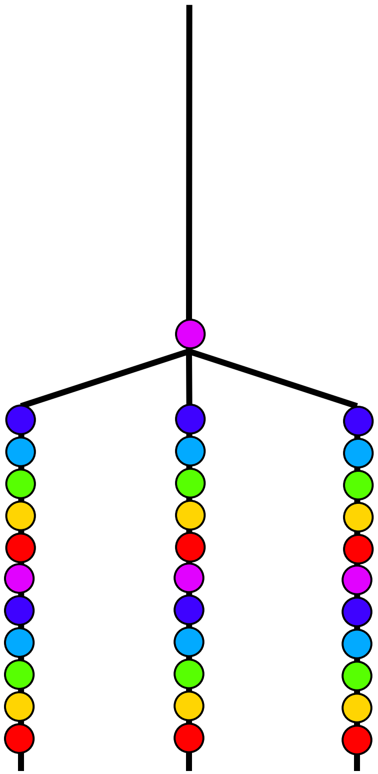


join roundrobin(N)

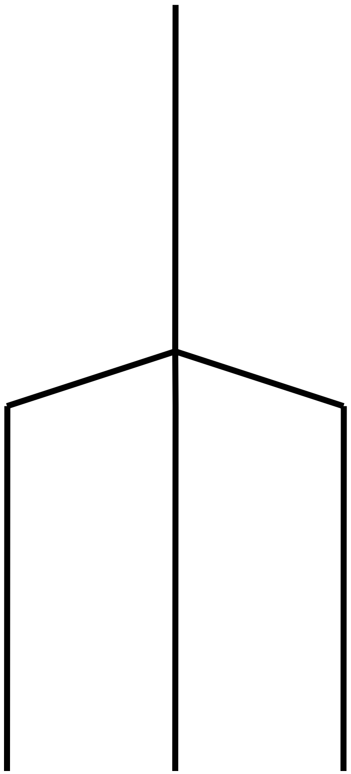


SplitJoins are Beautiful

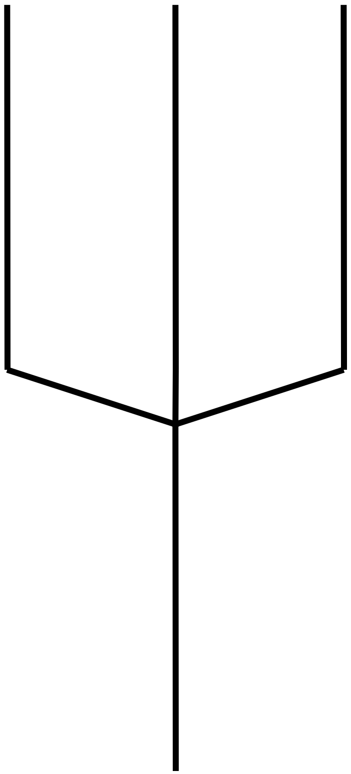
split duplicate



split roundrobin(N)

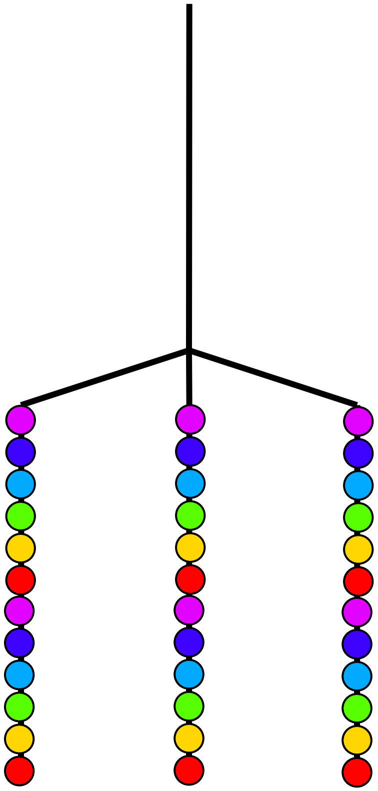


join roundrobin(N)

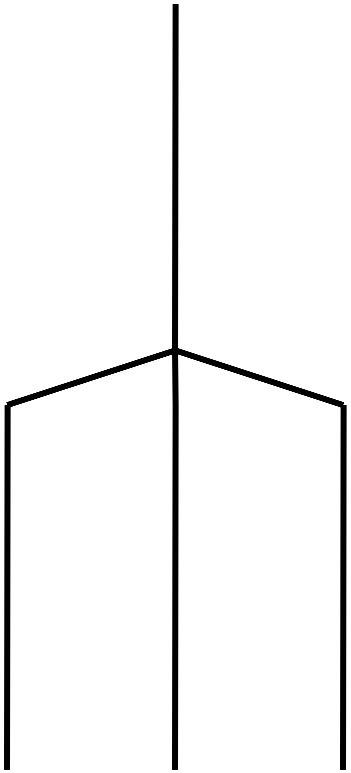


SplitJoins are Beautiful

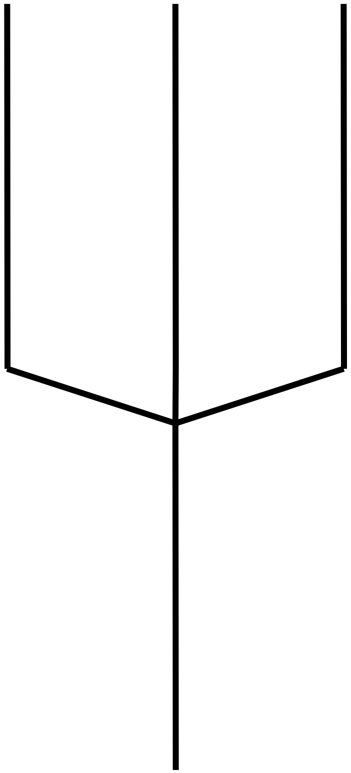
split duplicate



split roundrobin(N)

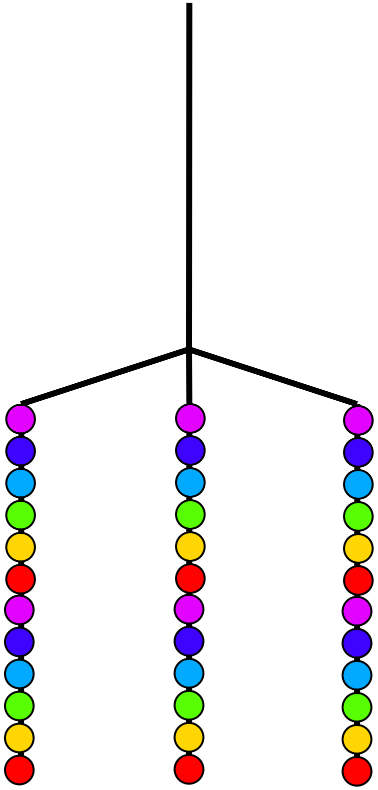


join roundrobin(N)

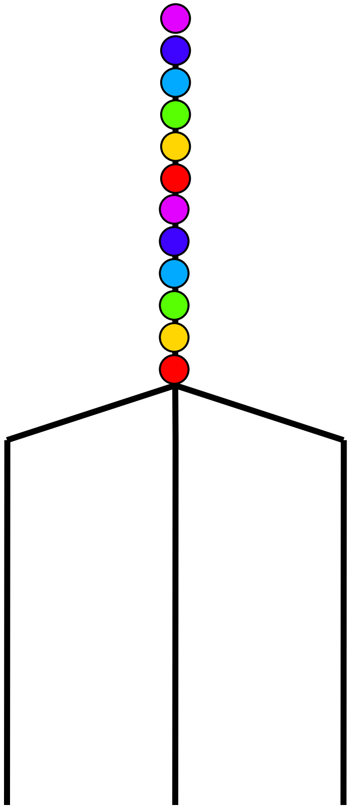


SplitJoins are Beautiful

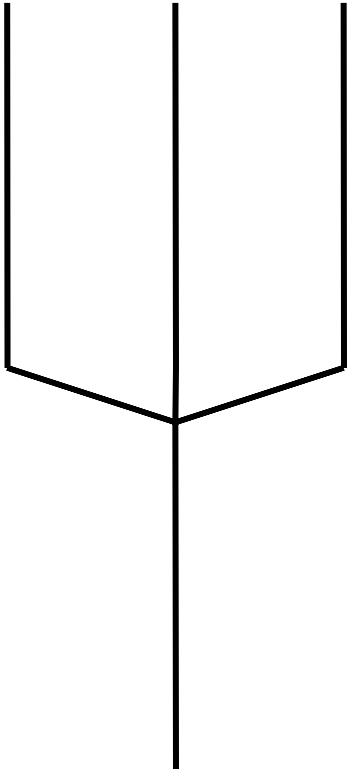
split duplicate



split roundrobin(N)

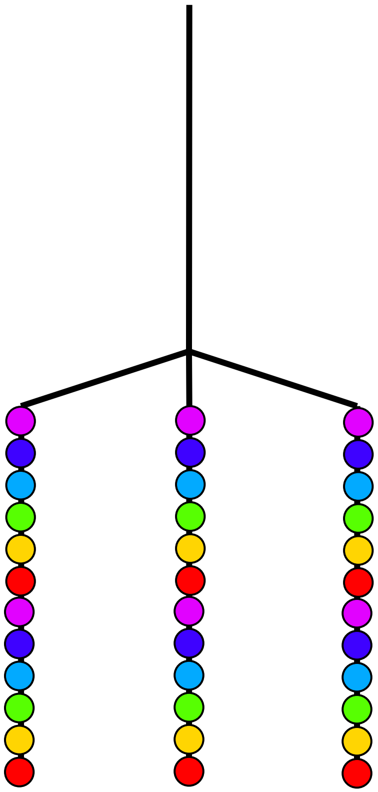


join roundrobin(N)

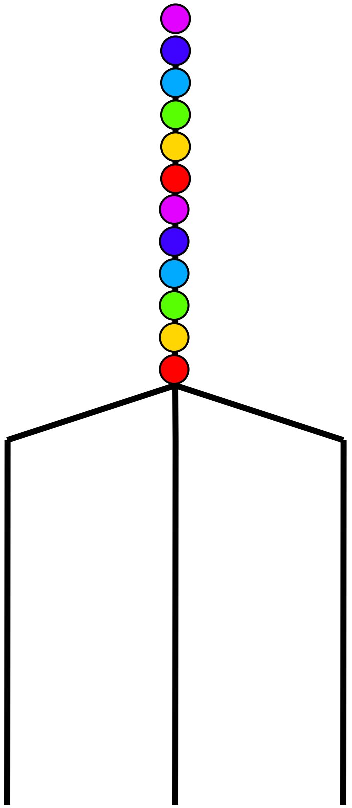


SplitJoins are Beautiful

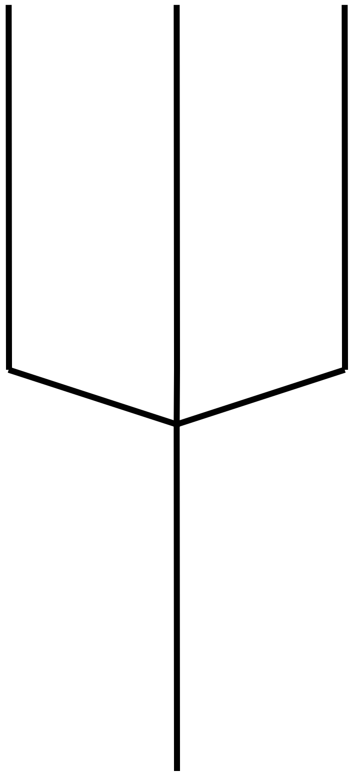
split duplicate



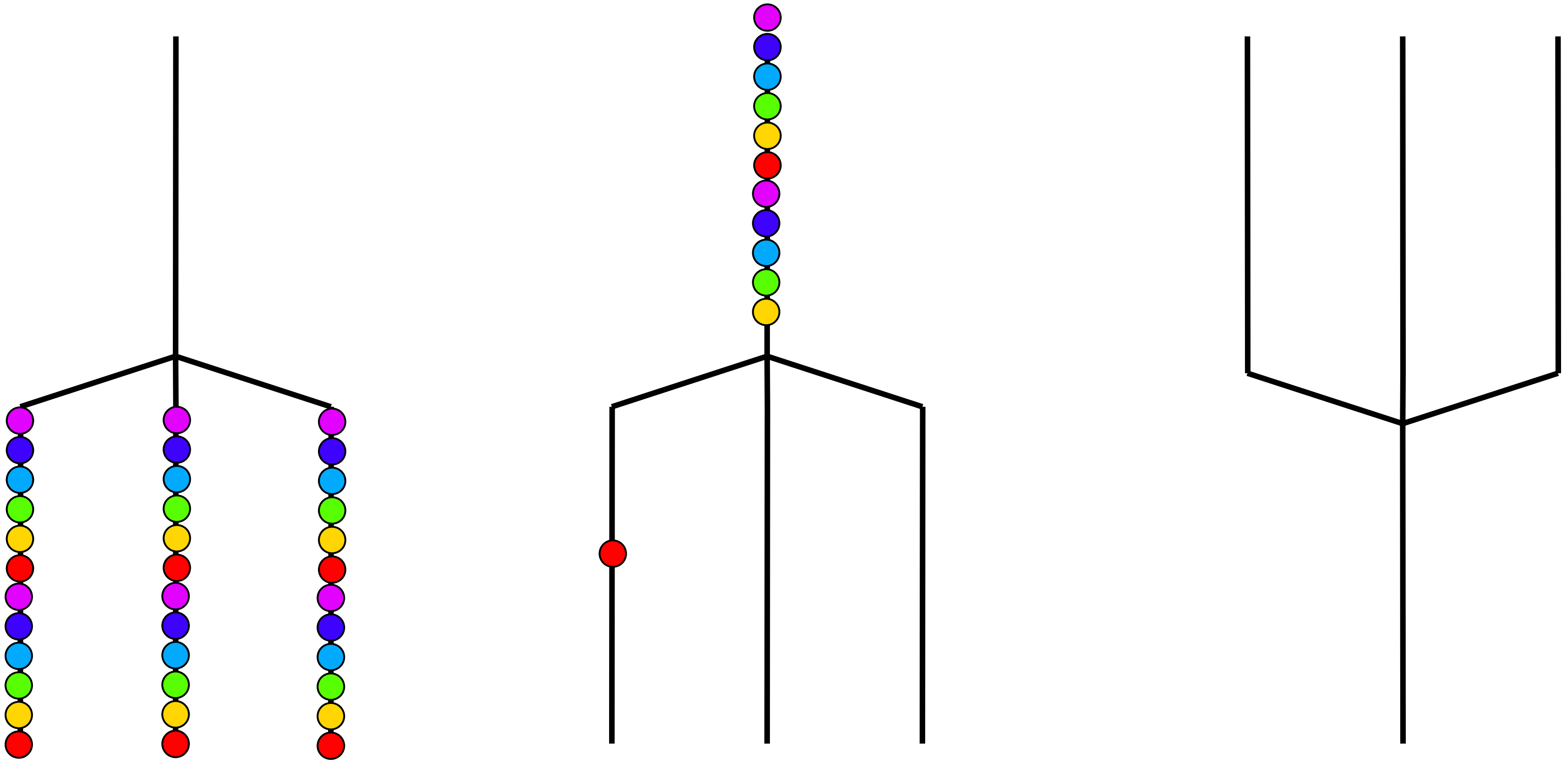
split roundrobin(1)



join roundrobin(1)



SplitJoins are Beautiful



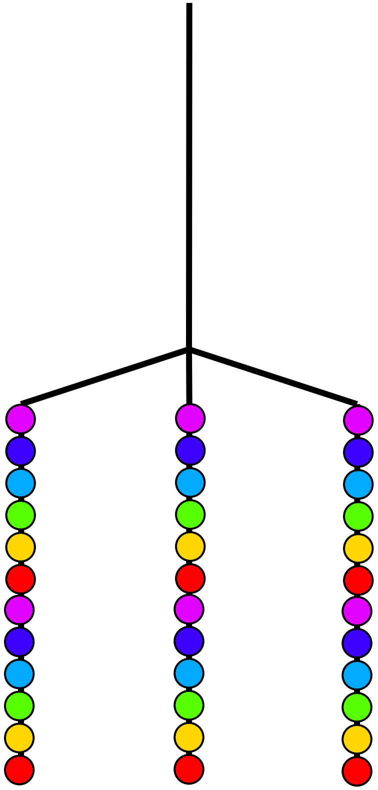
split duplicate

split roundrobin(1)

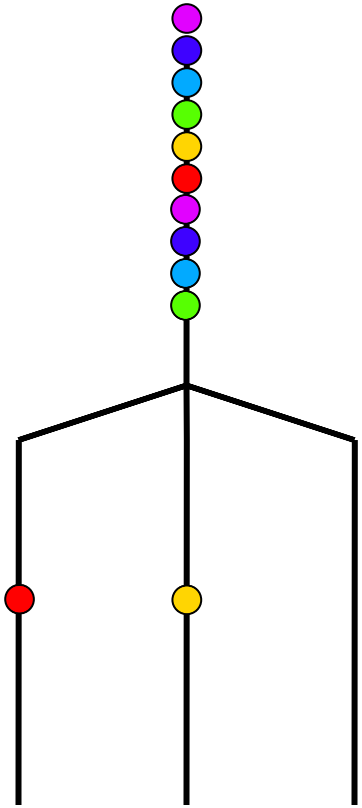
join roundrobin(1)

SplitJoins are Beautiful

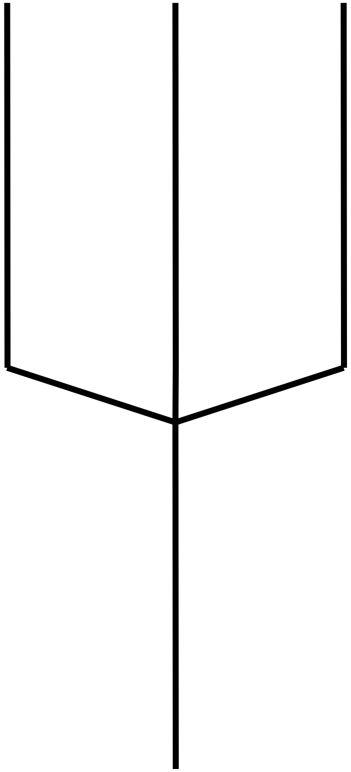
split duplicate



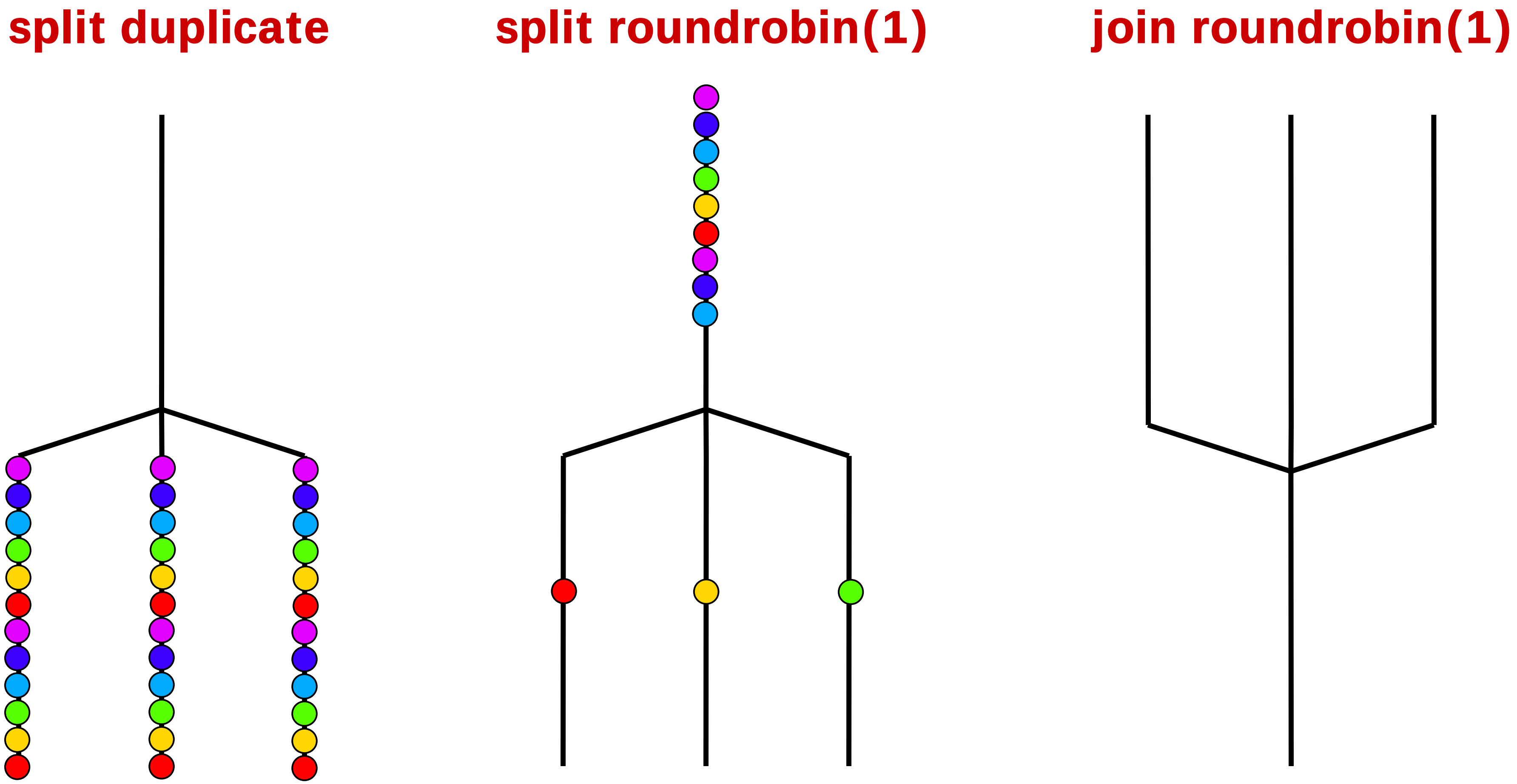
split roundrobin(1)



join roundrobin(1)



SplitJoins are Beautiful



split duplicate

split roundrobin(1)

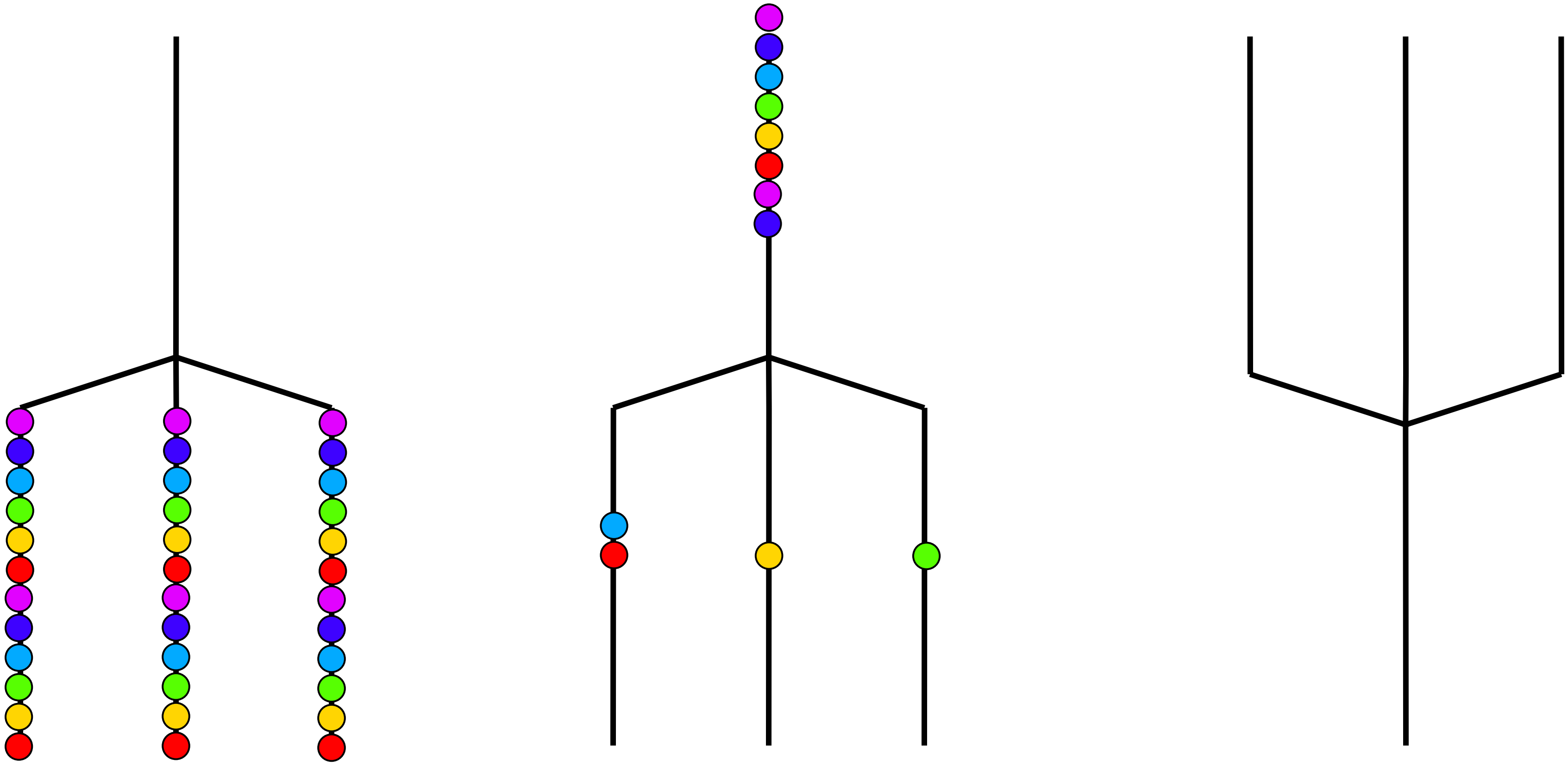
join roundrobin(1)

SplitJoins are Beautiful

split duplicate

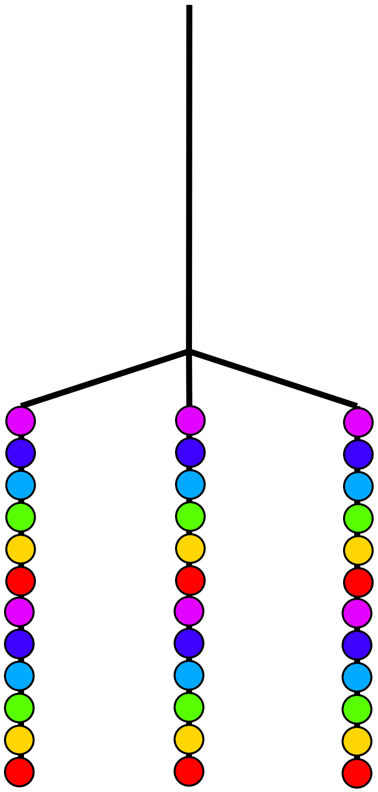
split roundrobin(1)

join roundrobin(1)

