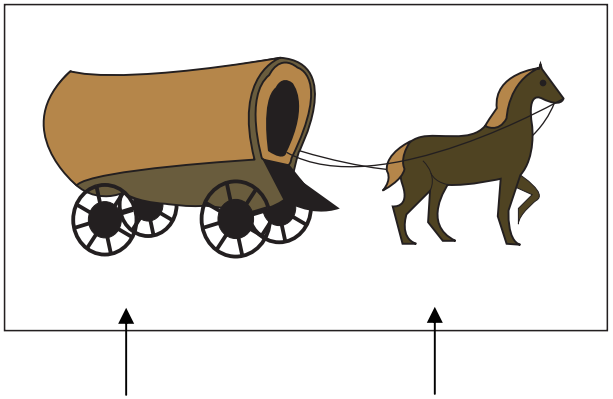
6.189 Multicore Programming Primer, January (IAP) 2007

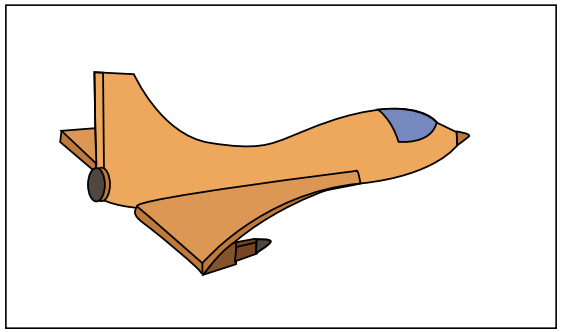
6.189 IAP 2007

Lecture 8

The StreamIt Language

Languages Have Not Kept Up





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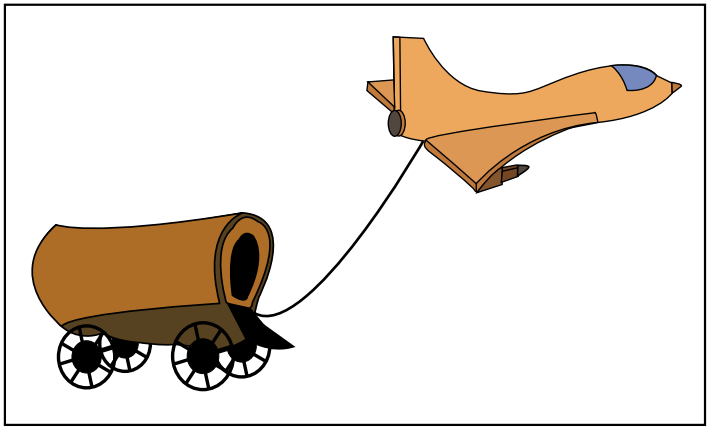
C ⇔ von-Neumann machine