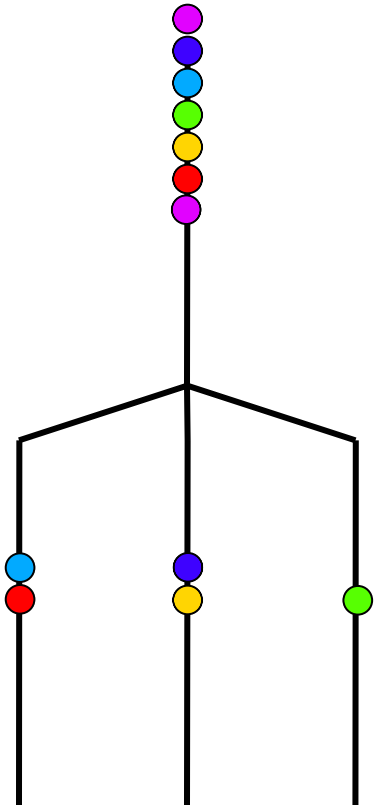


SplitJoins are Beautiful

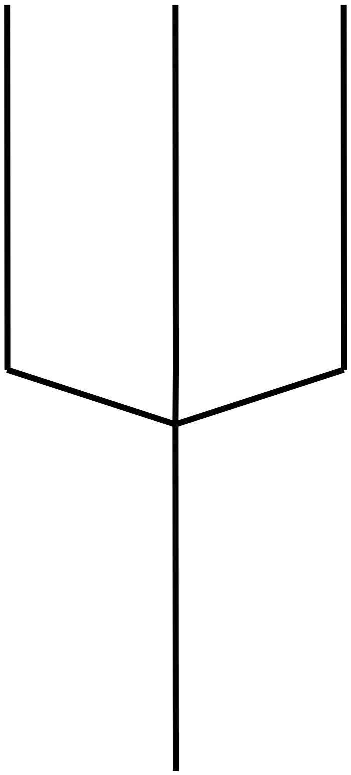
split duplicate



split roundrobin(1)

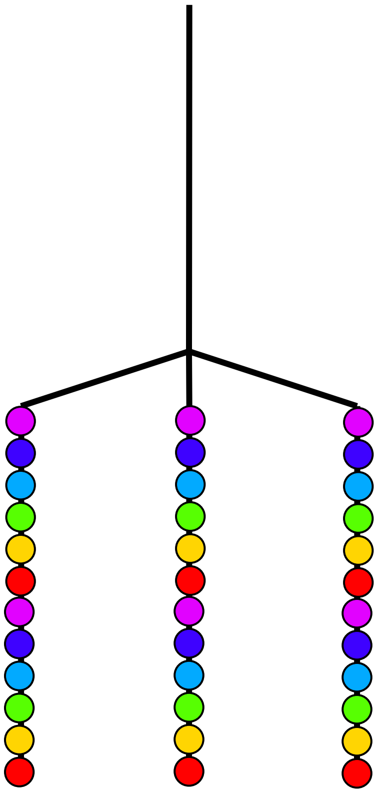


join roundrobin(1)

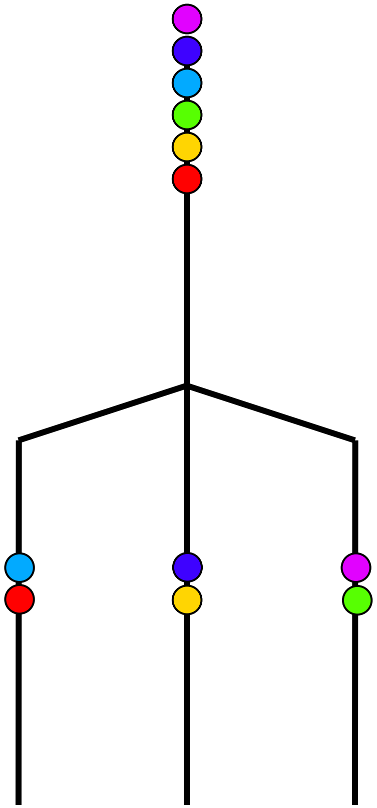


SplitJoins are Beautiful

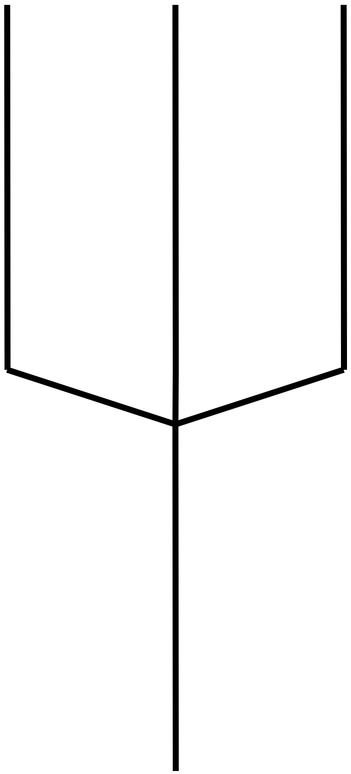
split duplicate



split roundrobin(1)

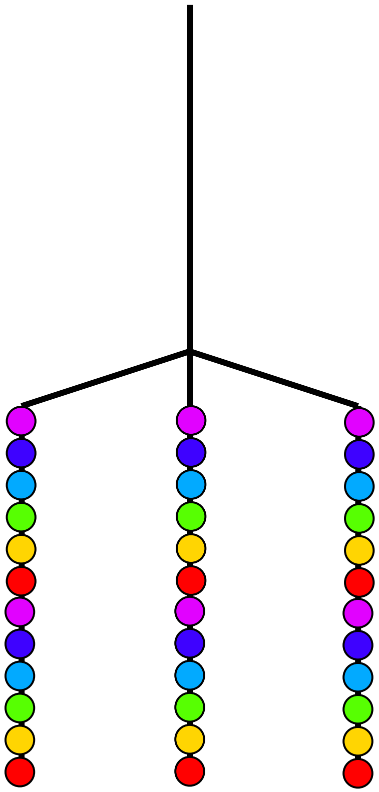


join roundrobin(1)

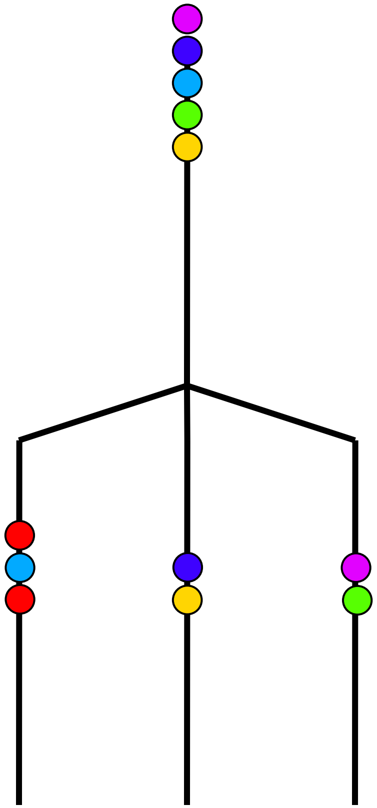


SplitJoins are Beautiful

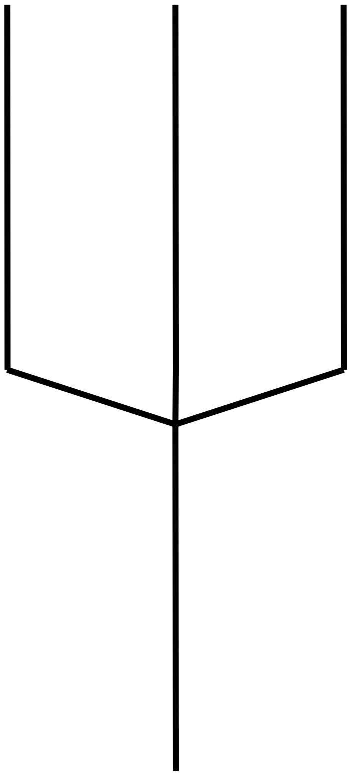
split duplicate



split roundrobin(1)

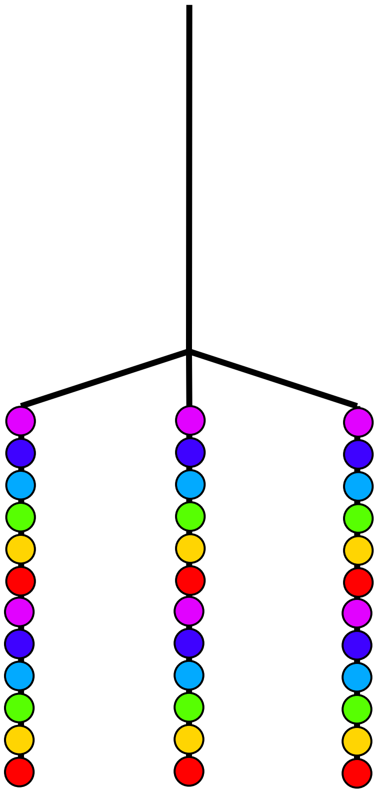


join roundrobin(1)

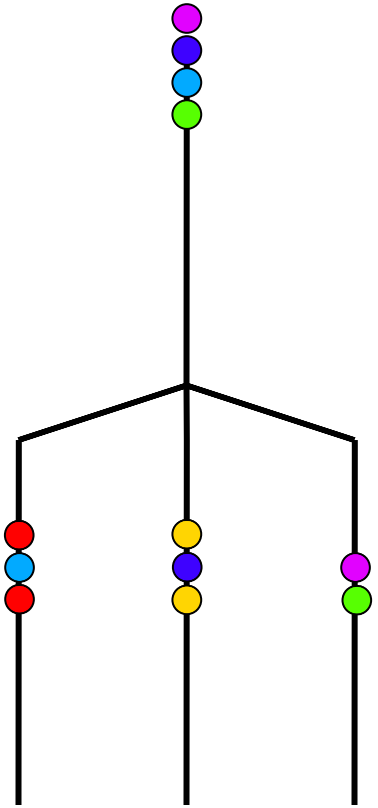


SplitJoins are Beautiful

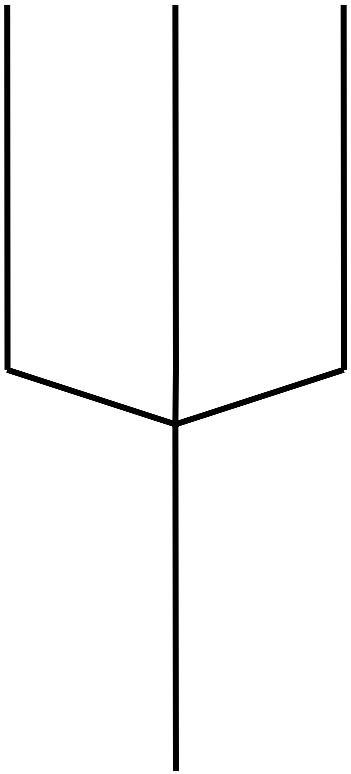
split duplicate



split roundrobin(1)

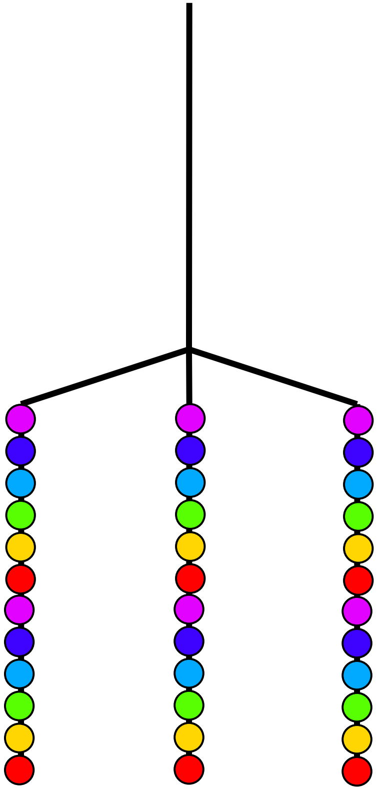


join roundrobin(1)

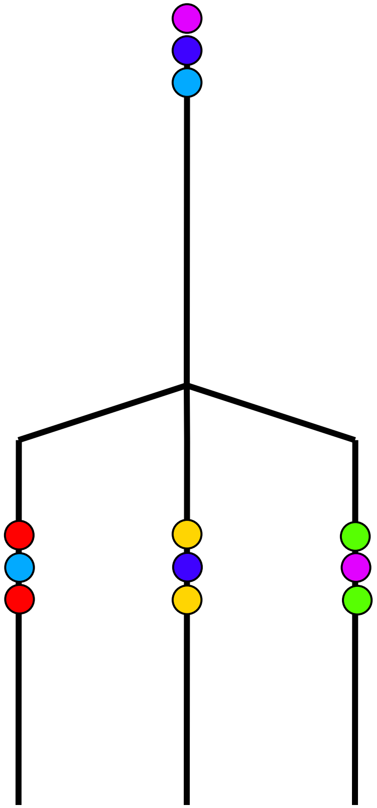


SplitJoins are Beautiful

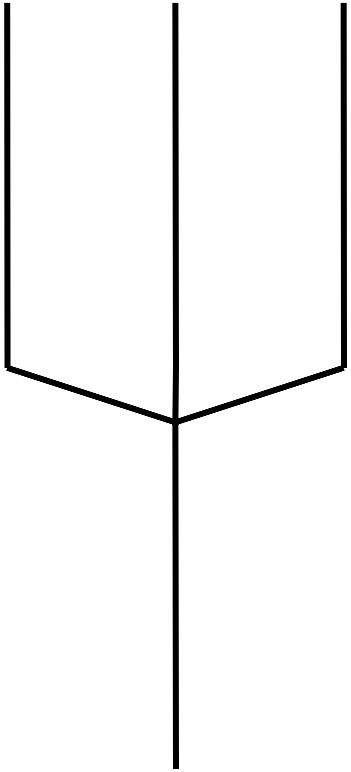
split duplicate



split roundrobin(1)

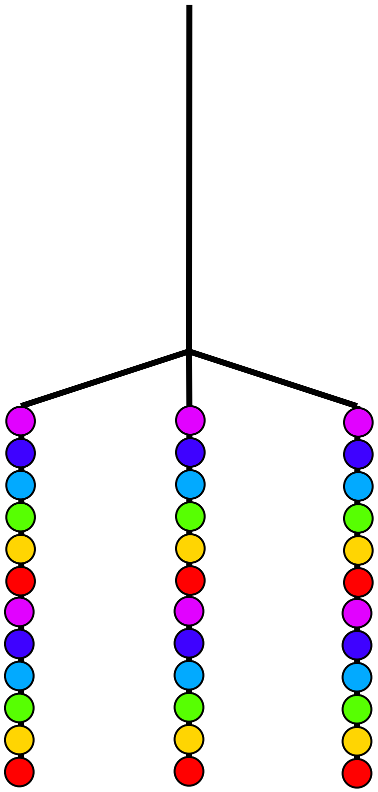


join roundrobin(1)

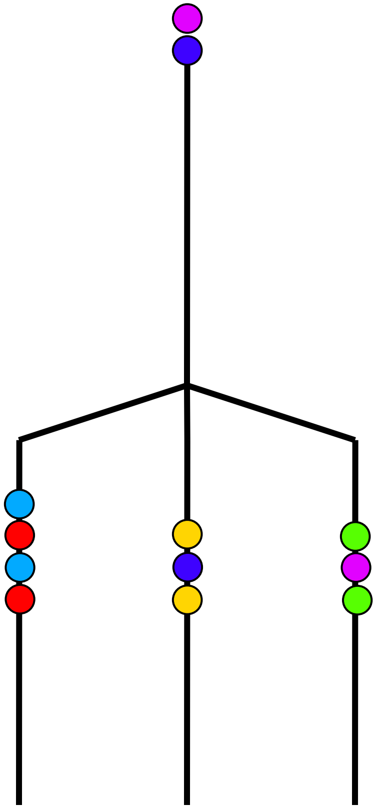


SplitJoins are Beautiful

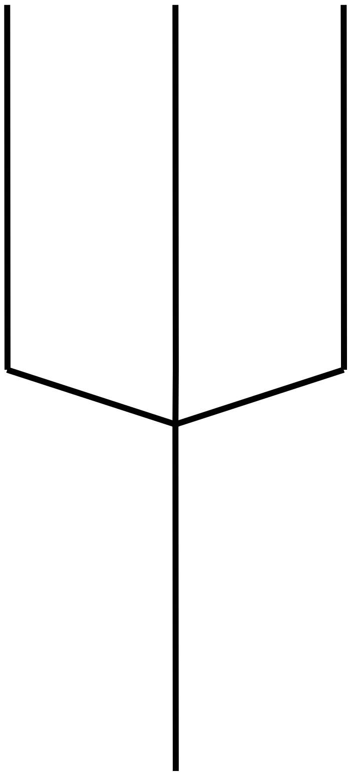
split duplicate



split roundrobin(1)



join roundrobin(1)

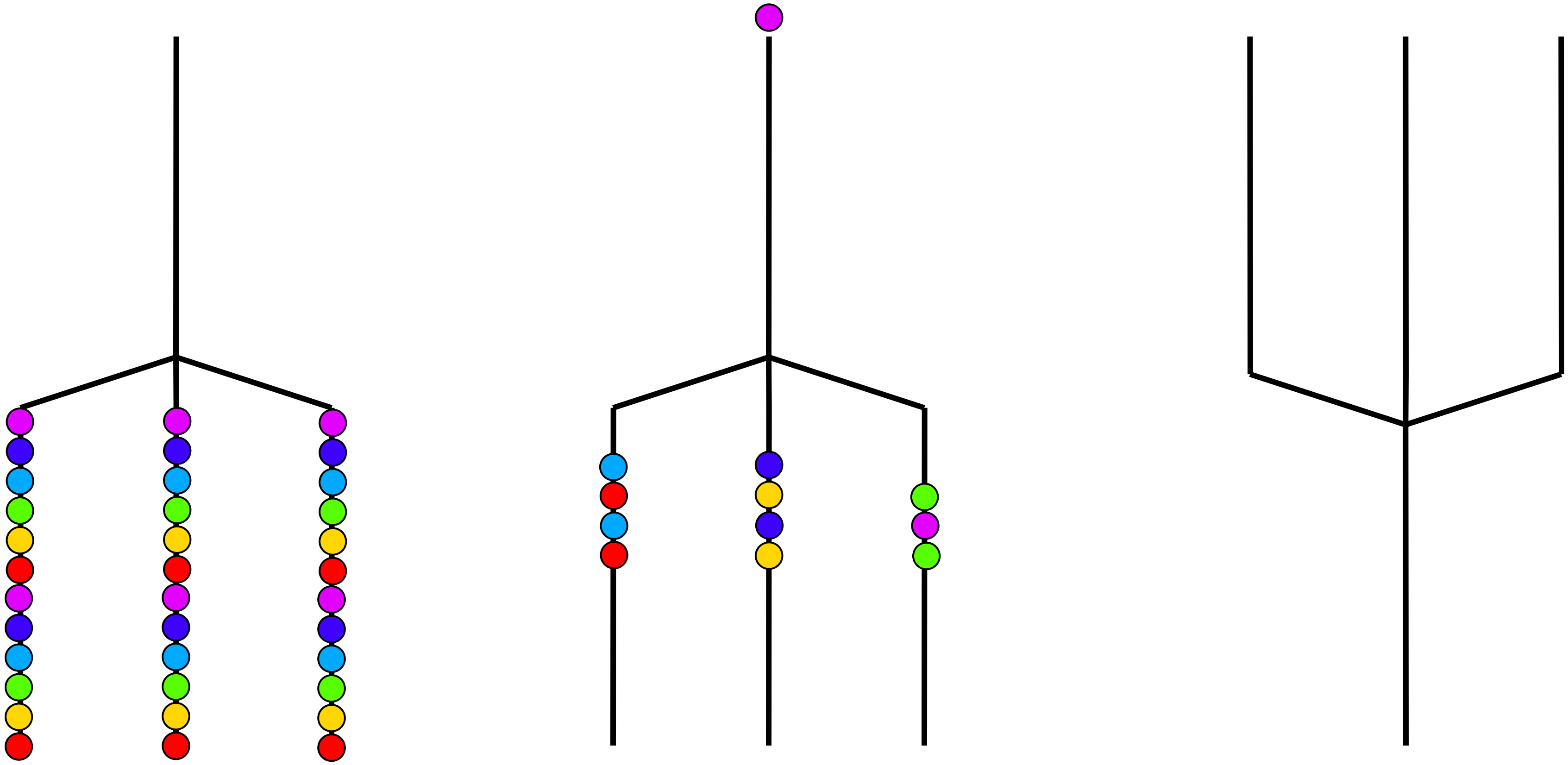


SplitJoins are Beautiful

split duplicate

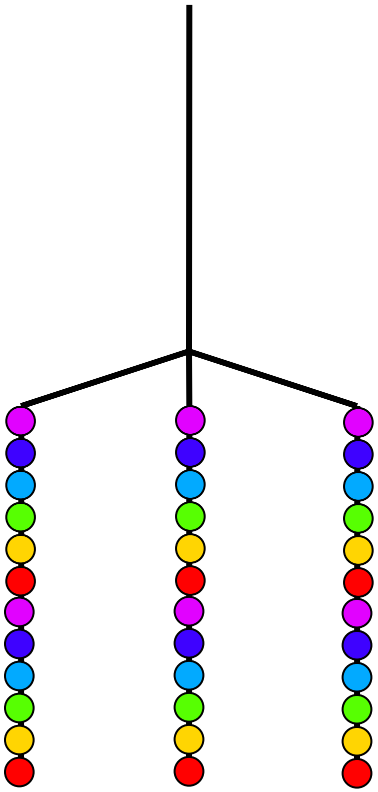
split roundrobin(1)

join roundrobin(1)

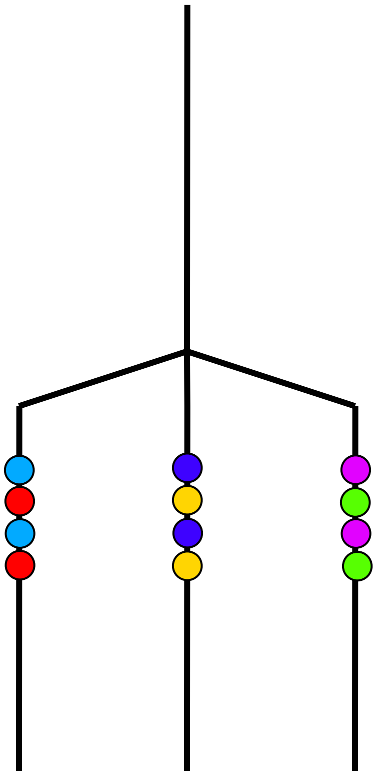


SplitJoins are Beautiful

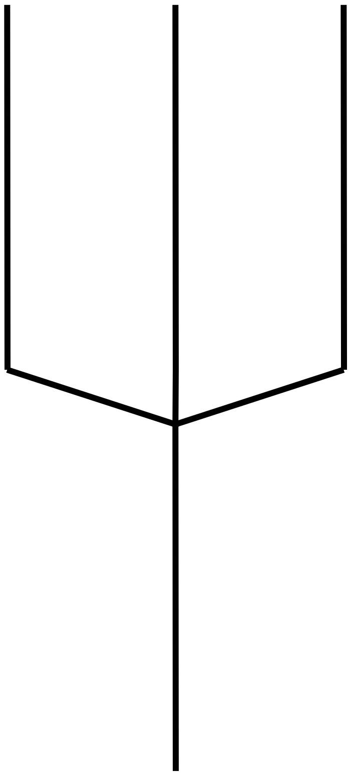
split duplicate



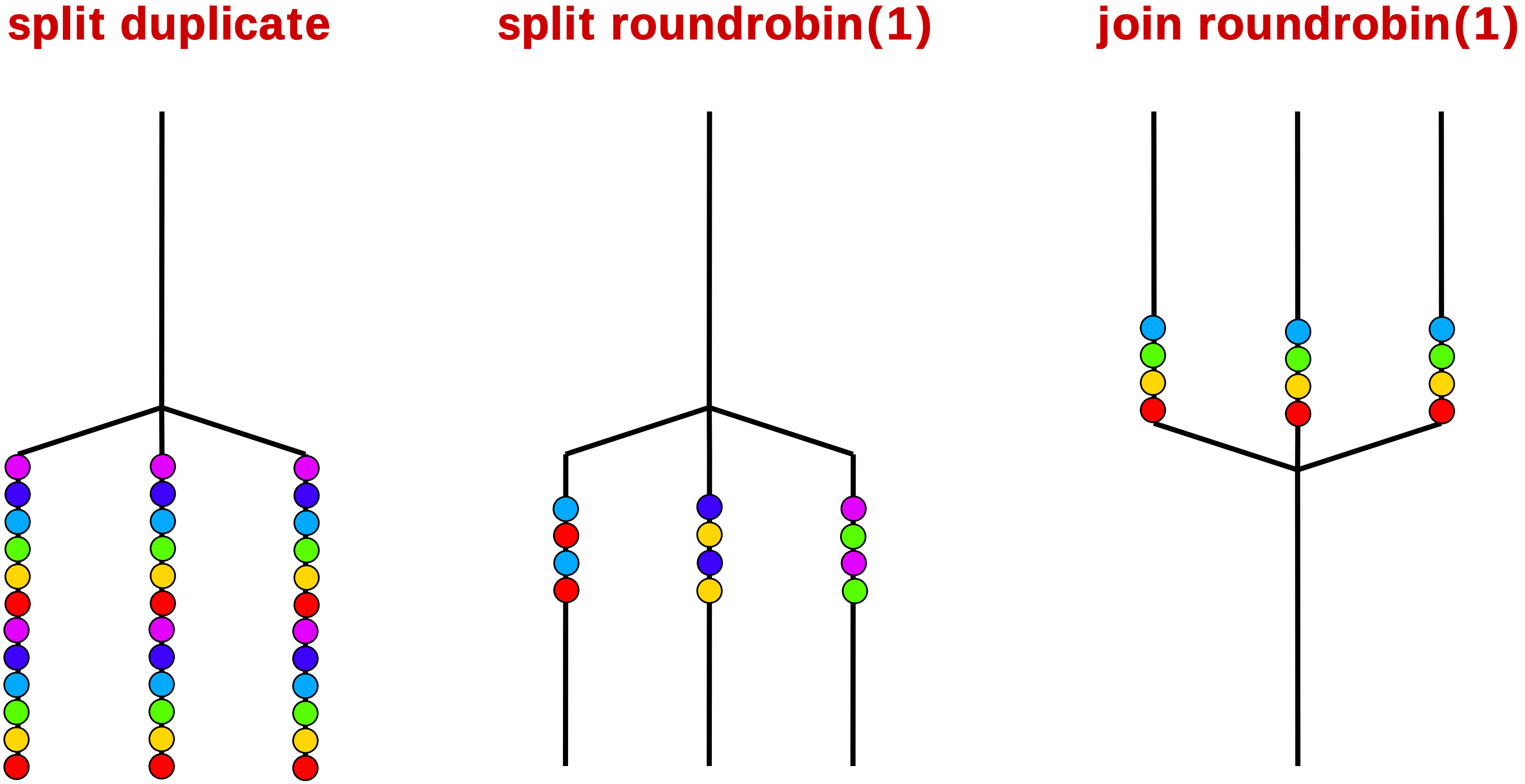
split roundrobin(1)



join roundrobin(1)



SplitJoins are Beautiful



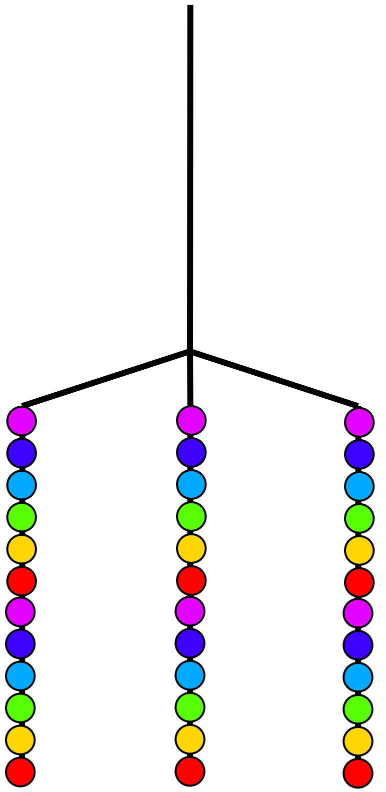
split duplicate

split roundrobin(1)

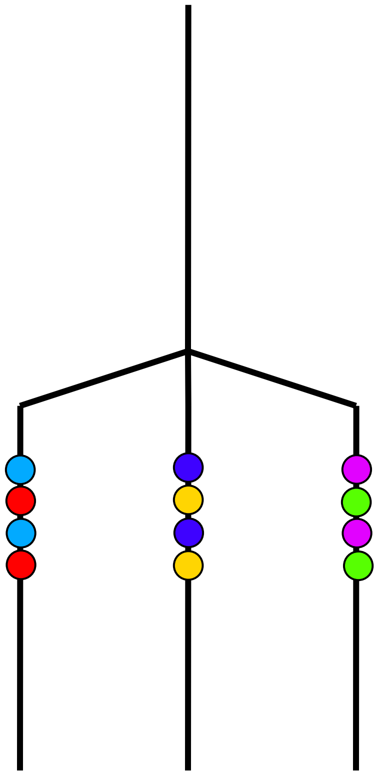
join roundrobin(1)

SplitJoins are Beautiful

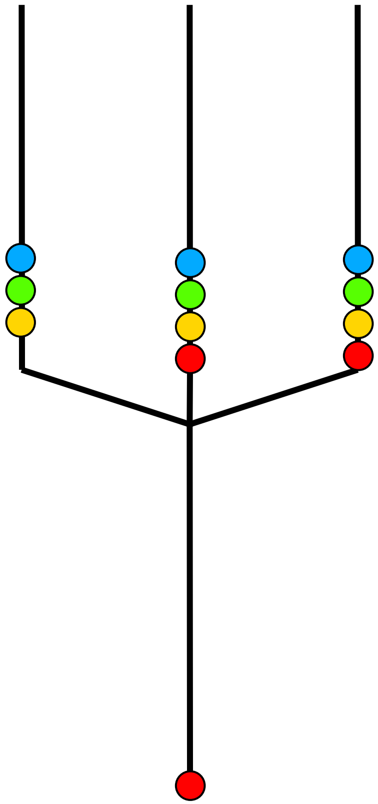
split duplicate



split roundrobin(1)

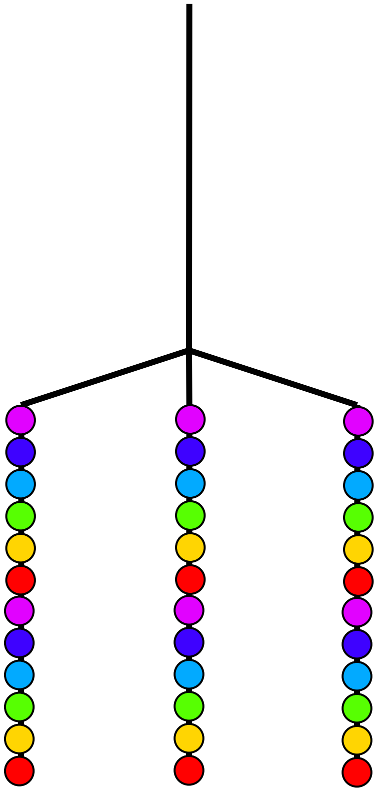


join roundrobin(1)

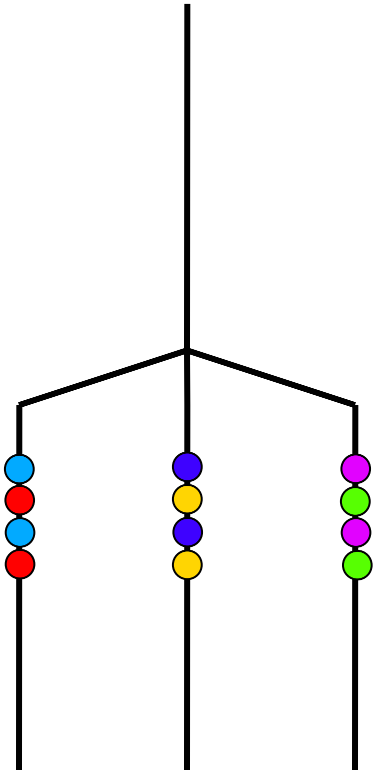


SplitJoins are Beautiful

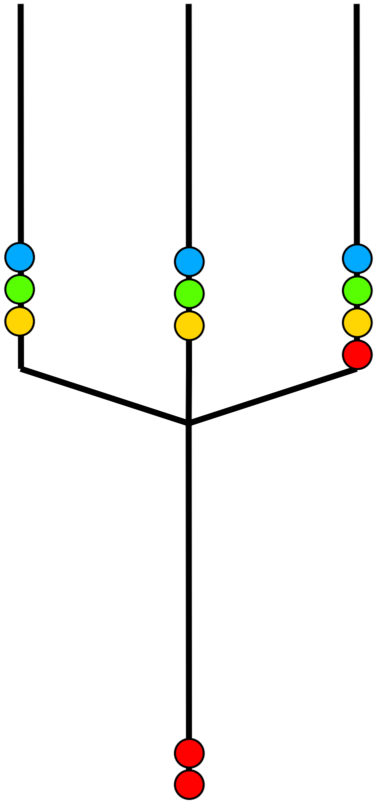
split duplicate



split roundrobin(1)

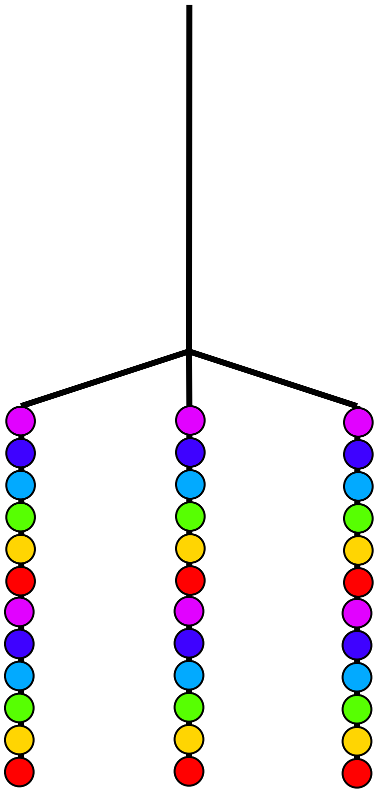


join roundrobin(1)

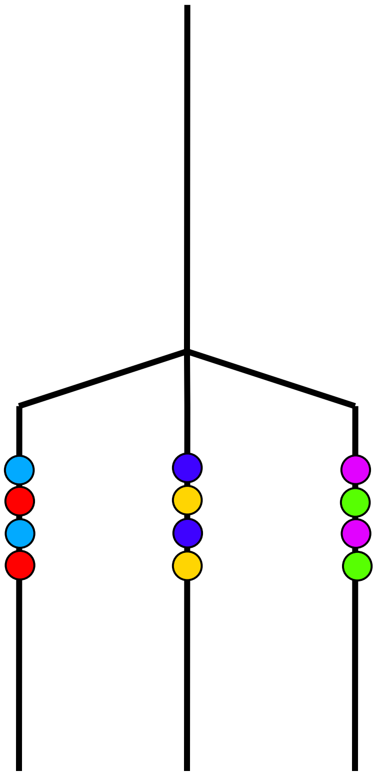


SplitJoins are Beautiful

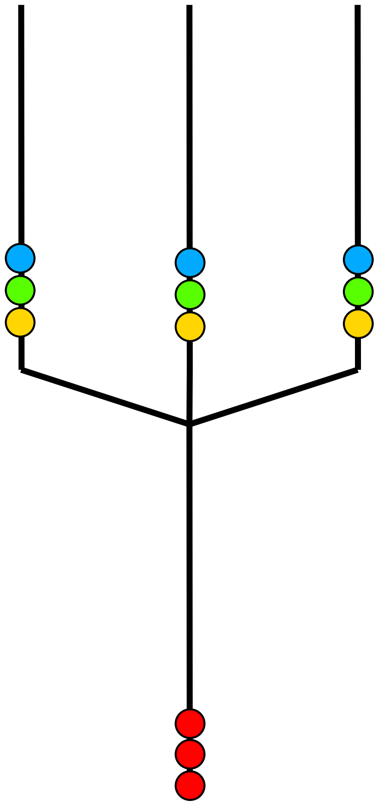
split duplicate



split roundrobin(1)

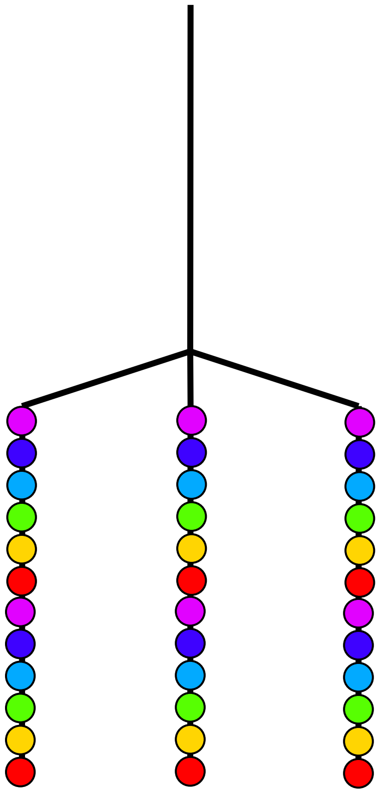


join roundrobin(1)

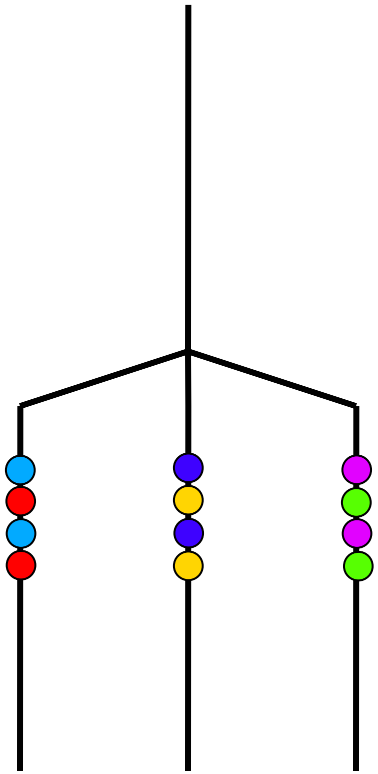


SplitJoins are Beautiful

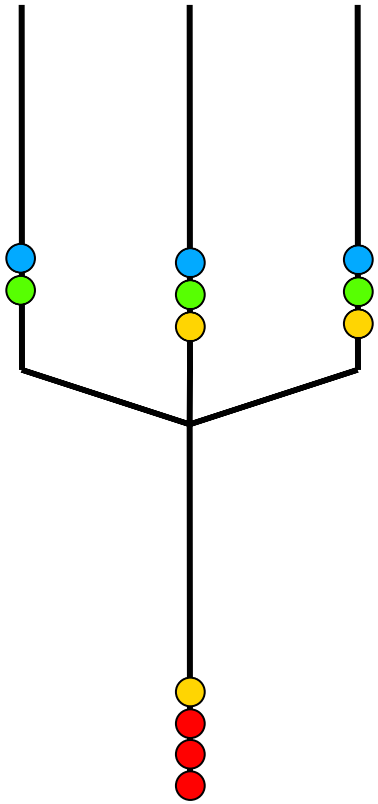
split duplicate



split roundrobin(1)

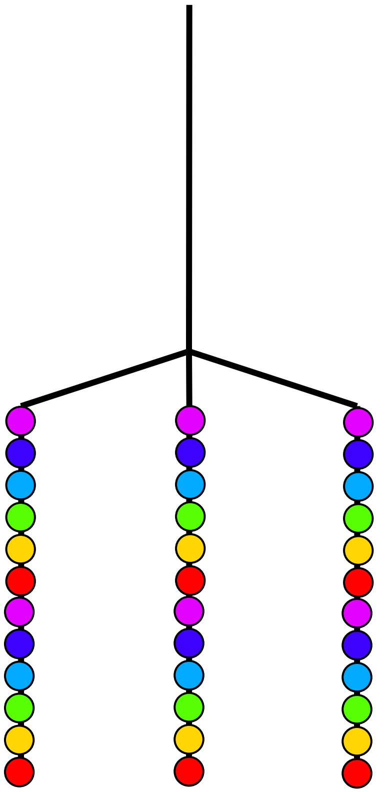


join roundrobin(1)

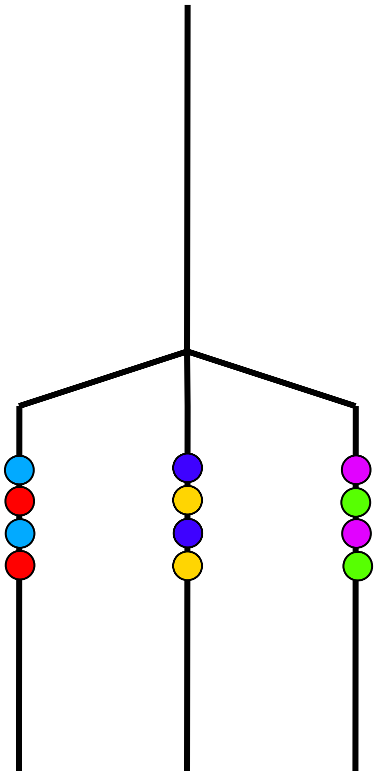


SplitJoins are Beautiful

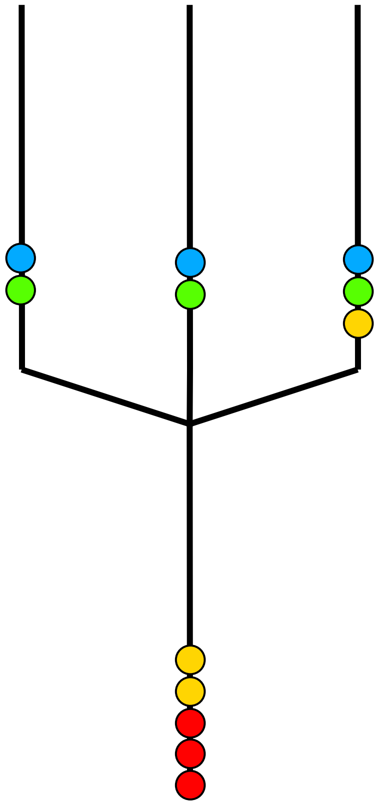
split duplicate



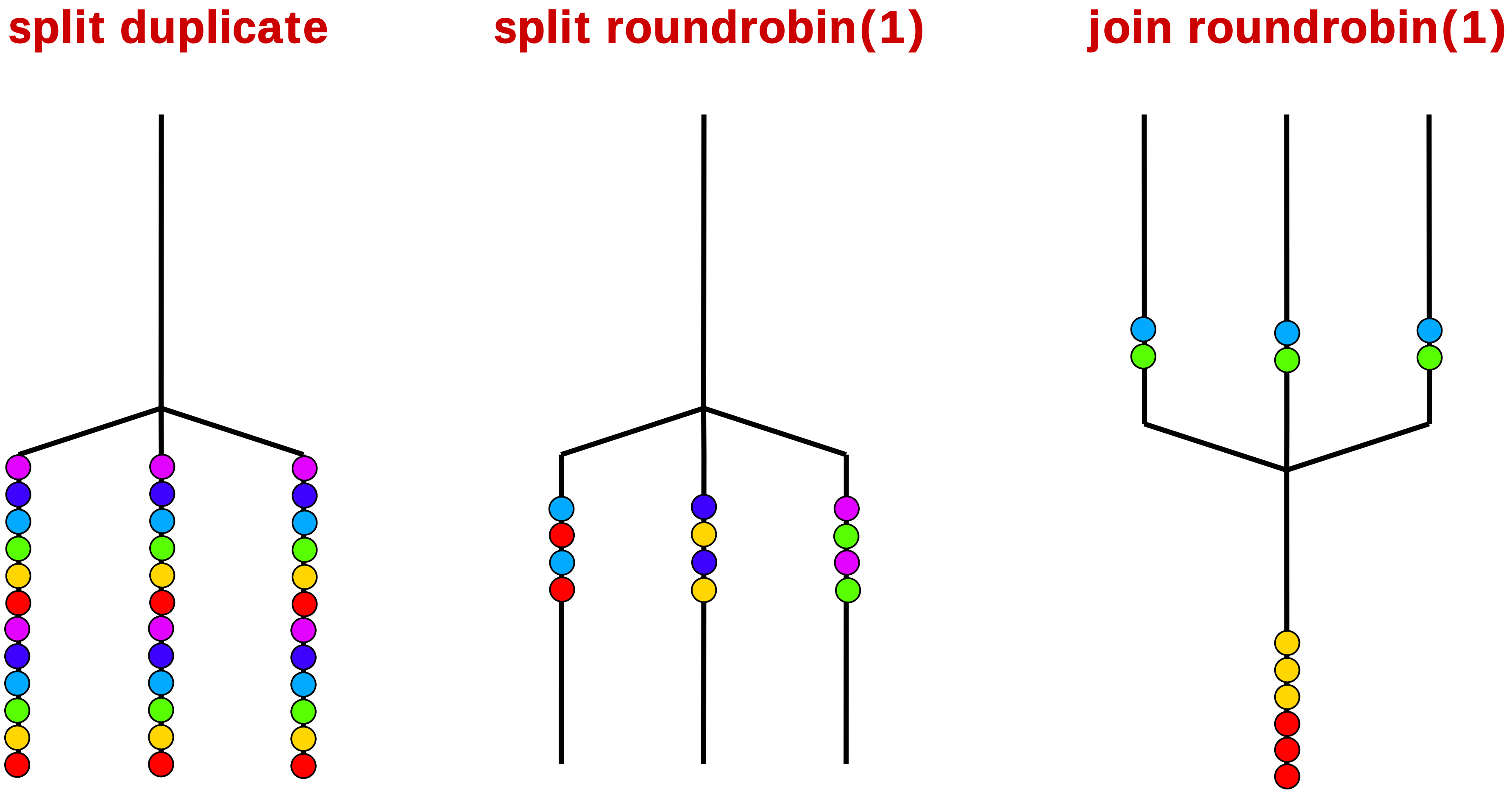
split roundrobin(1)



join roundrobin(1)

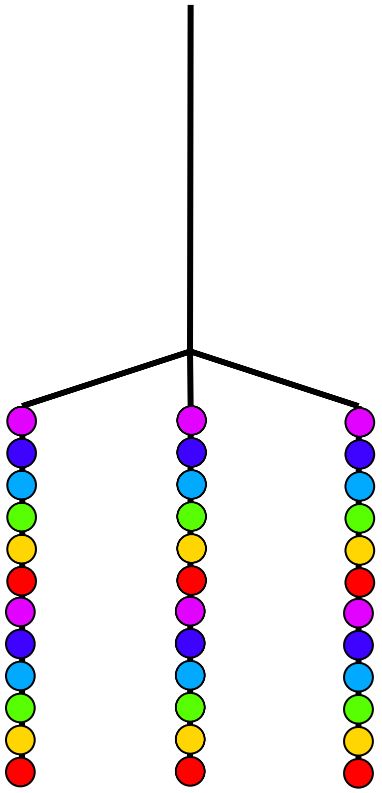


SplitJoins are Beautiful

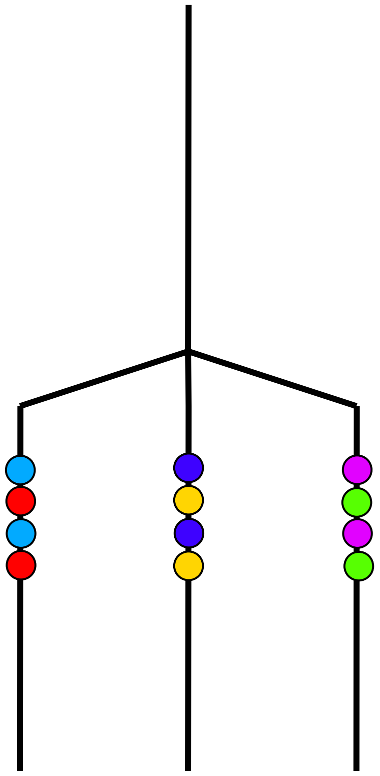


SplitJoins are Beautiful

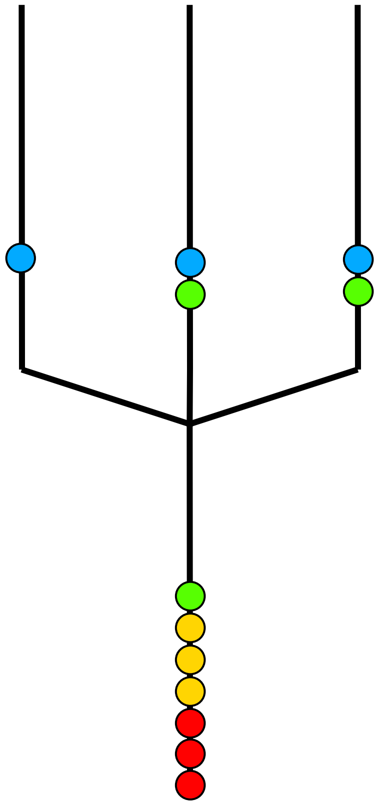
split duplicate



split roundrobin(1)

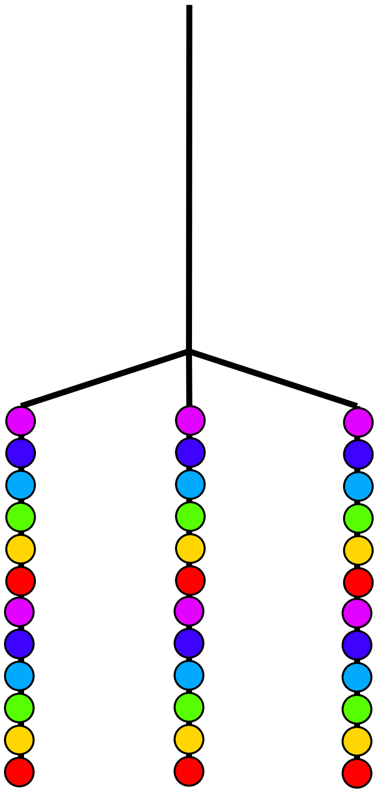


join roundrobin(1)

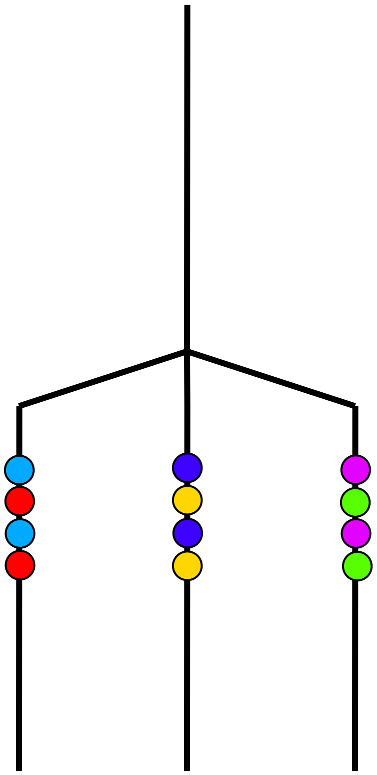


SplitJoins are Beautiful

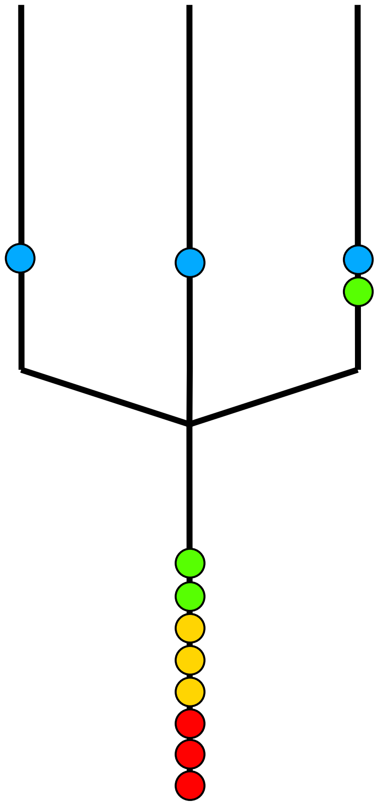
split duplicate



split roundrobin(1)

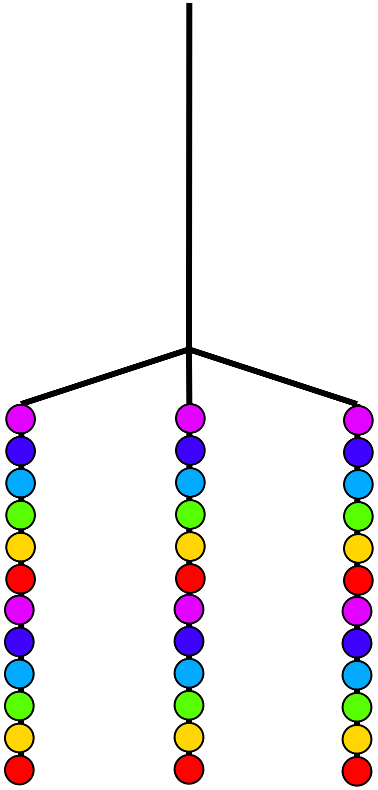


join roundrobin(1)

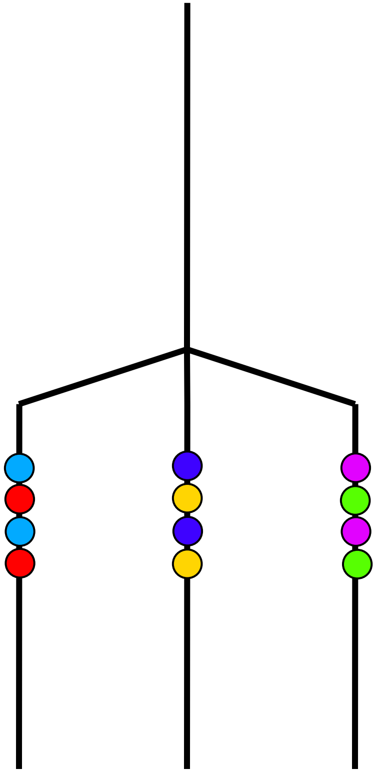


SplitJoins are Beautiful

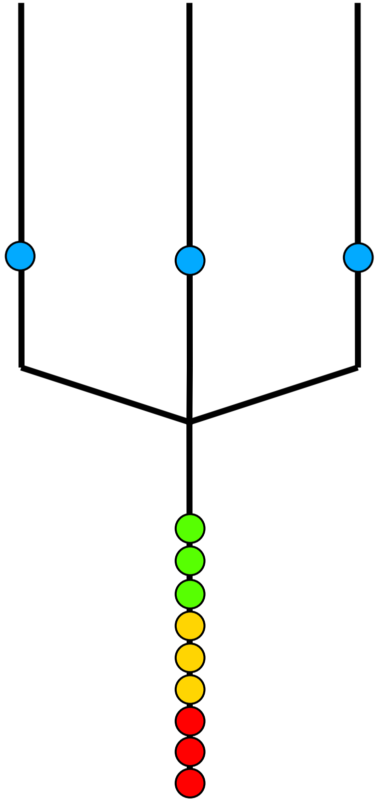
split duplicate



split roundrobin(1)

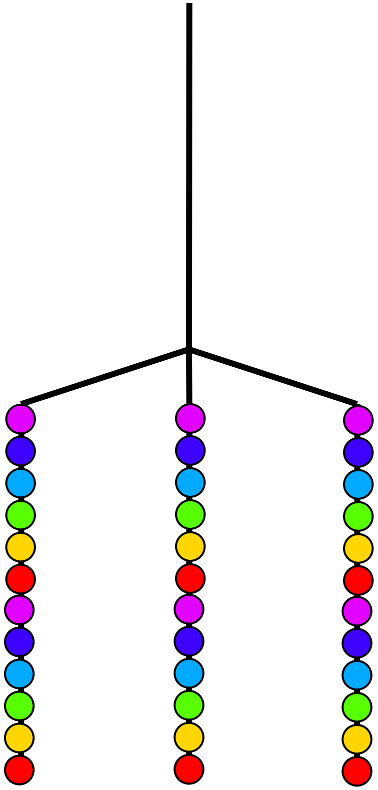


join roundrobin(1)

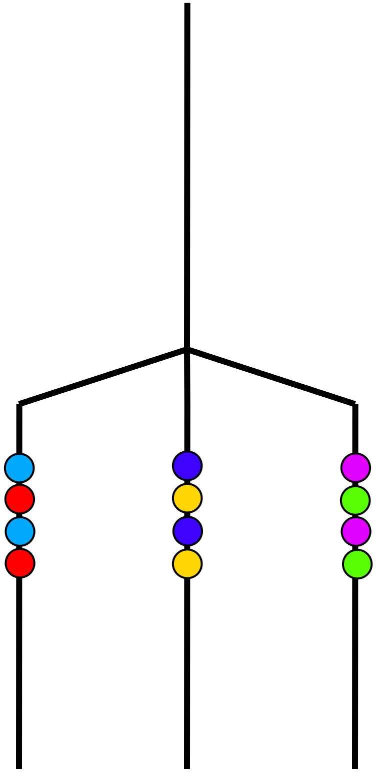


SplitJoins are Beautiful

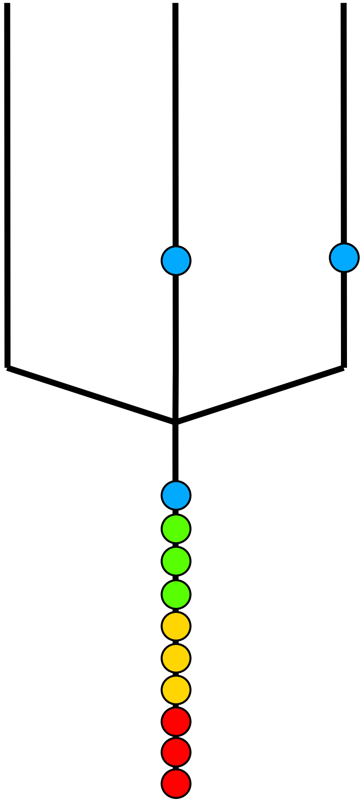
split duplicate



split roundrobin(1)

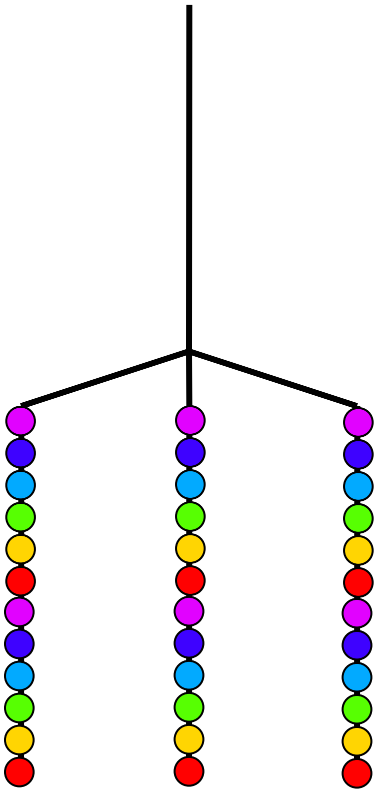


join roundrobin(1)

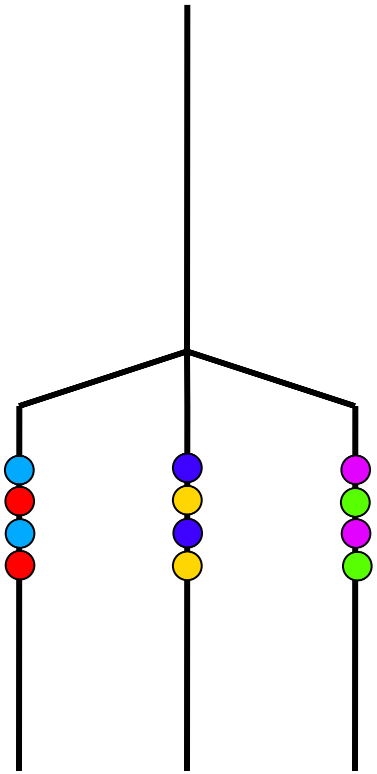


SplitJoins are Beautiful

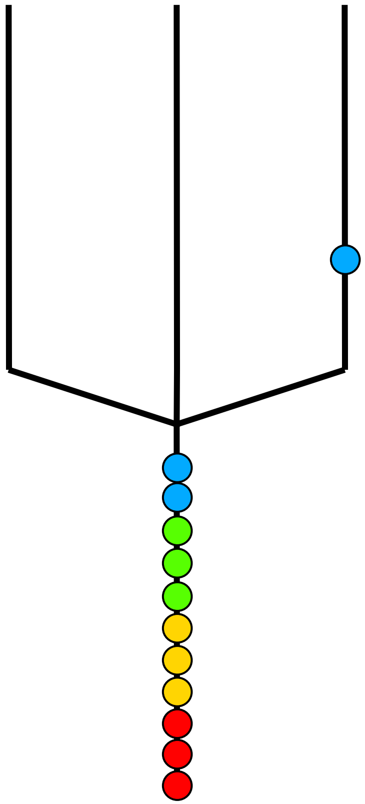
split duplicate



split roundrobin(1)

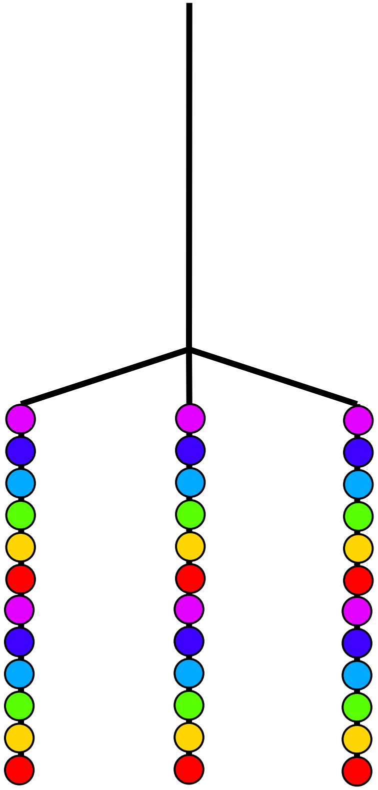


join roundrobin(1)

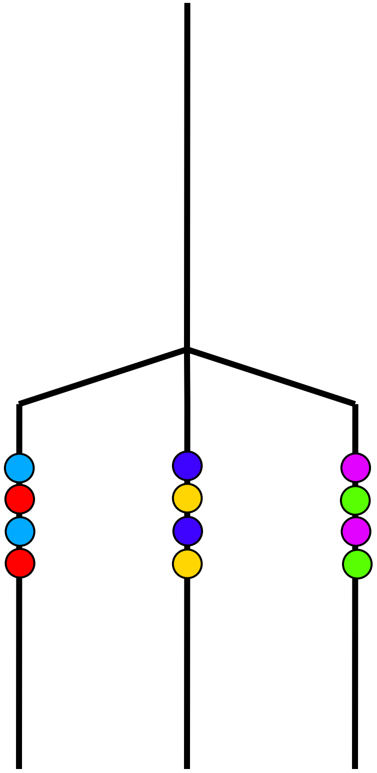


SplitJoins are Beautiful

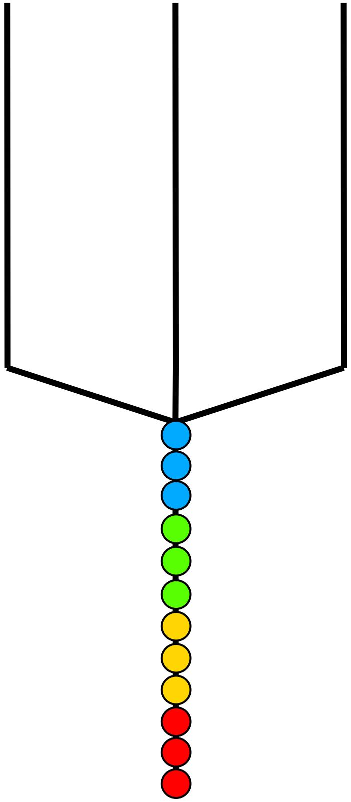
split duplicate



split roundrobin(1)

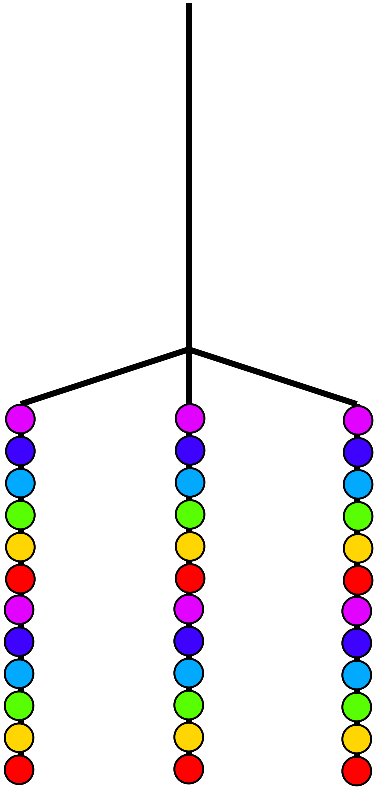


join roundrobin(1)

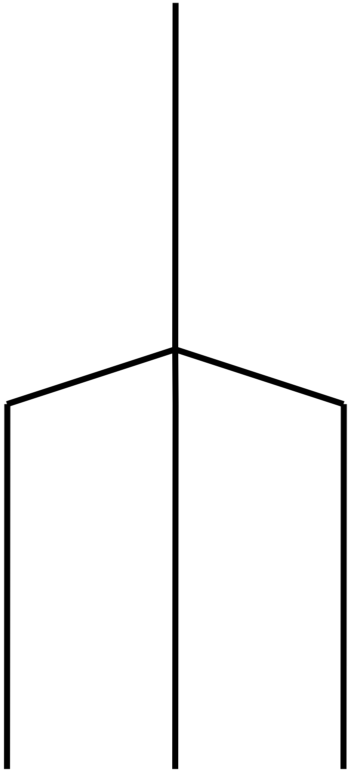


SplitJoins are Beautiful

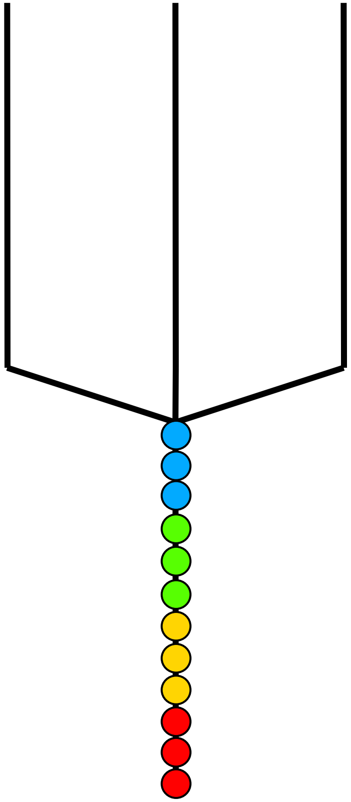
split duplicate



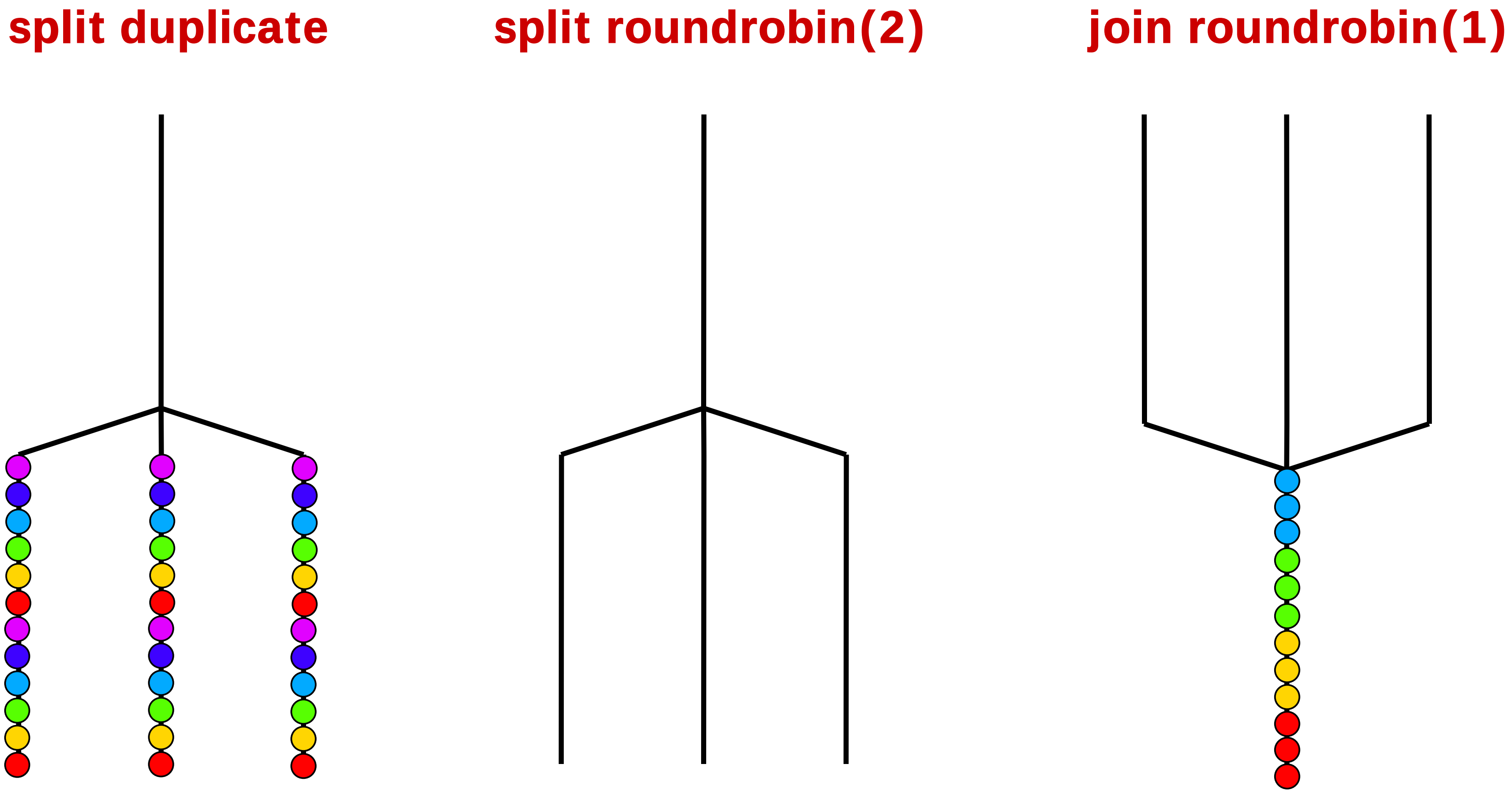
split roundrobin(1)



join roundrobin(1)

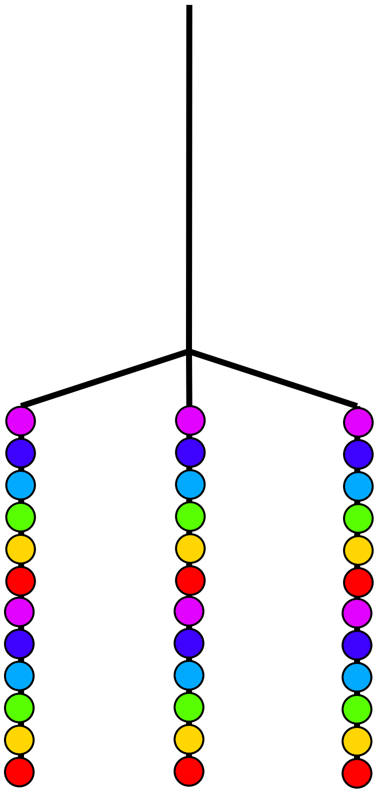


SplitJoins are Beautiful

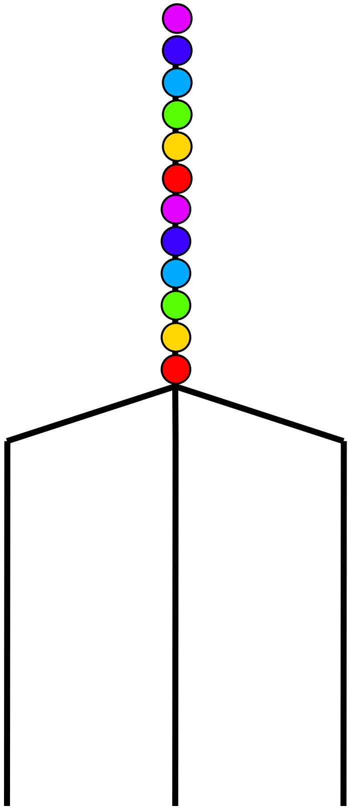


SplitJoins are Beautiful

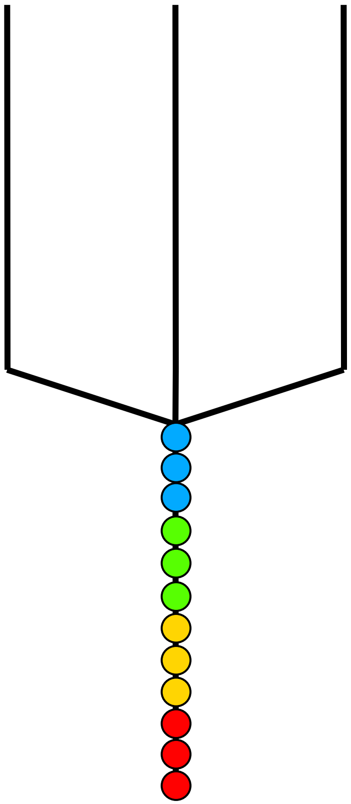
split duplicate



split roundrobin(2)

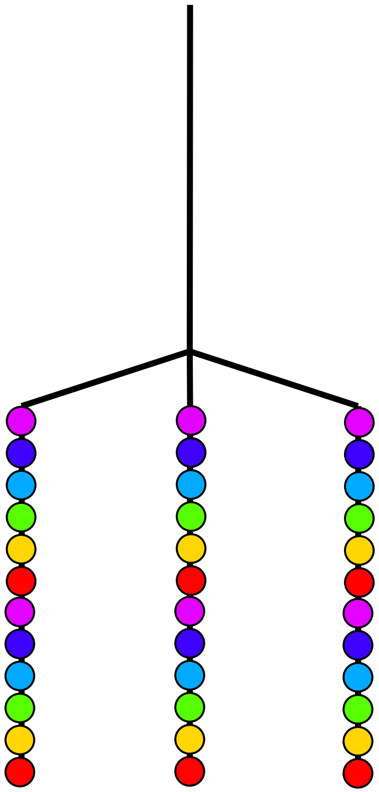


join roundrobin(1)

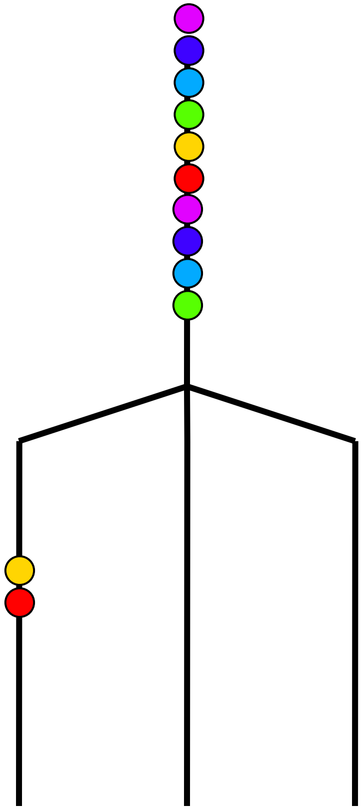


SplitJoins are Beautiful

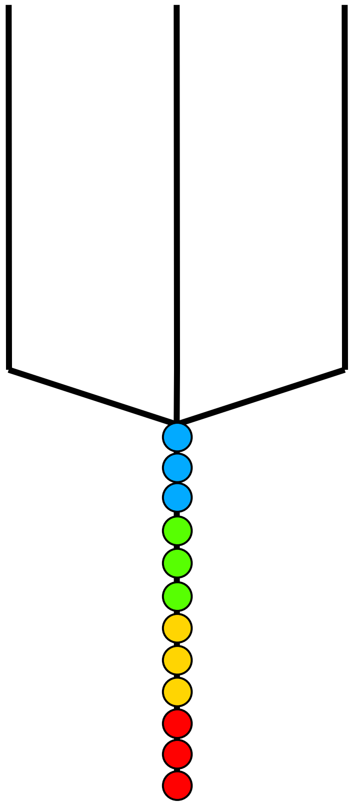
split duplicate



split roundrobin(2)

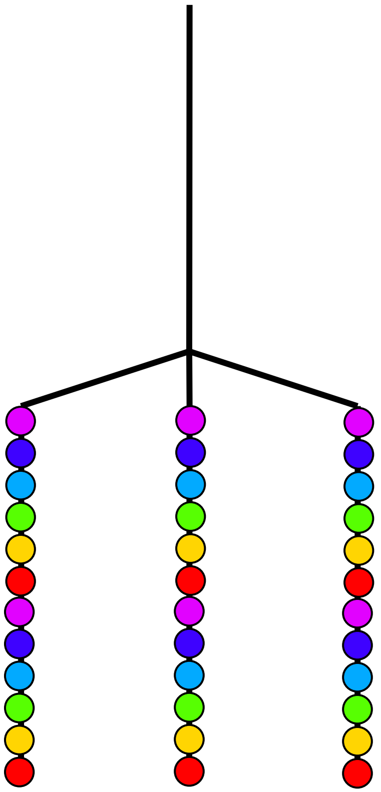


join roundrobin(1)

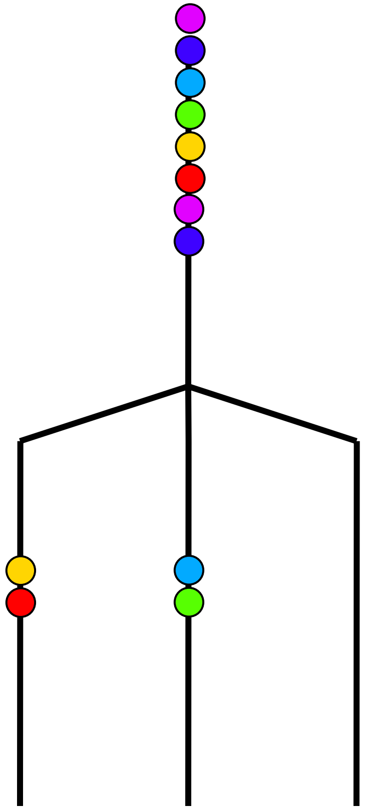


SplitJoins are Beautiful

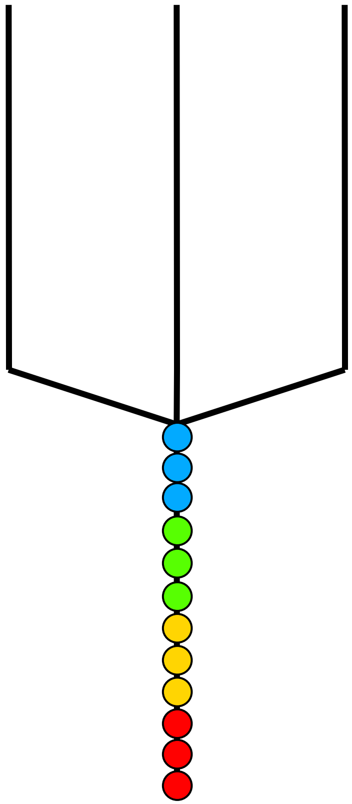
split duplicate



split roundrobin(2)

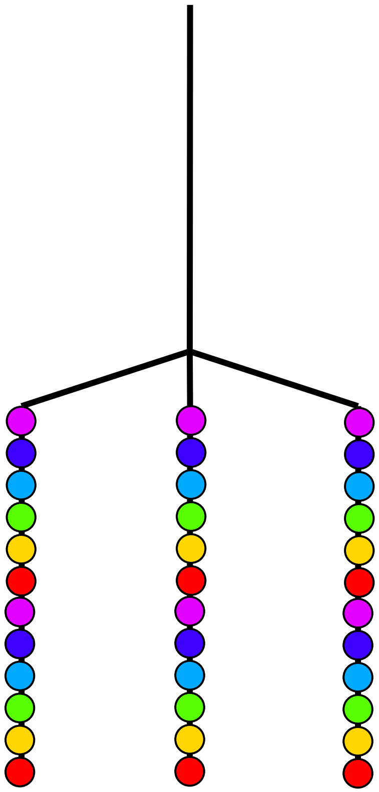


join roundrobin(1)

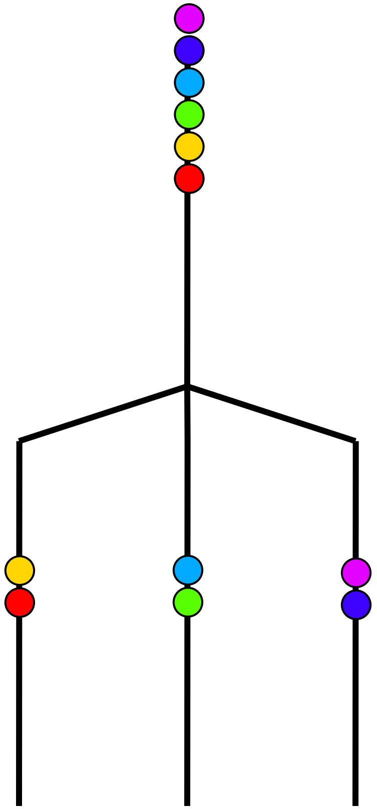


SplitJoins are Beautiful

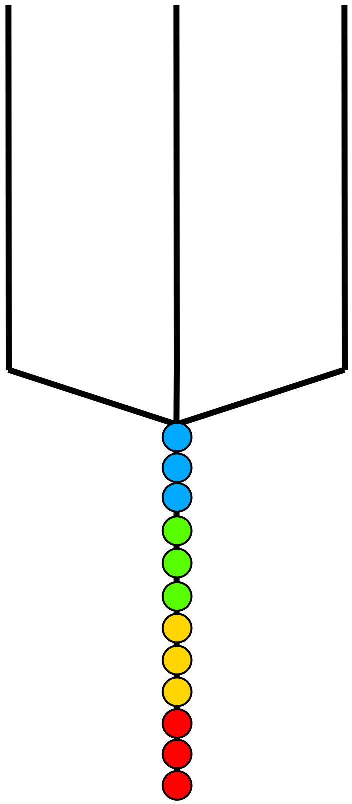
split duplicate



split roundrobin(2)

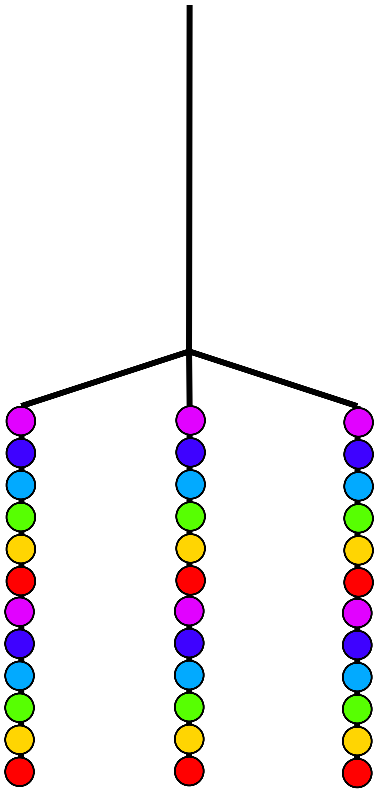


join roundrobin(1)

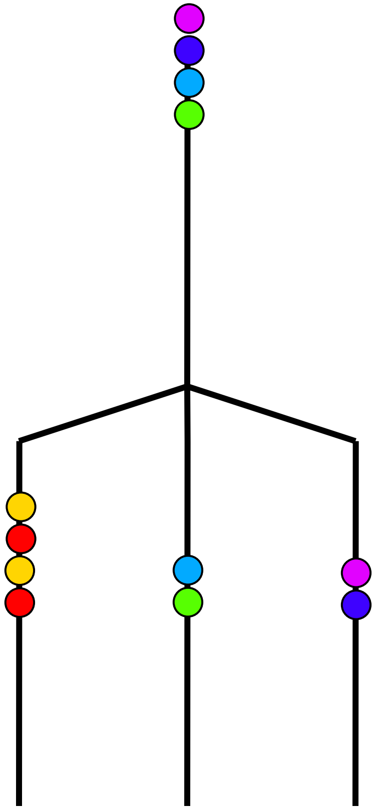


SplitJoins are Beautiful

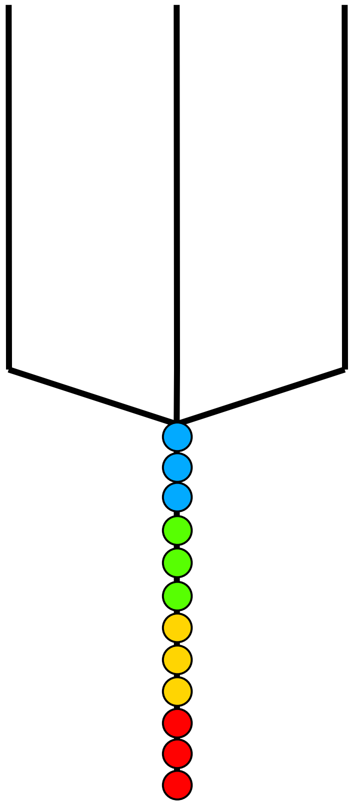
split duplicate



split roundrobin(2)

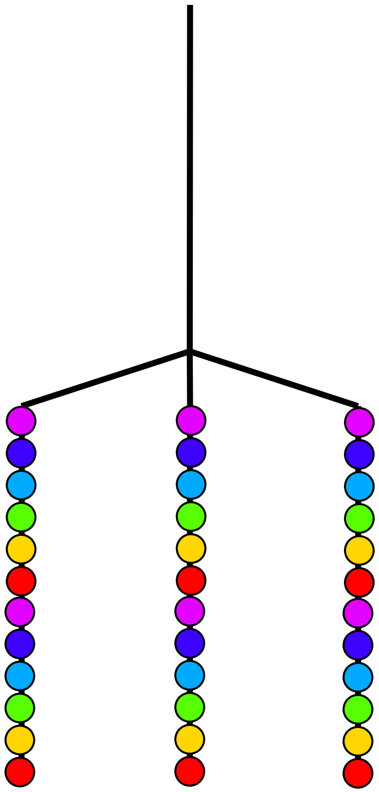


join roundrobin(1)

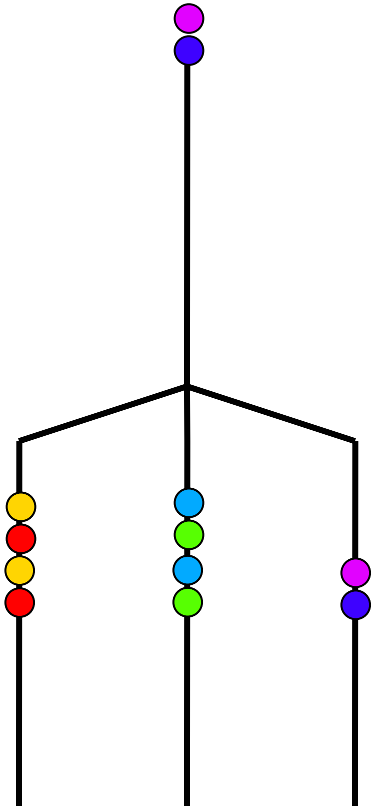


SplitJoins are Beautiful

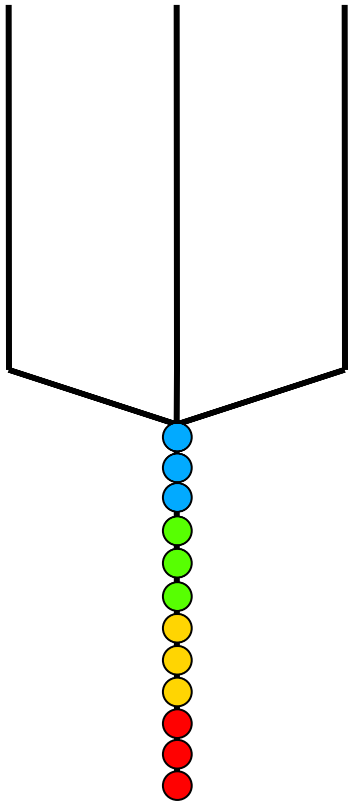
split duplicate



split roundrobin(2)

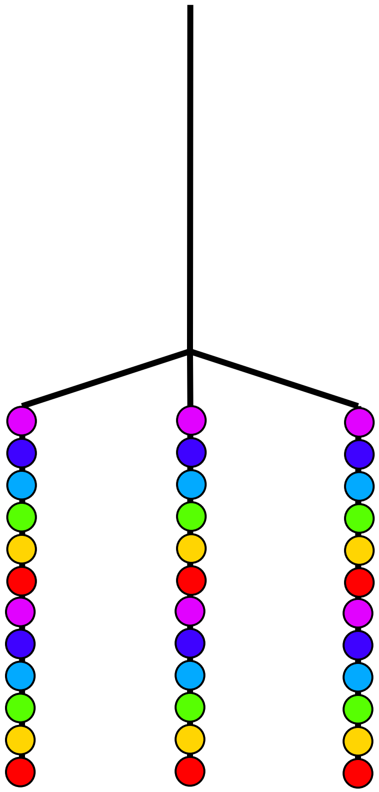


join roundrobin(1)

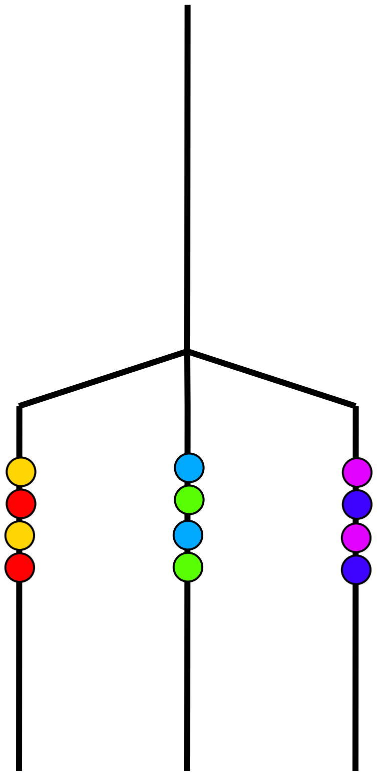


SplitJoins are Beautiful

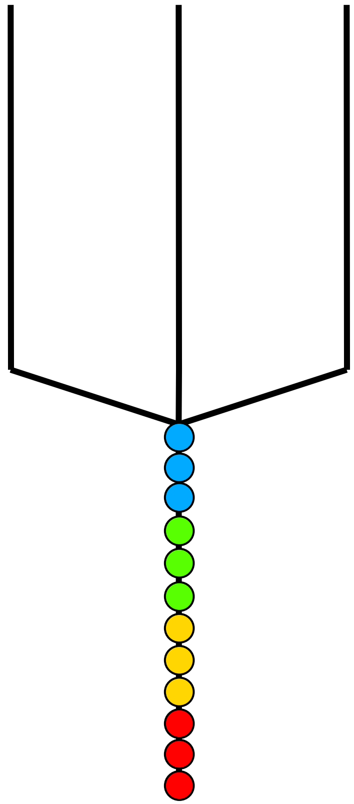
split duplicate



split roundrobin(2)

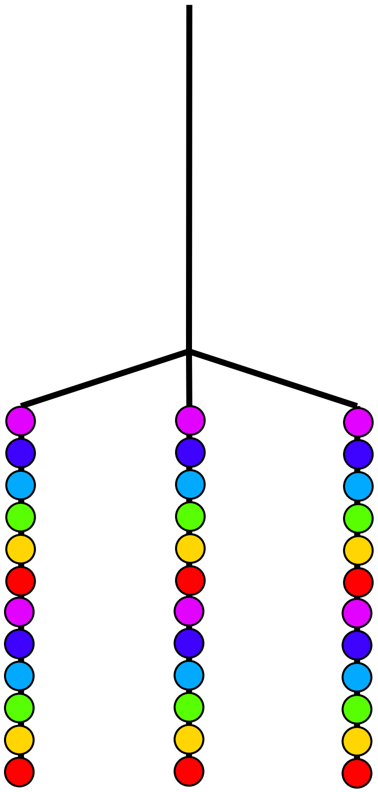


join roundrobin(1)

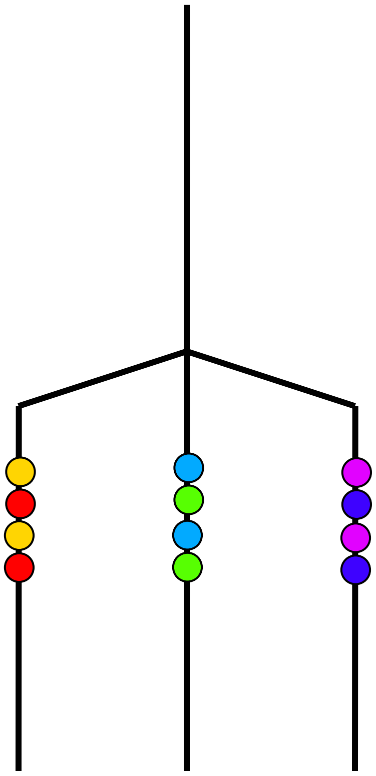


SplitJoins are Beautiful

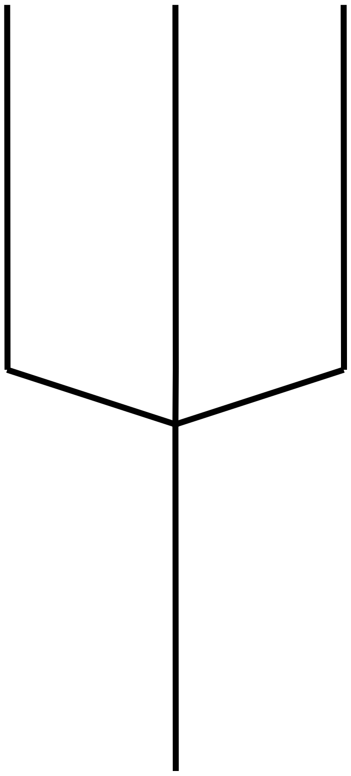
split duplicate



split roundrobin(2)



join roundrobin(1)

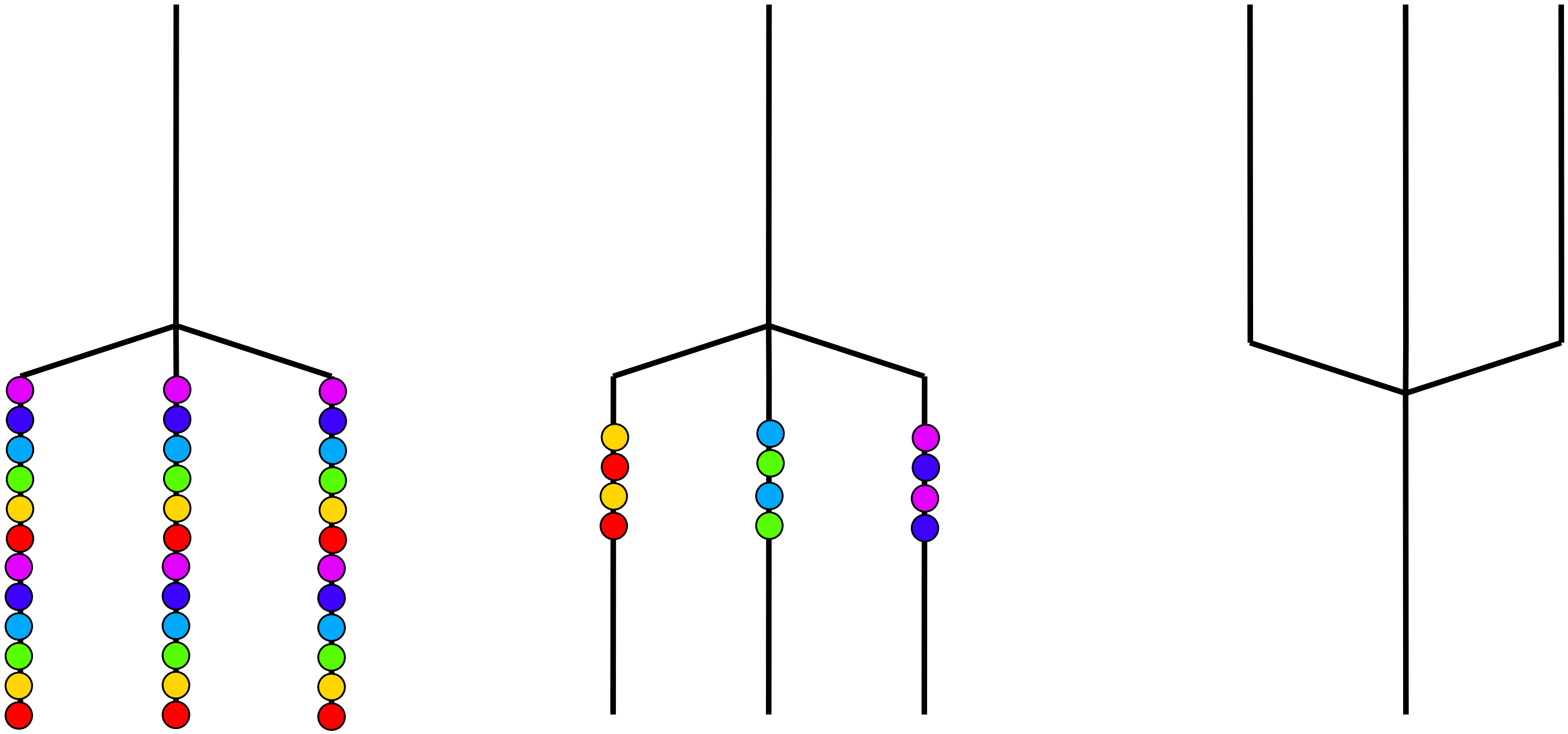


SplitJoins are Beautiful

split duplicate

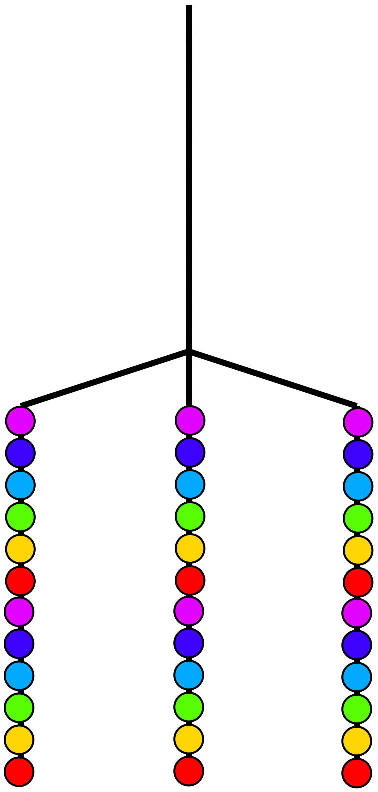
split roundrobin(2)

join roundrobin(1,2,3)

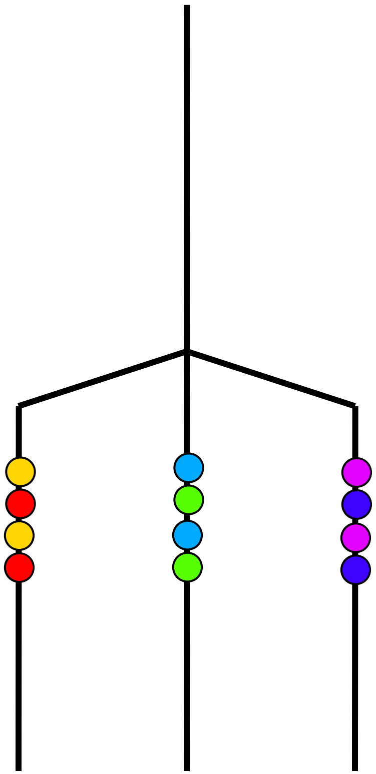


SplitJoins are Beautiful

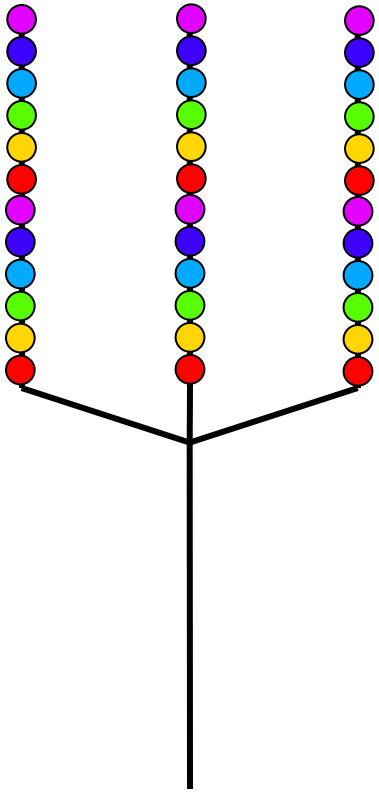
split duplicate



split roundrobin(2)

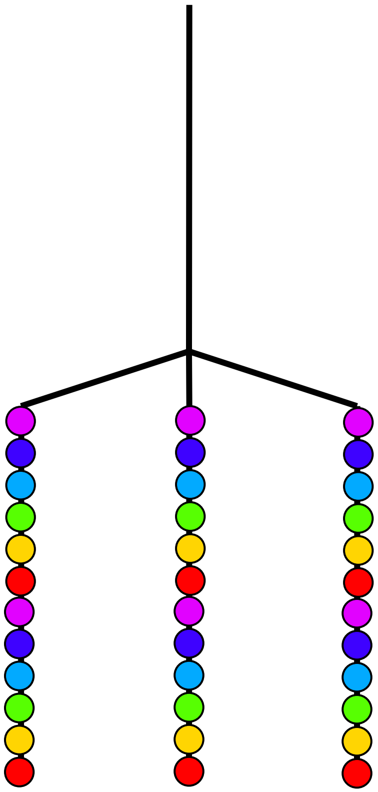


join roundrobin(1,2,3)

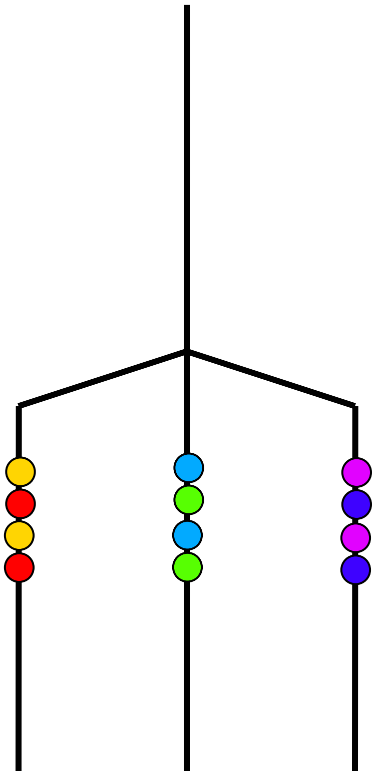


SplitJoins are Beautiful

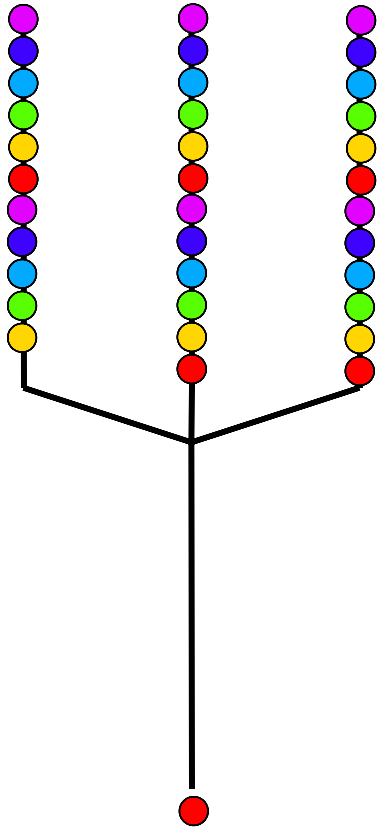
split duplicate



split roundrobin(2)

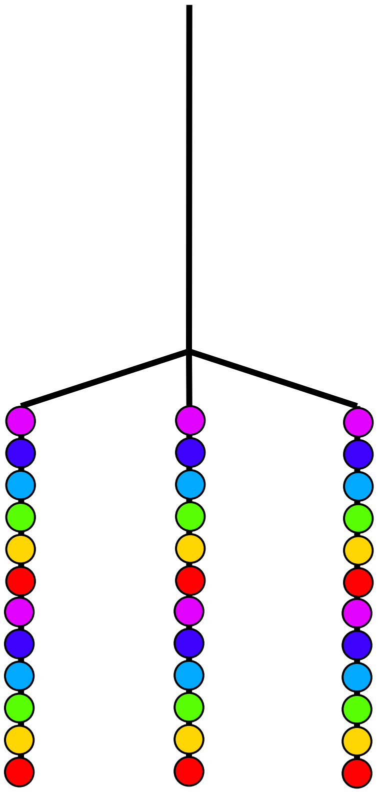


join roundrobin(1,2,3)

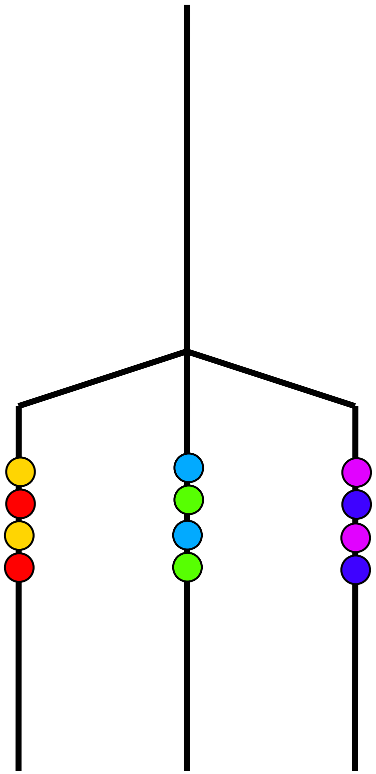


SplitJoins are Beautiful

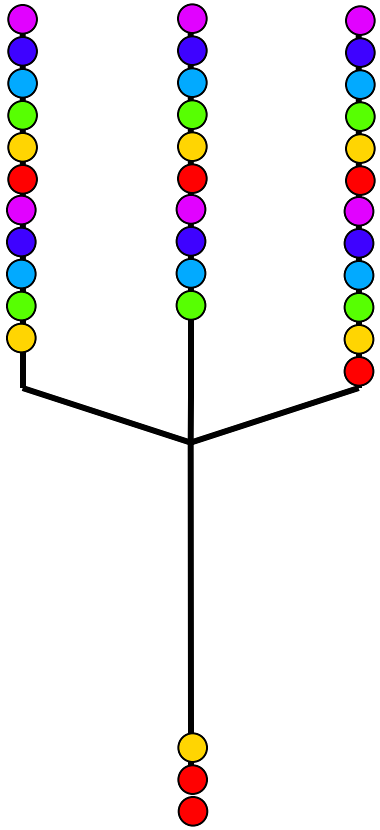
split duplicate



split roundrobin(2)

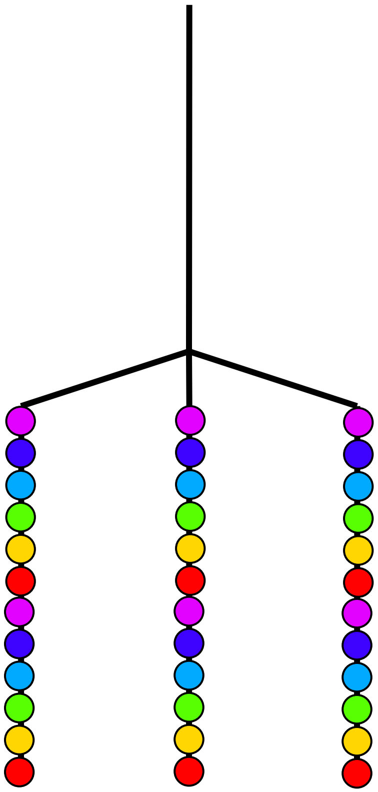


join roundrobin(1,2,3)

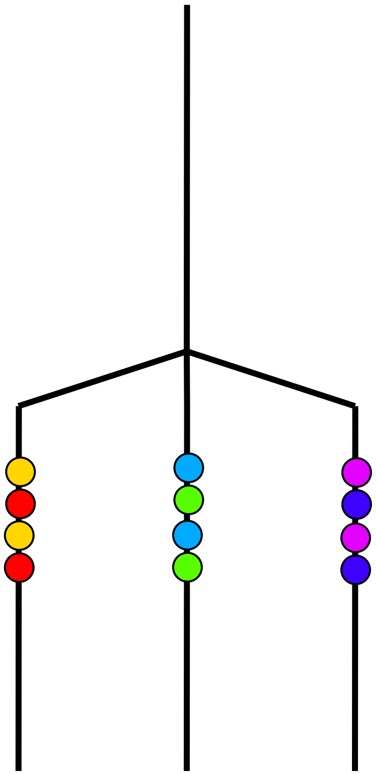


SplitJoins are Beautiful

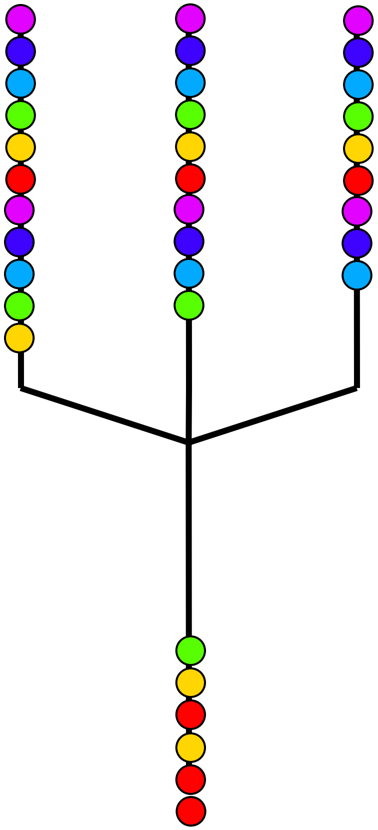
split duplicate



split roundrobin(2)

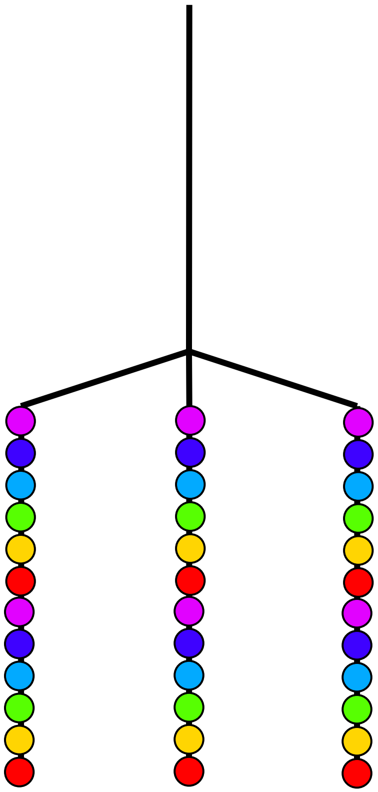


join roundrobin(1,2,3)

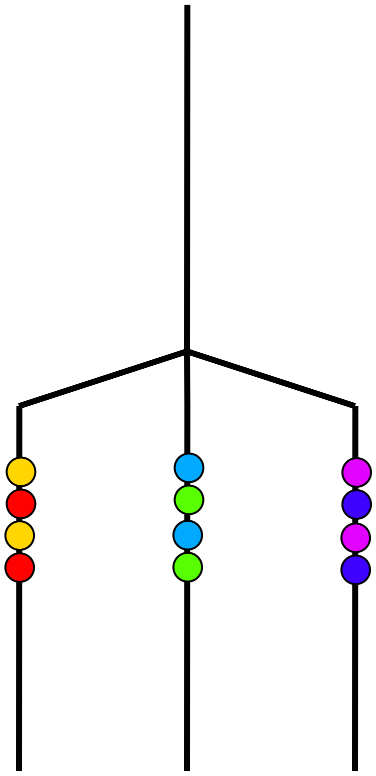


SplitJoins are Beautiful

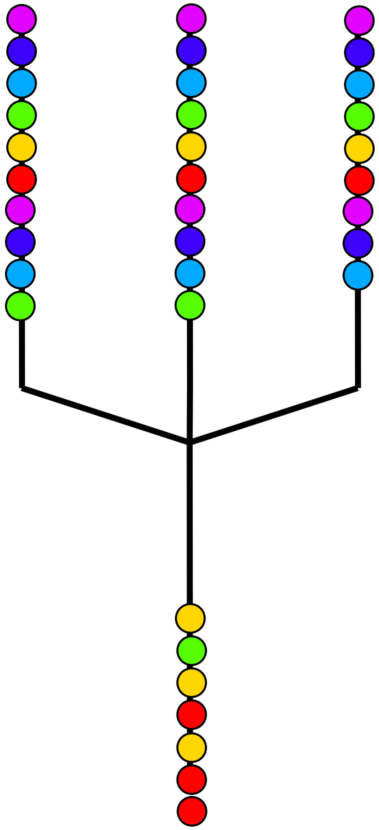
split duplicate



split roundrobin(2)

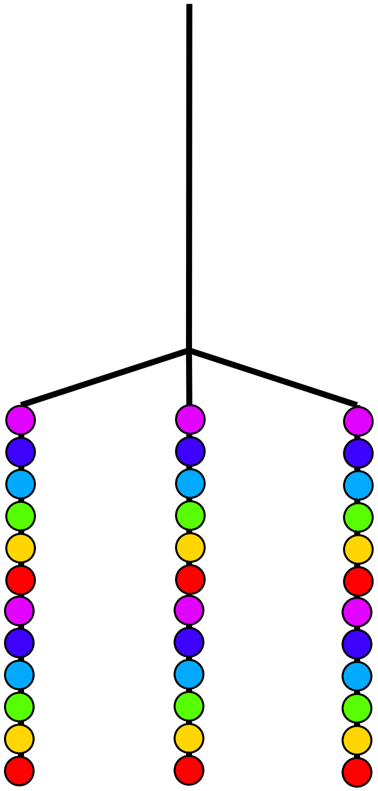


join roundrobin(1,2,3)

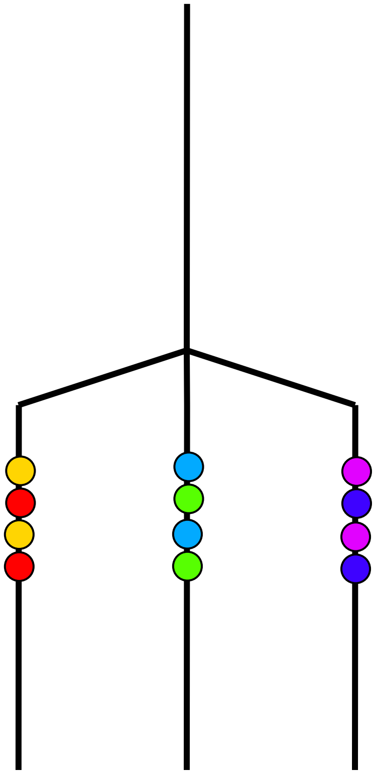


SplitJoins are Beautiful

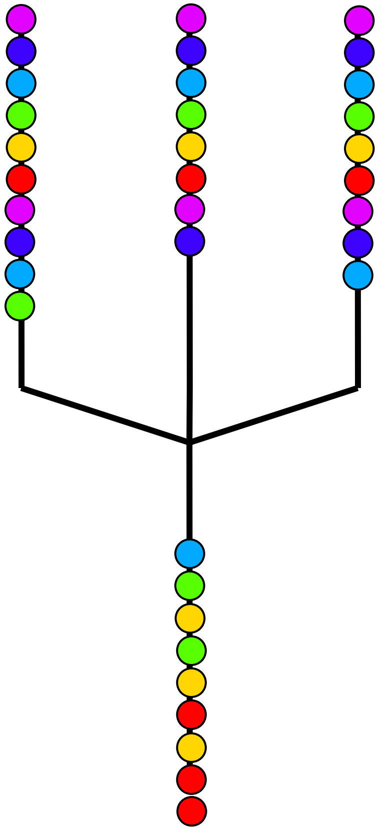
split duplicate



split roundrobin(2)

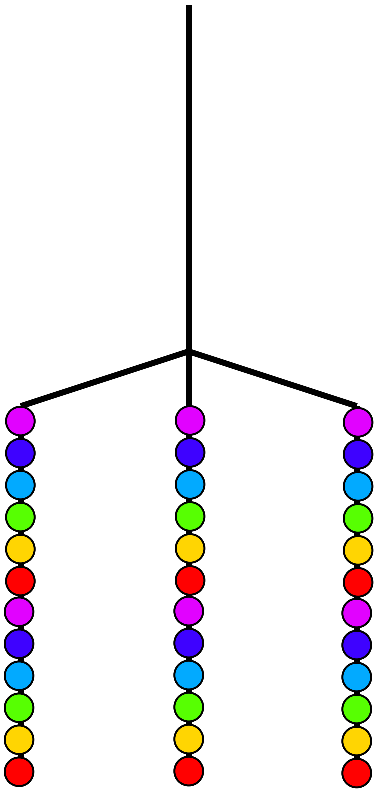


join roundrobin(1,2,3)

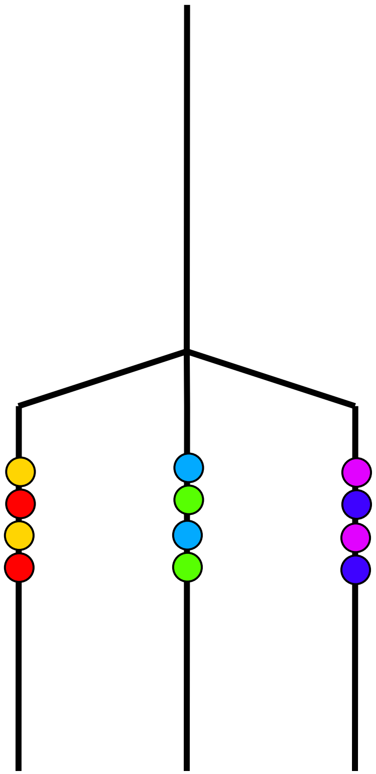


SplitJoins are Beautiful

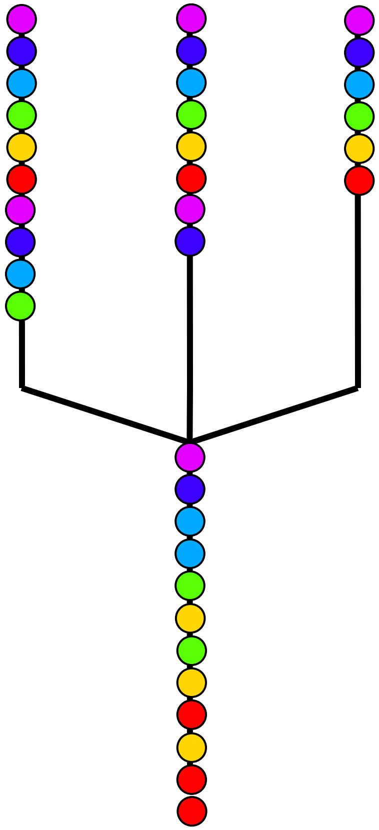
split duplicate



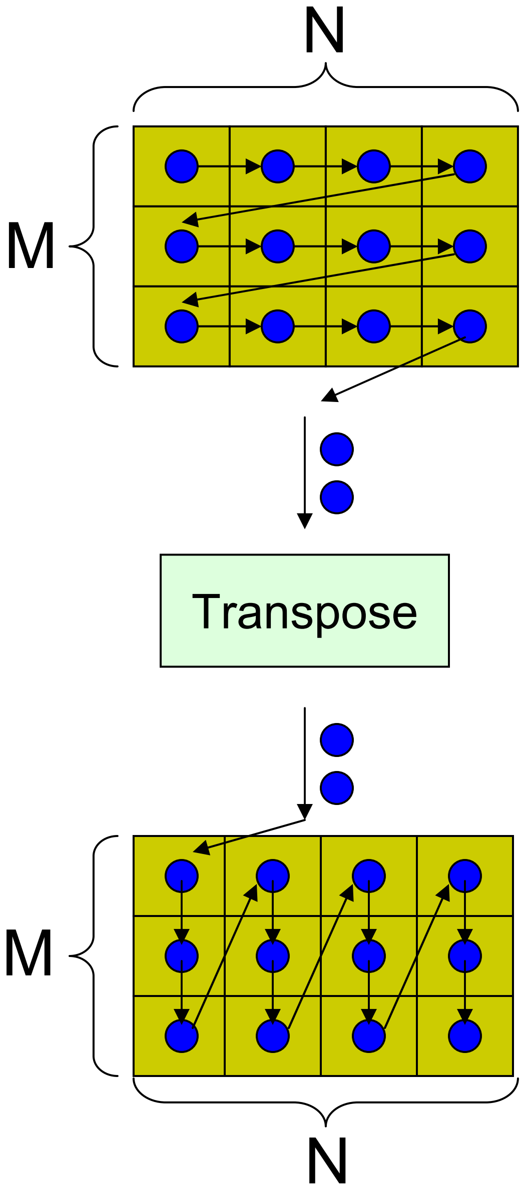
split roundrobin(2)



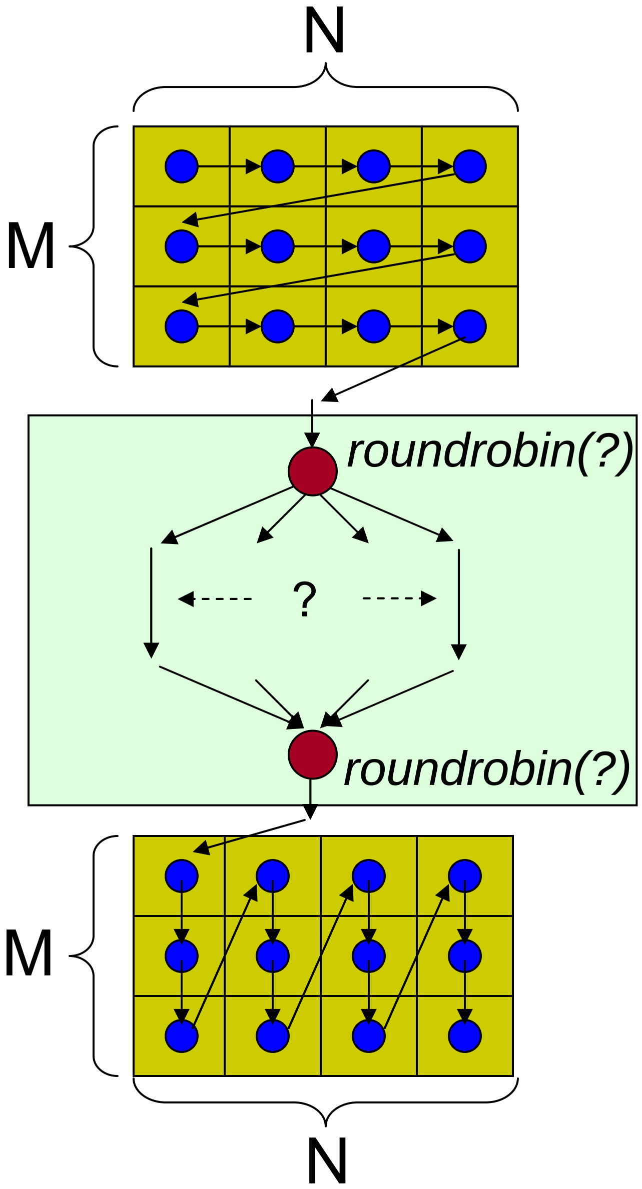
join roundrobin(1,2,3)



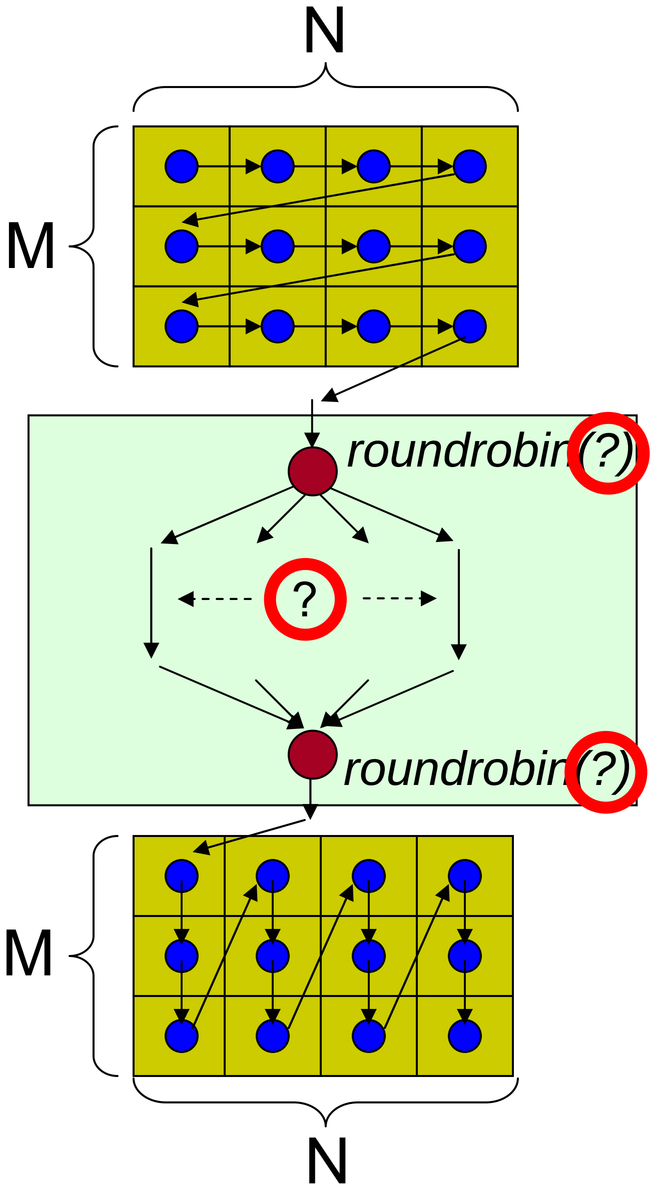
Matrix Transpose



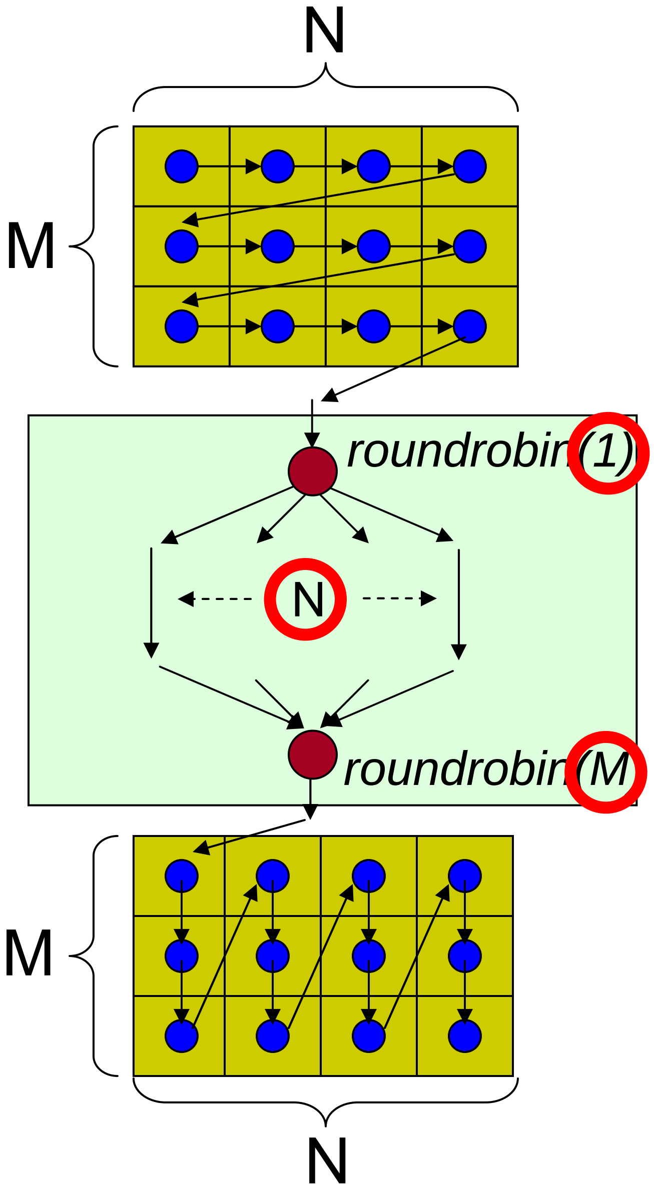
Matrix Transpose



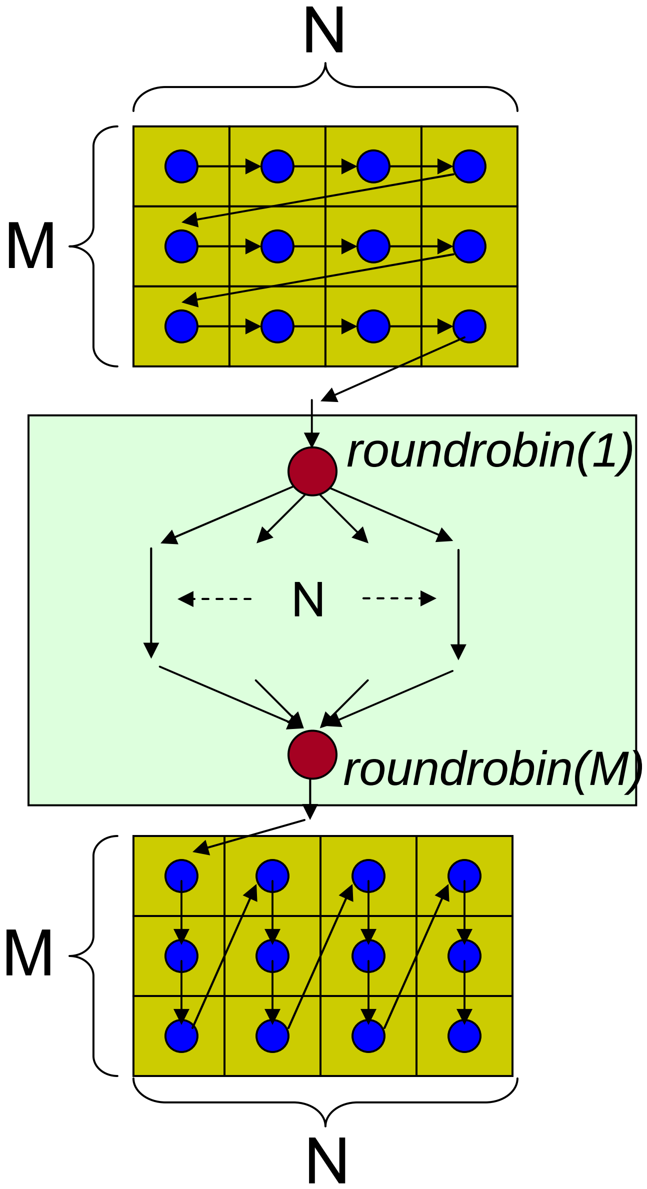
Matrix Transpose



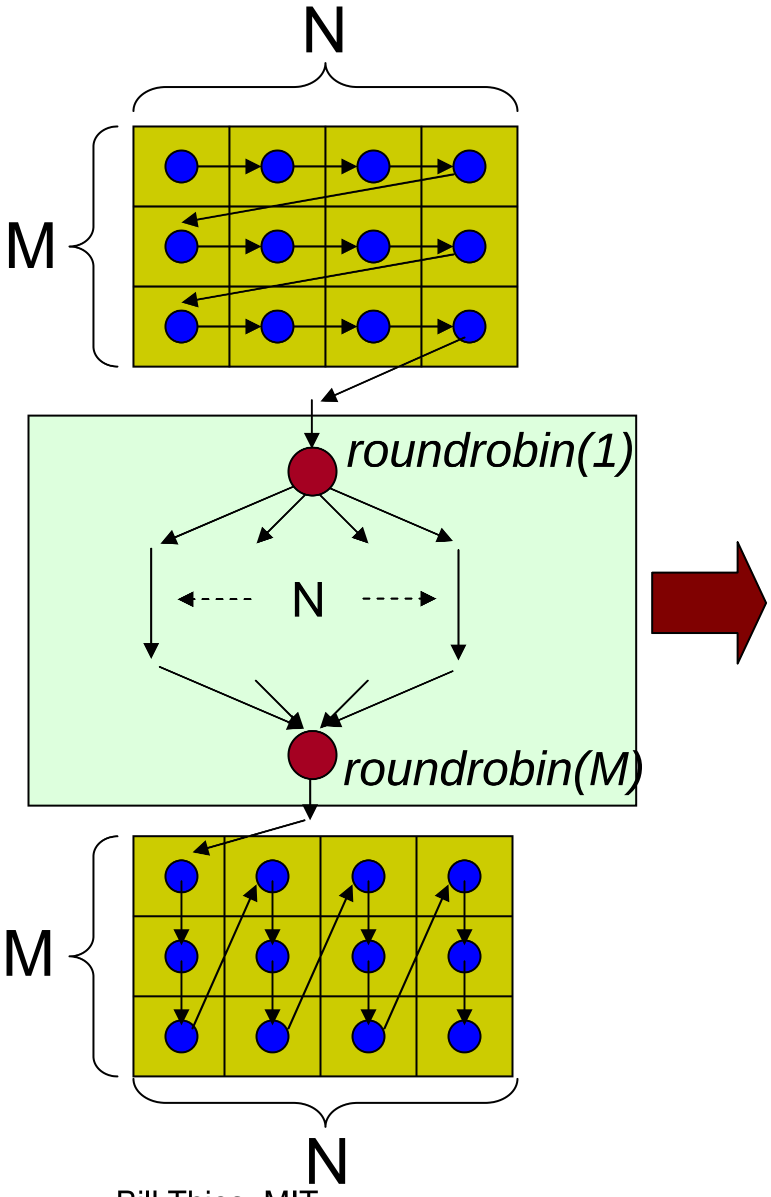
Matrix Transpose



Matrix Transpose



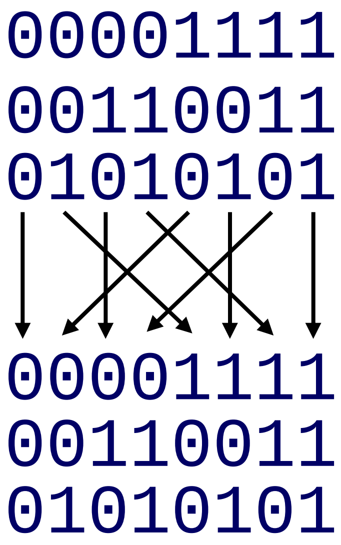
Matrix Transpose



```
float->float splitjoin Transpose (int M,
                                  int N) {
   split roundrobin(1);
   for (int i = 0; i<N; i++) {
      add Identity<float>;
   }
   join roundrobin(M);
}
```

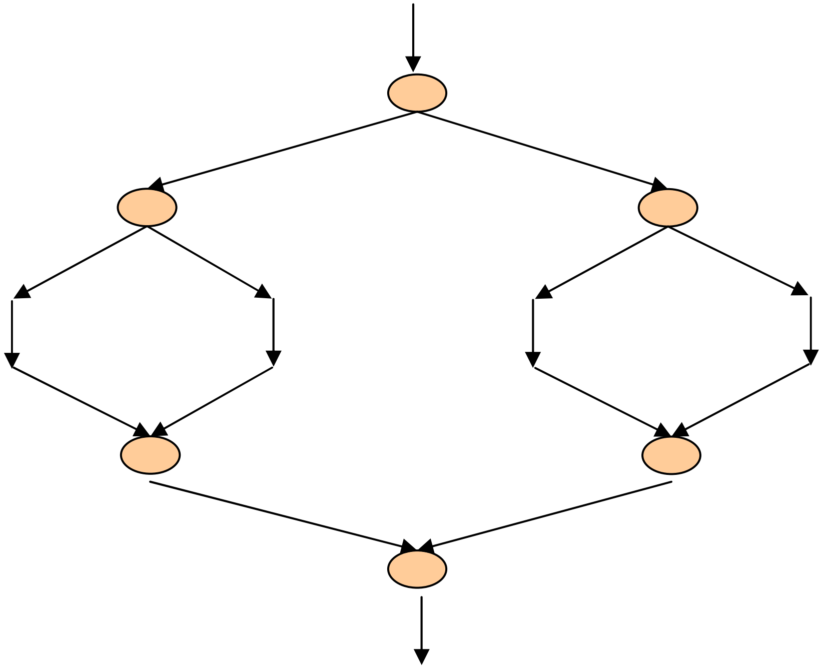
Bit-reversed ordering

- Many FFT algorithms require a bit-reversal stage
- If item is at index *n* (with binary digits $b_0\, b_1 \ldots b_k$), then it is transferred to reversed index $b_k \ldots b_1\, b_0$
- For 3-digit binary numbers:



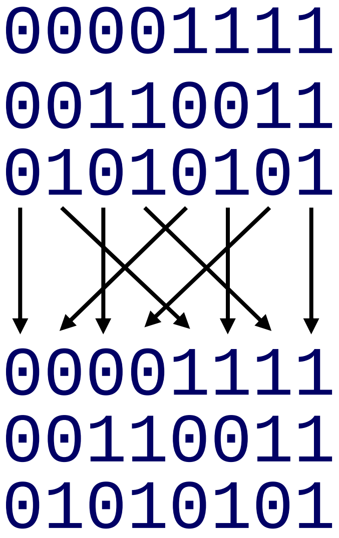
```
00001111
00110011
01010101
```

```
00001111
00110011
01010101
```



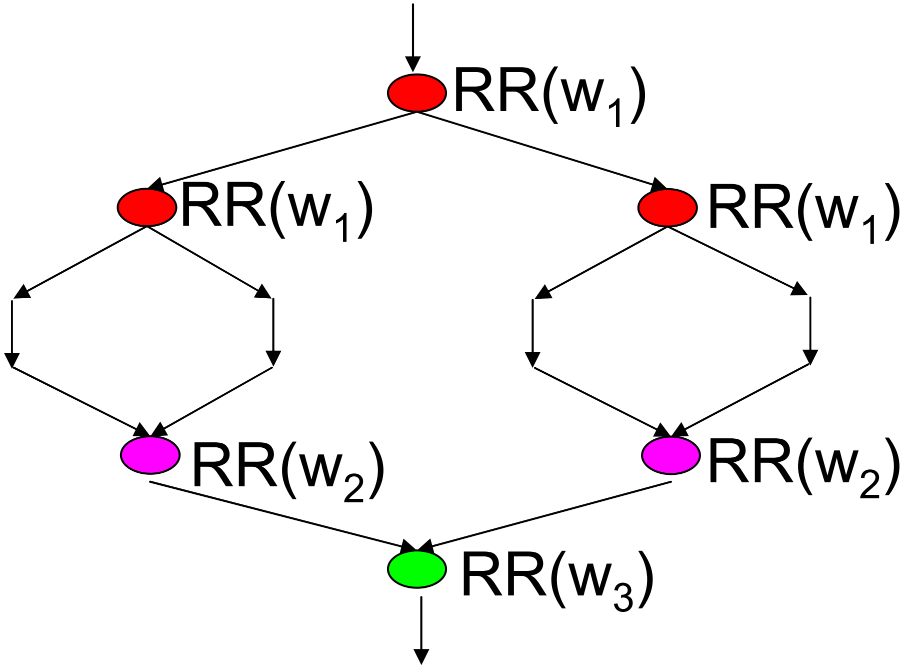
Bit-reversed ordering

- Many FFT algorithms require a bit-reversal stage
- If item is at index *n* (with binary digits $b_0\ b_1 \ldots\ b_k$), then it is transferred to reversed index $b_k \ldots\ b_1\ b_0$
- For 3-digit binary numbers:



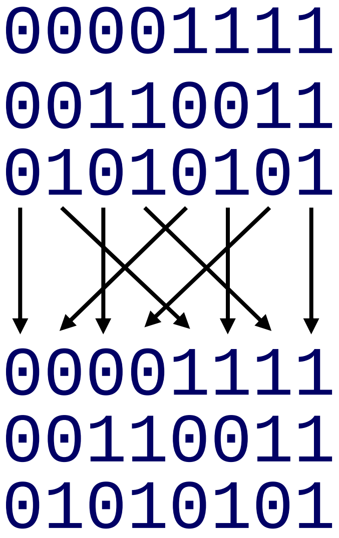
00001111
00110011
01010101

00001111
00110011
01010101



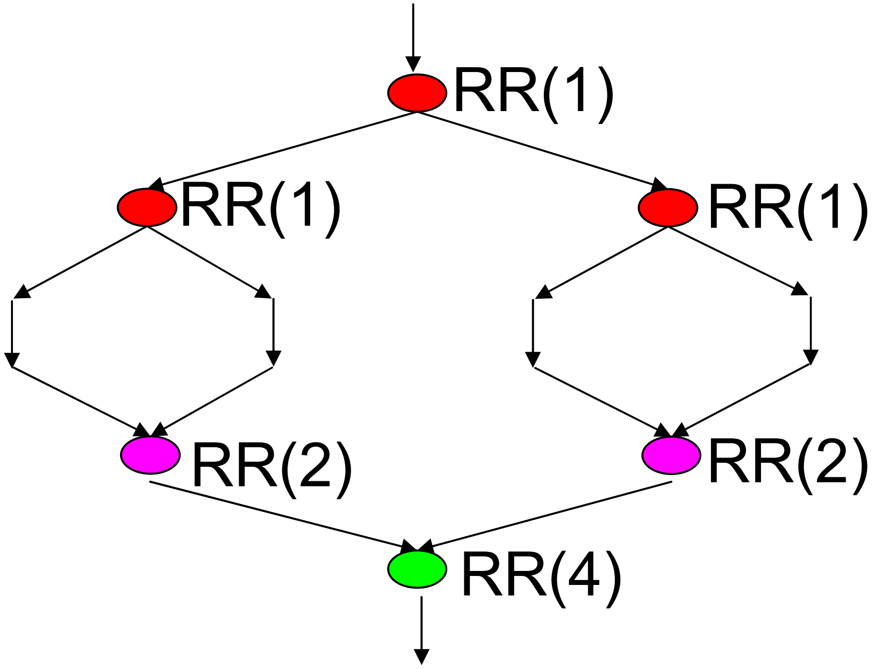
Bit-reversed ordering

- Many FFT algorithms require a bit-reversal stage
- If item is at index *n* (with binary digits $b_0\, b_1 \ldots b_k$), then it is transferred to reversed index $b_k \ldots b_1\, b_0$
- For 3-digit binary numbers:



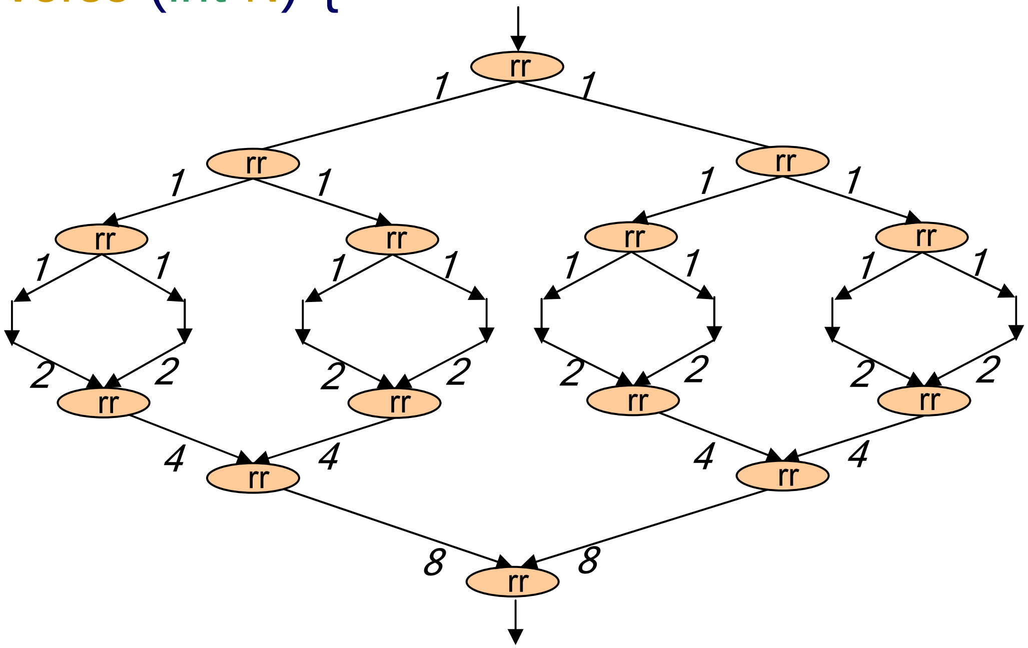
00001111
00110011
01010101

00001111
00110011
01010101



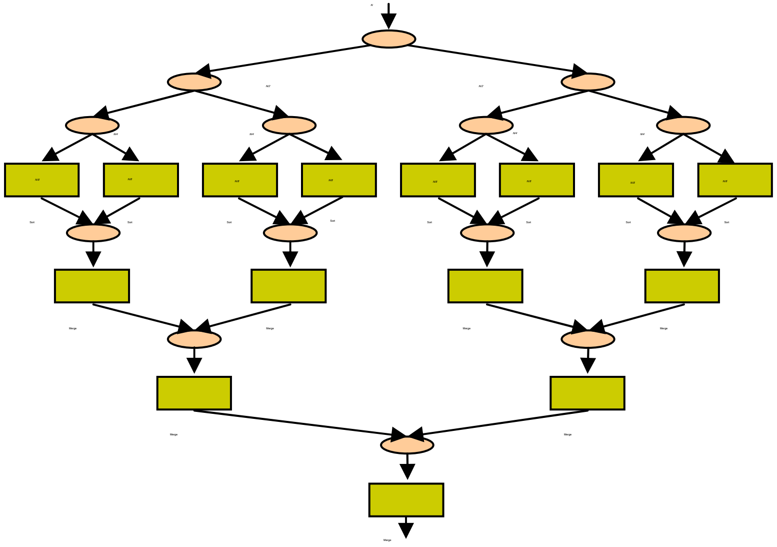
Bit-reversed ordering

```
complex->complex pipeline BitReverse (int N) {
    if (N==2) {
        add Identity<complex>;
    } else {
        add splitjoin {
            split roundrobin(1);
            add BitReverse(N/2);
            add BitReverse(N/2);
            join roundrobin(N/2);
        }
    }
}
```

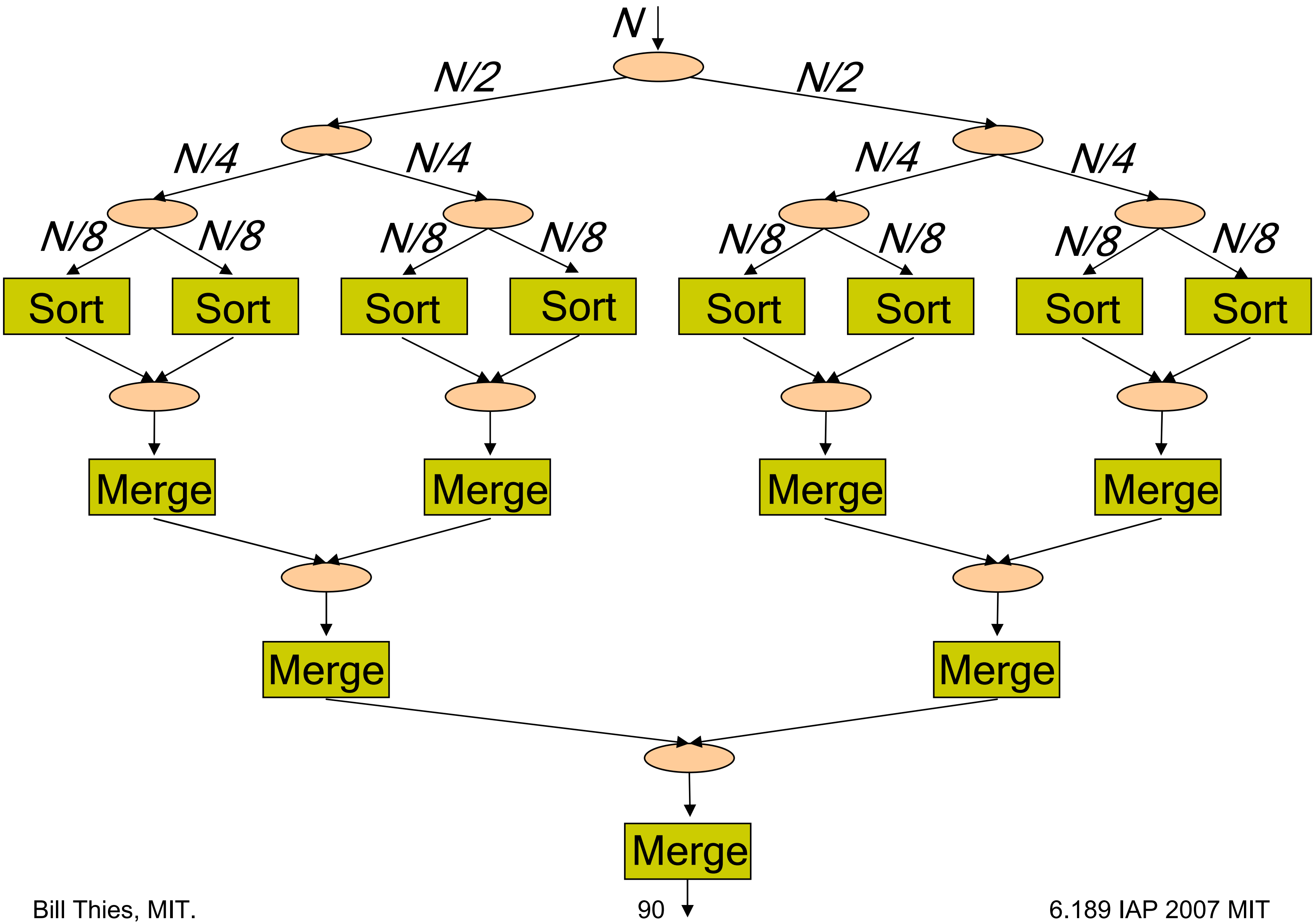


N-Element Merge Sort

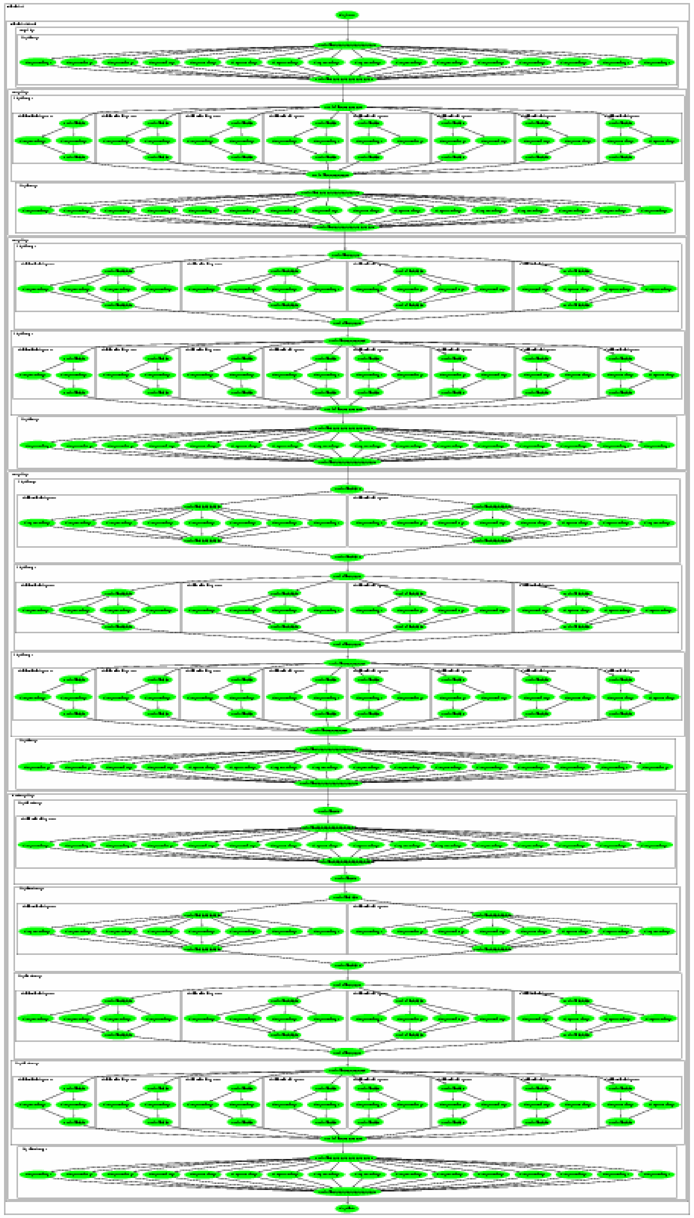
```
int->int pipeline MergeSort (int N) {
    if (N==2) {
        add Sort(N);
    } else {
        add splitjoin {
            split roundrobin(N/2);
            add MergeSort(N/2);
            add MergeSort(N/2);
            join roundrobin(N/2);
        }
    }
    add Merge(N);
}
```



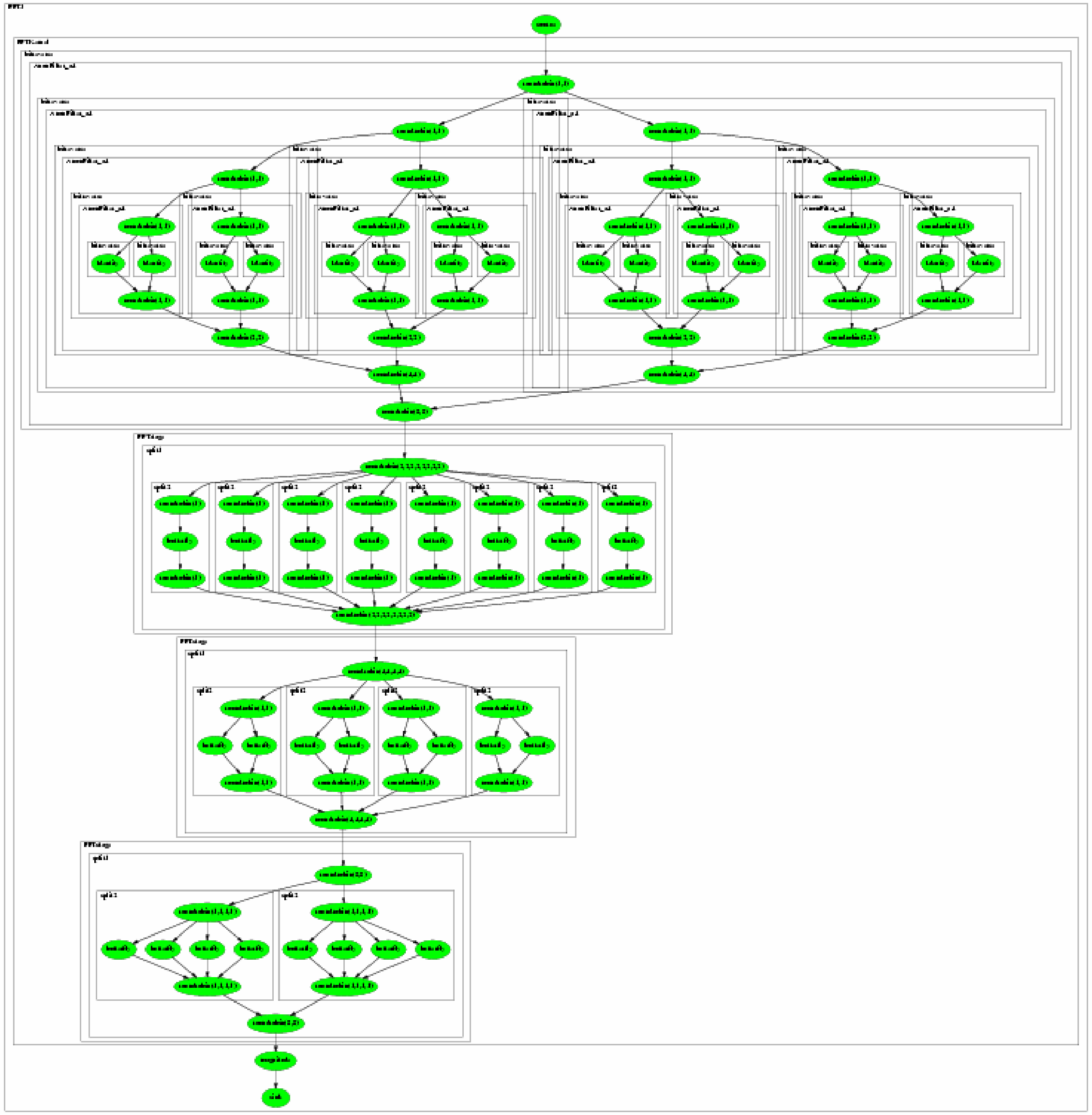
N-Element Merge Sort (3-level)



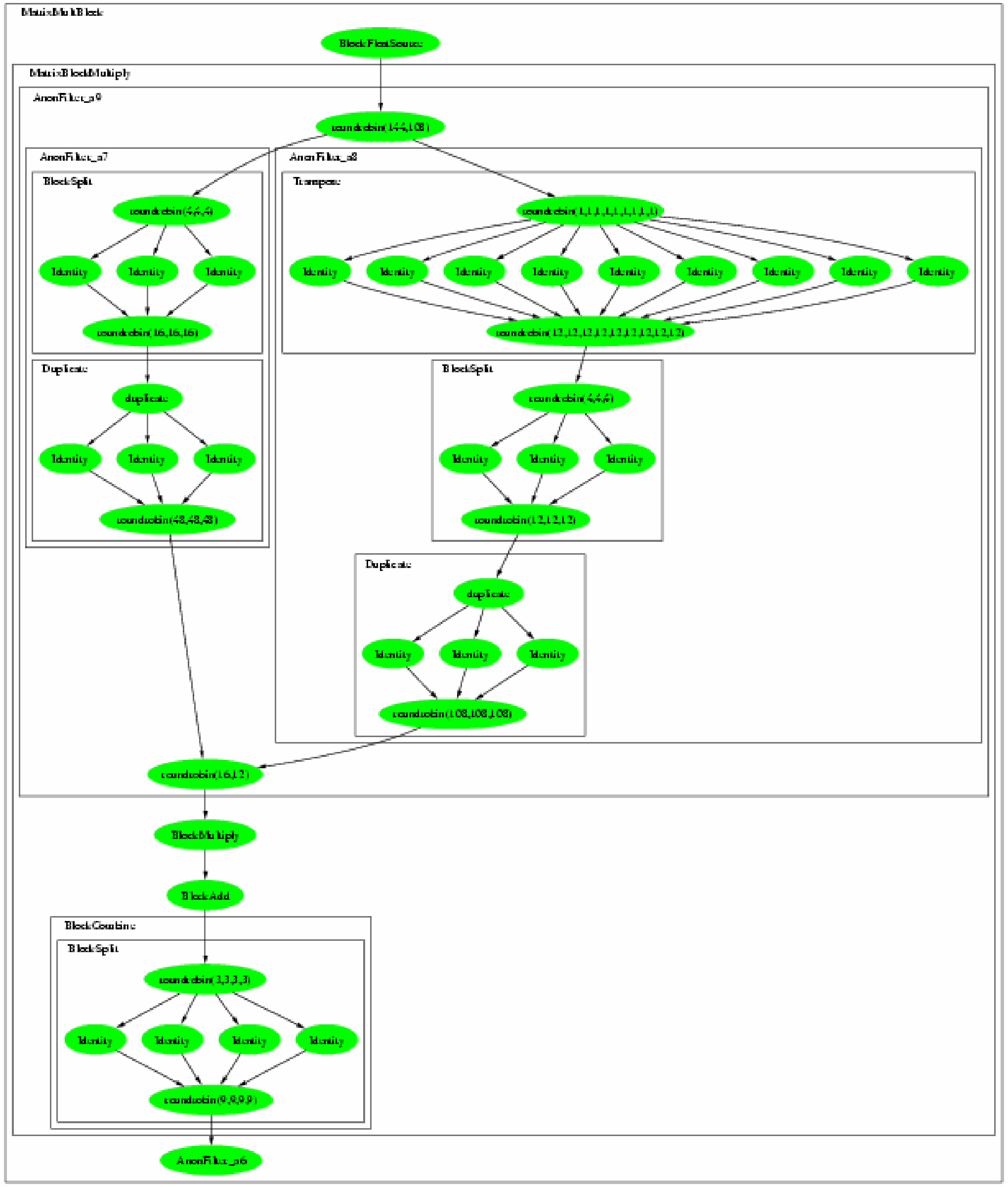
Bitonic Sort



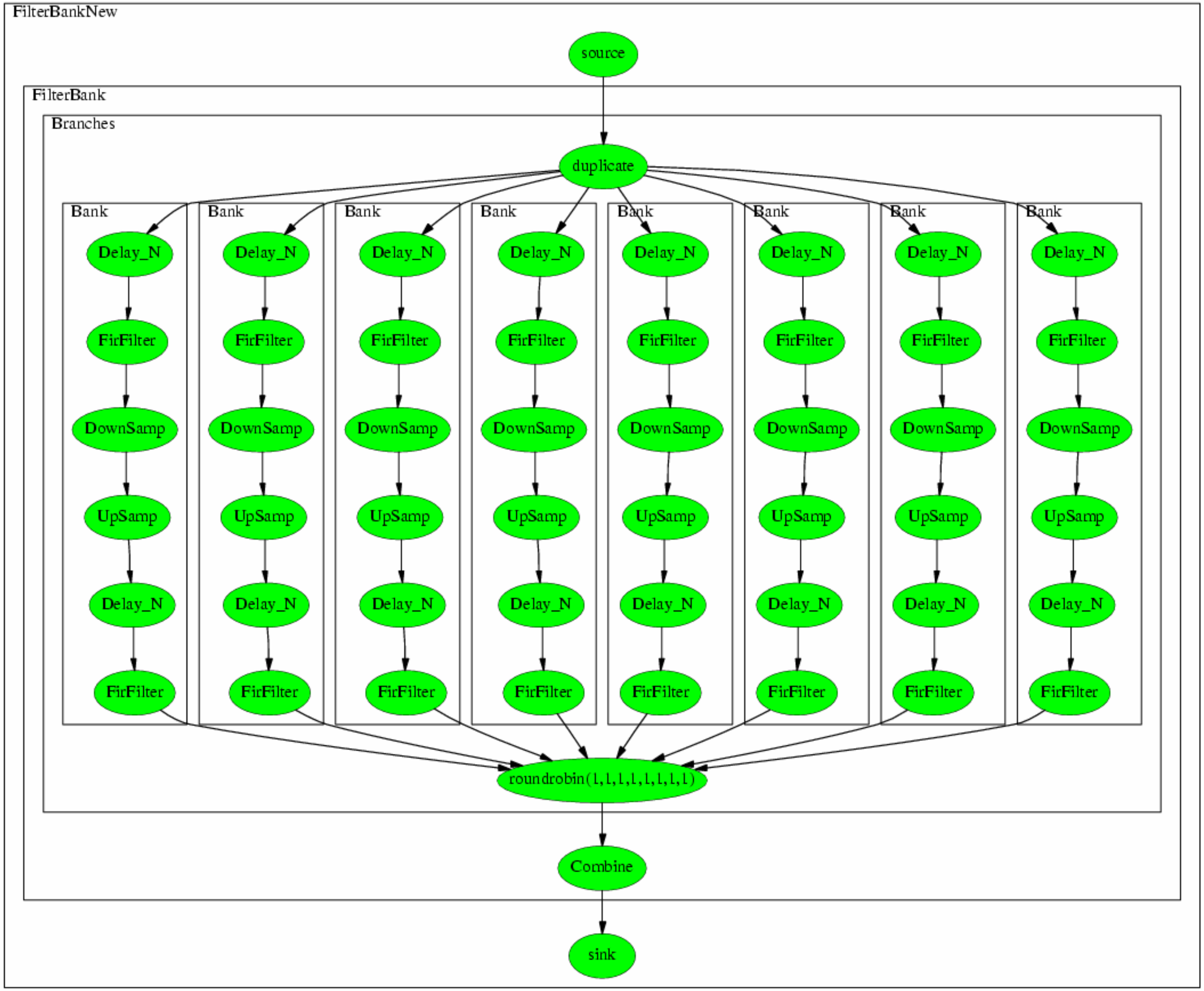
FFT



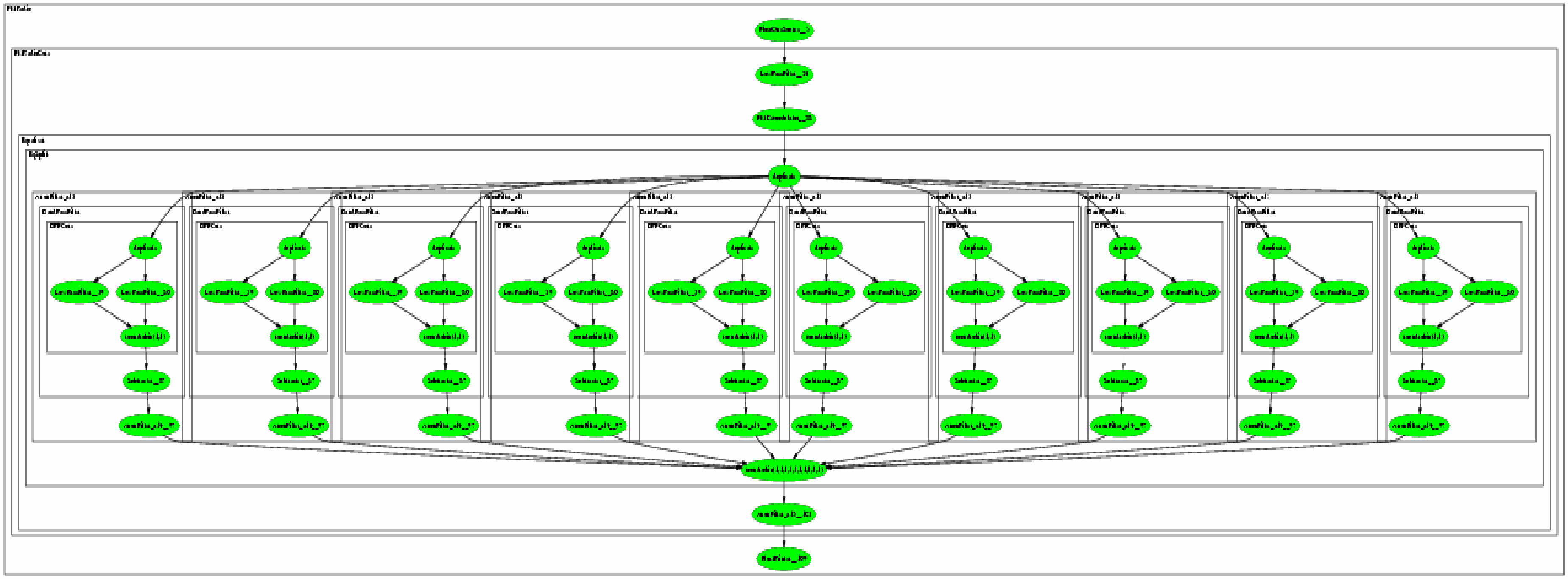
Block Matrix Multiply



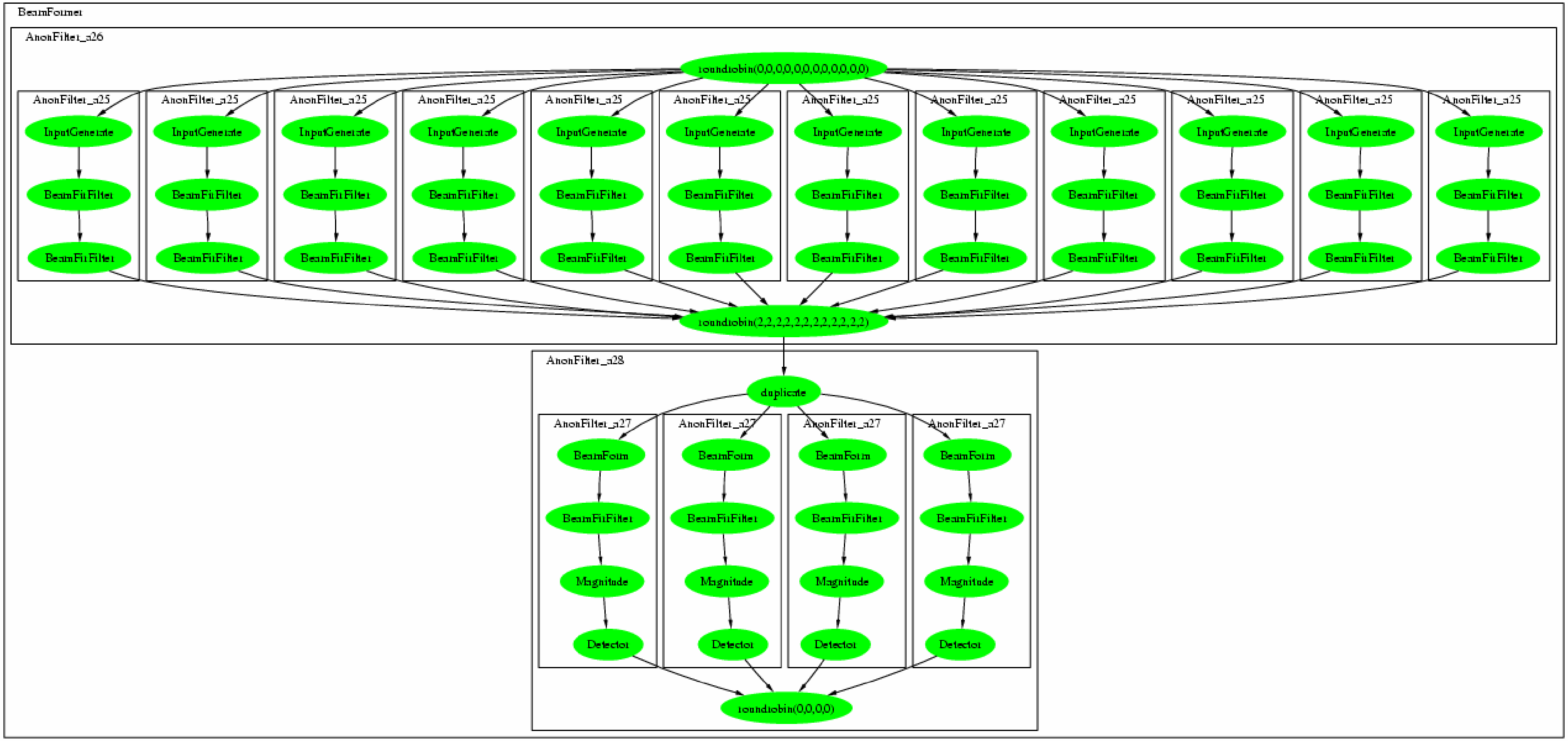
Filterbank


FilterBankNew
source
FilterBank
Branches
duplicate
Bank
Delay_N
FirFilter
DownSamp
UpSamp
Delay_N
FirFilter
Bank
Delay_N
FirFilter
DownSamp
UpSamp
Delay_N
FirFilter
Bank
Delay_N
FirFilter
DownSamp
UpSamp
Delay_N
FirFilter
Bank
Delay_N
FirFilter
DownSamp
UpSamp
Delay_N
FirFilter
Bank
Delay_N
FirFilter
DownSamp
UpSamp
Delay_N
FirFilter
Bank
Delay_N
FirFilter
DownSamp
UpSamp
Delay_N
FirFilter
Bank
Delay_N
FirFilter
DownSamp
UpSamp
Delay_N
FirFilter
Bank
Delay_N
FirFilter
DownSamp
UpSamp
Delay_N
FirFilter
roundrobin(1,1,1,1,1,1,1,1)
Combine
sink

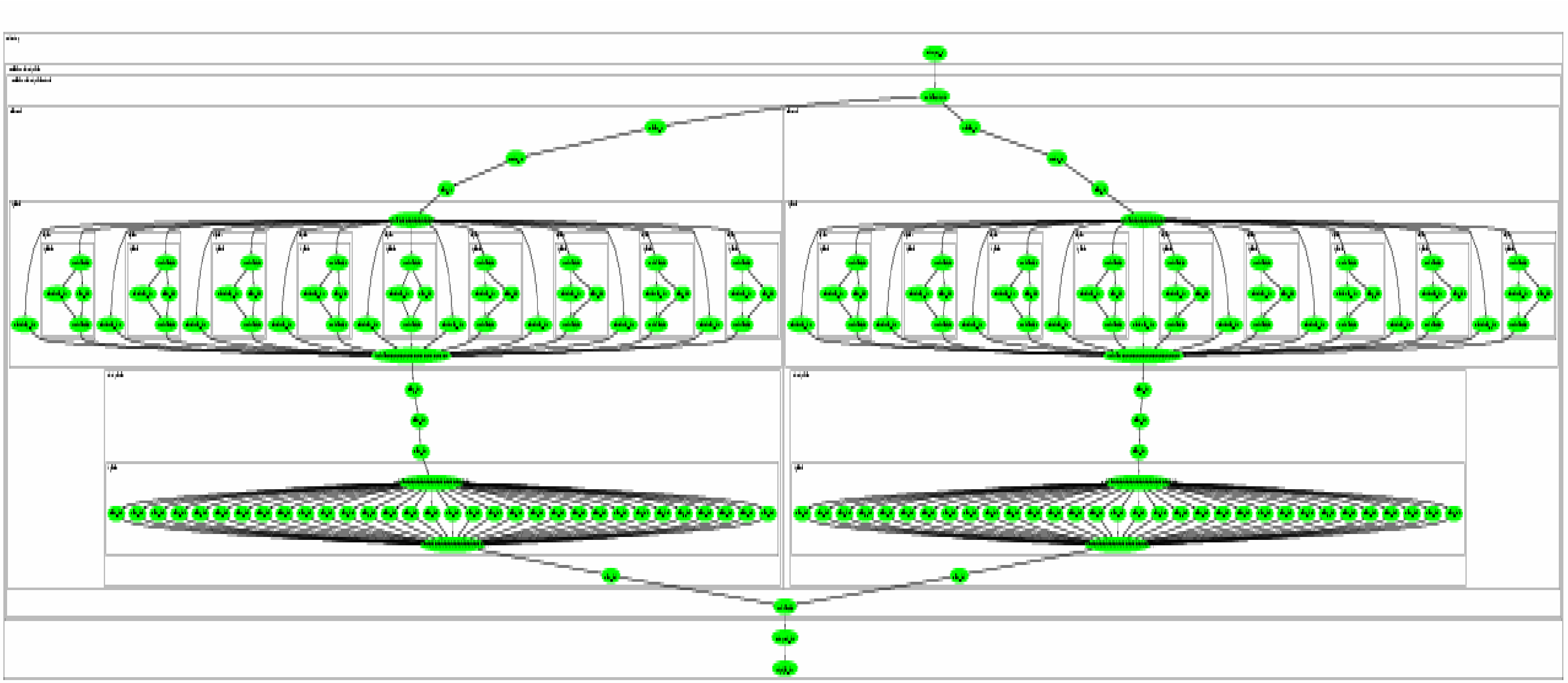
FM Radio with Equalizer



Radar-Array Front End

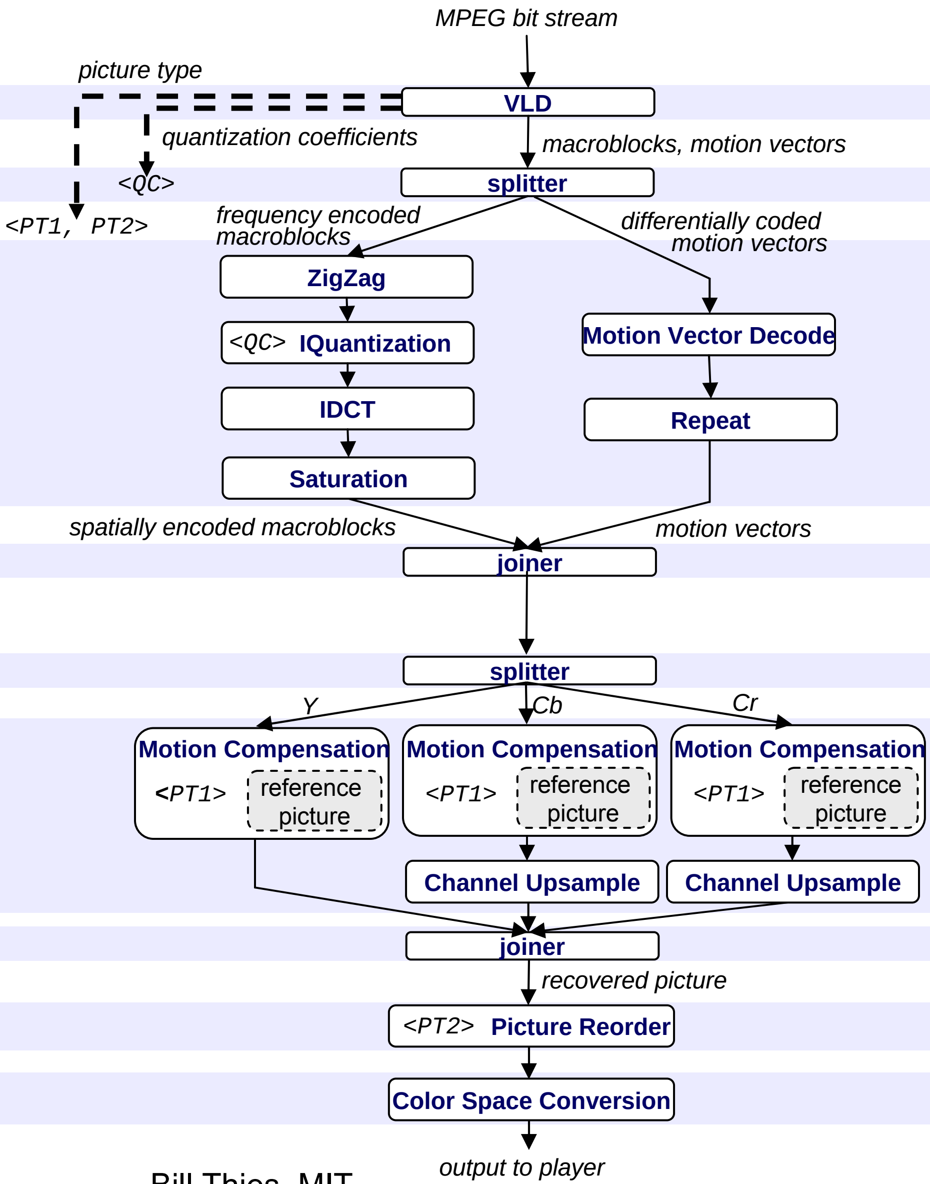


MP3 Decoder



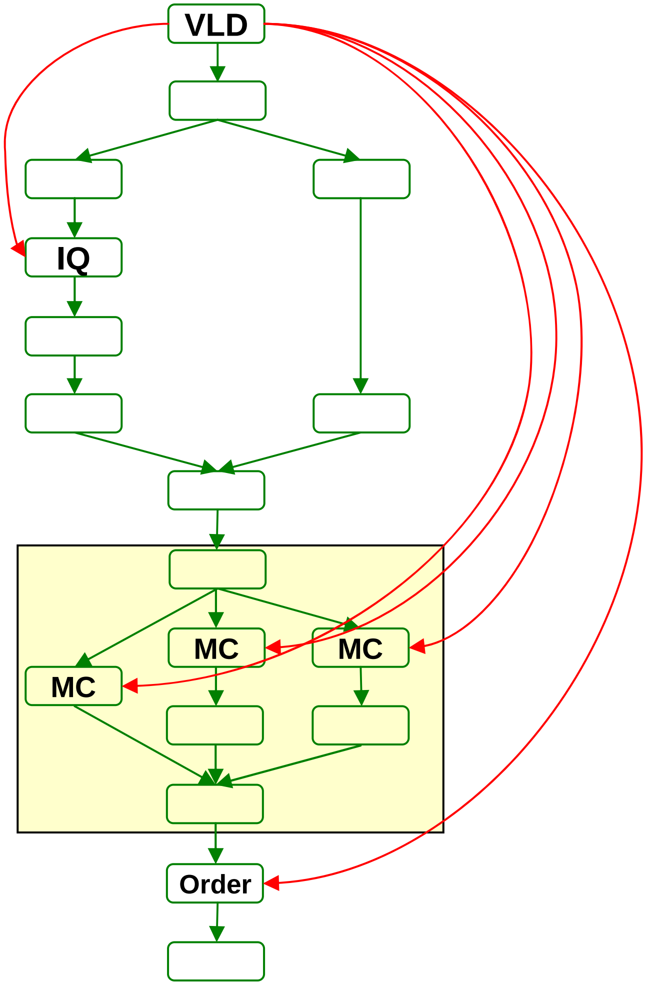
Case Study:
MPEG-2 Decoder in StreamIt

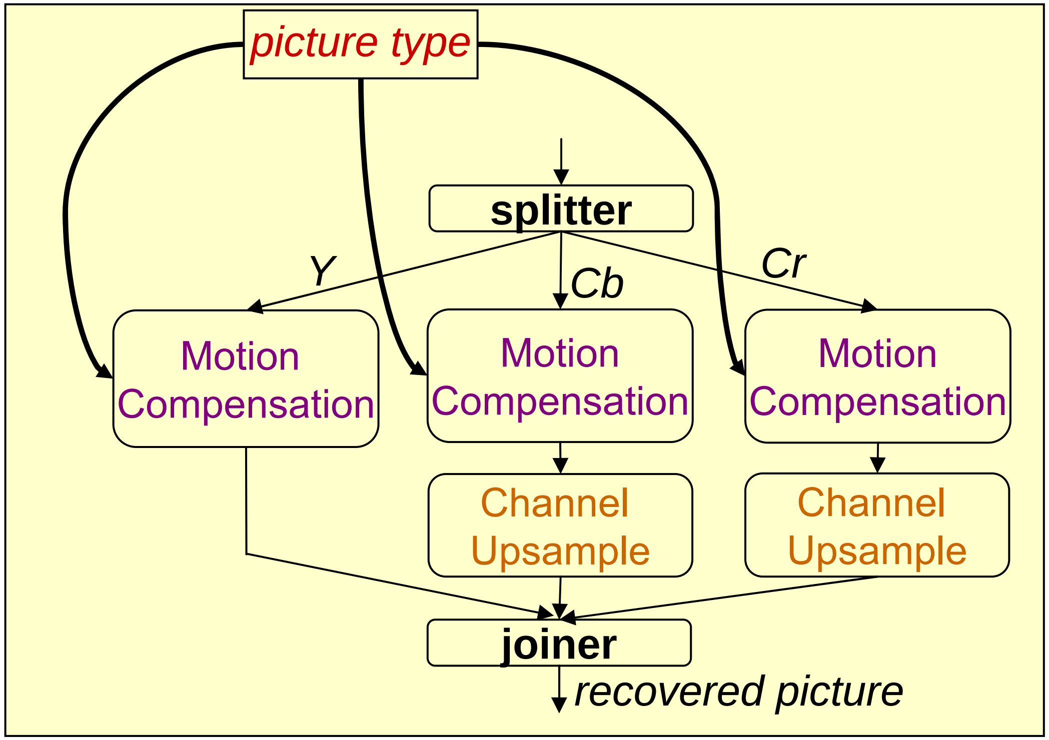
MPEG-2 Decoder in StreamIt



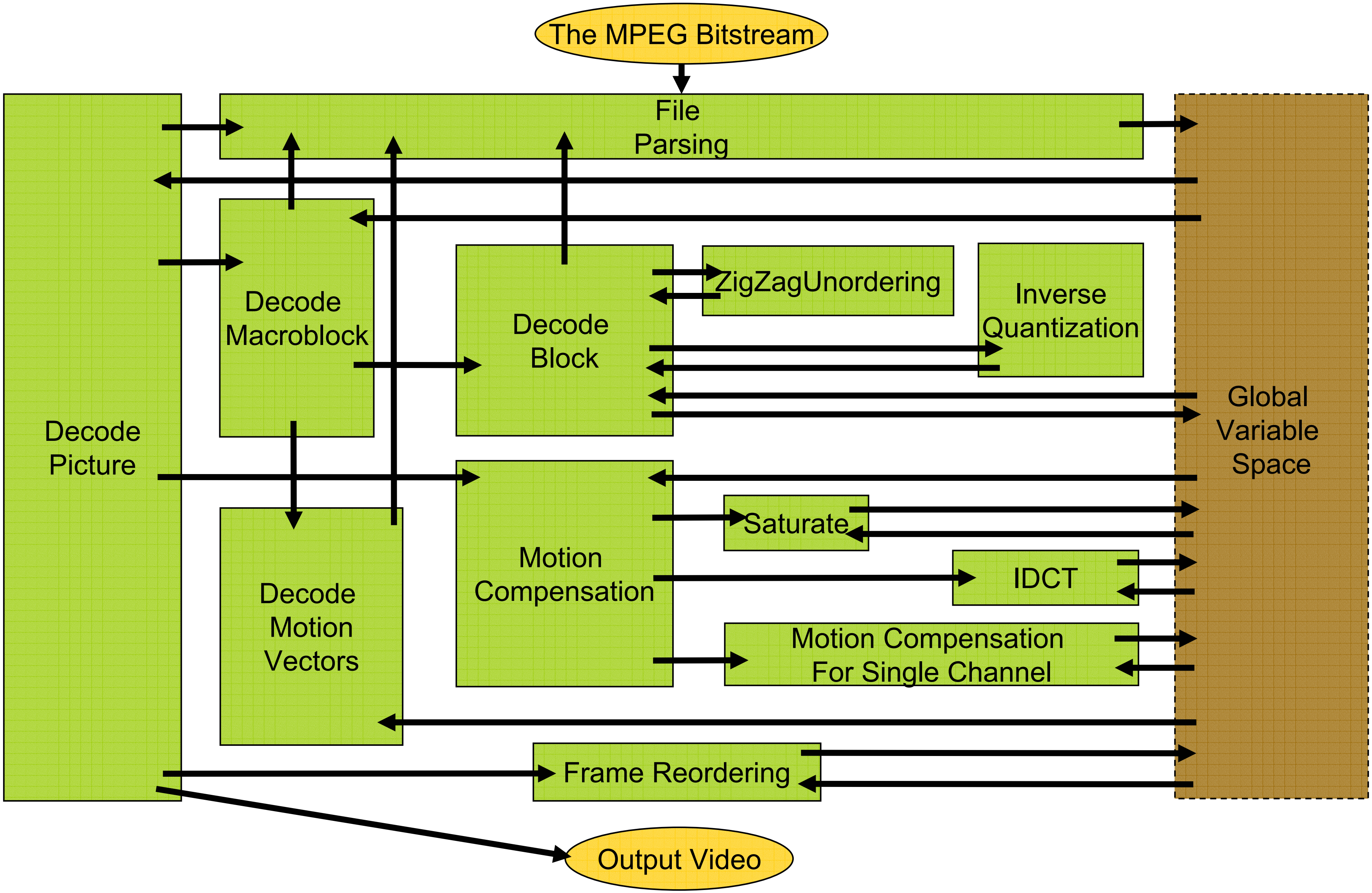
```
add VLD(QC, PT1, PT2);
add splitjoin {
    split roundrobin(N*B, V);

    add pipeline {
        add ZigZag(B);
        add IQuantization(B) to QC;
        add IDCT(B);
        add Saturation(B);
    }
    add pipeline {
        add MotionVectorDecode();
        add Repeat(V, N);
    }

    join roundrobin(B, V);
}
add splitjoin {
    split roundrobin(4*(B+V), B+V, B+V);

    add MotionCompensation(4*(B+V)) to PT1;
    for (int i = 0; i < 2; i++) {
        add pipeline {
            add MotionCompensation(B+V) to PT1;
            add ChannelUpsample(B);
        }
    }

    join roundrobin(1, 1, 1);
}
add PictureReorder(3*W*H) to PT2;

add ColorSpaceConversion(3*W*H);
```

Teleport Messaging in MPEG-2





Messaging Equivalent in C



MPEG-2 Implementation

- Fully-functional MPEG-2 decoder and encoder
- Developed by 1 programmer in 8 weeks
- 2257 lines of code
  - Vs. 3477 lines of C code in MPEG-2 reference
- 48 static streams, 643 instantiated filters

Conclusions

- StreamIt language preserves program structure
  - Natural for programmers
- Parallelism and communication naturally exposed
  - Compiler managed buffers, and portable parallelization technology
- StreamIt increases programmer productivity, enables parallel performance