Modern architecture

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



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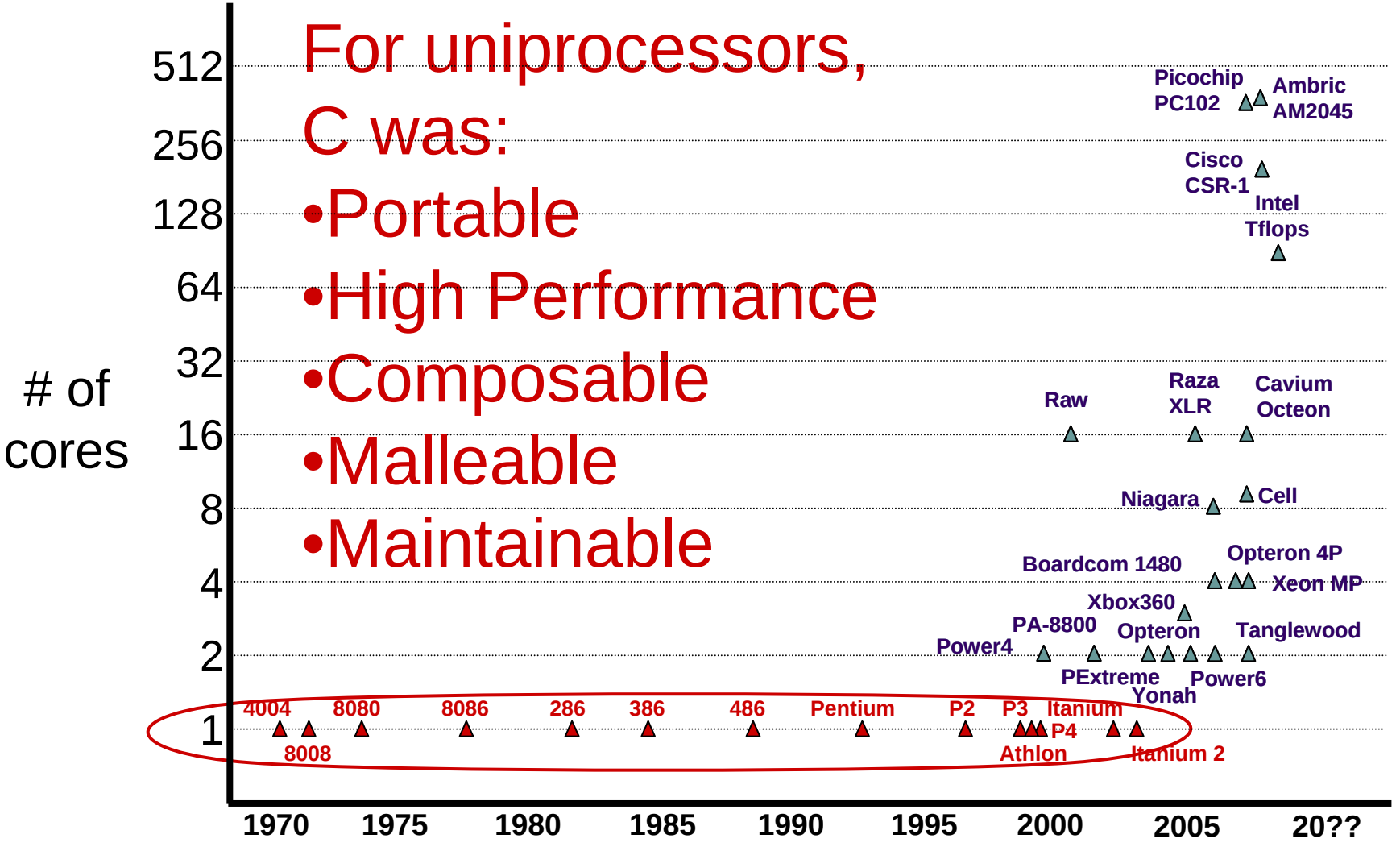
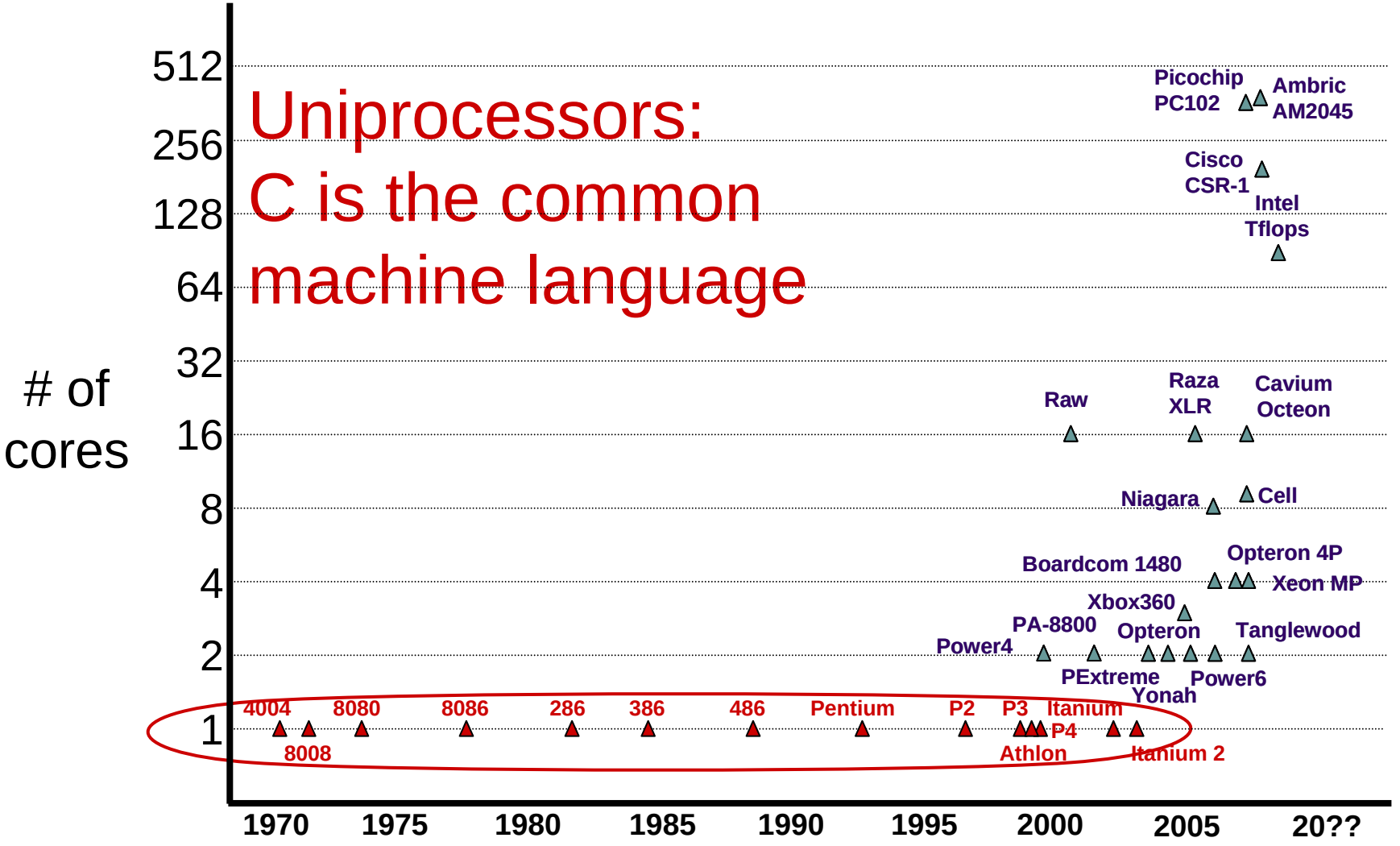
Why a New Language?



Why a New Language?



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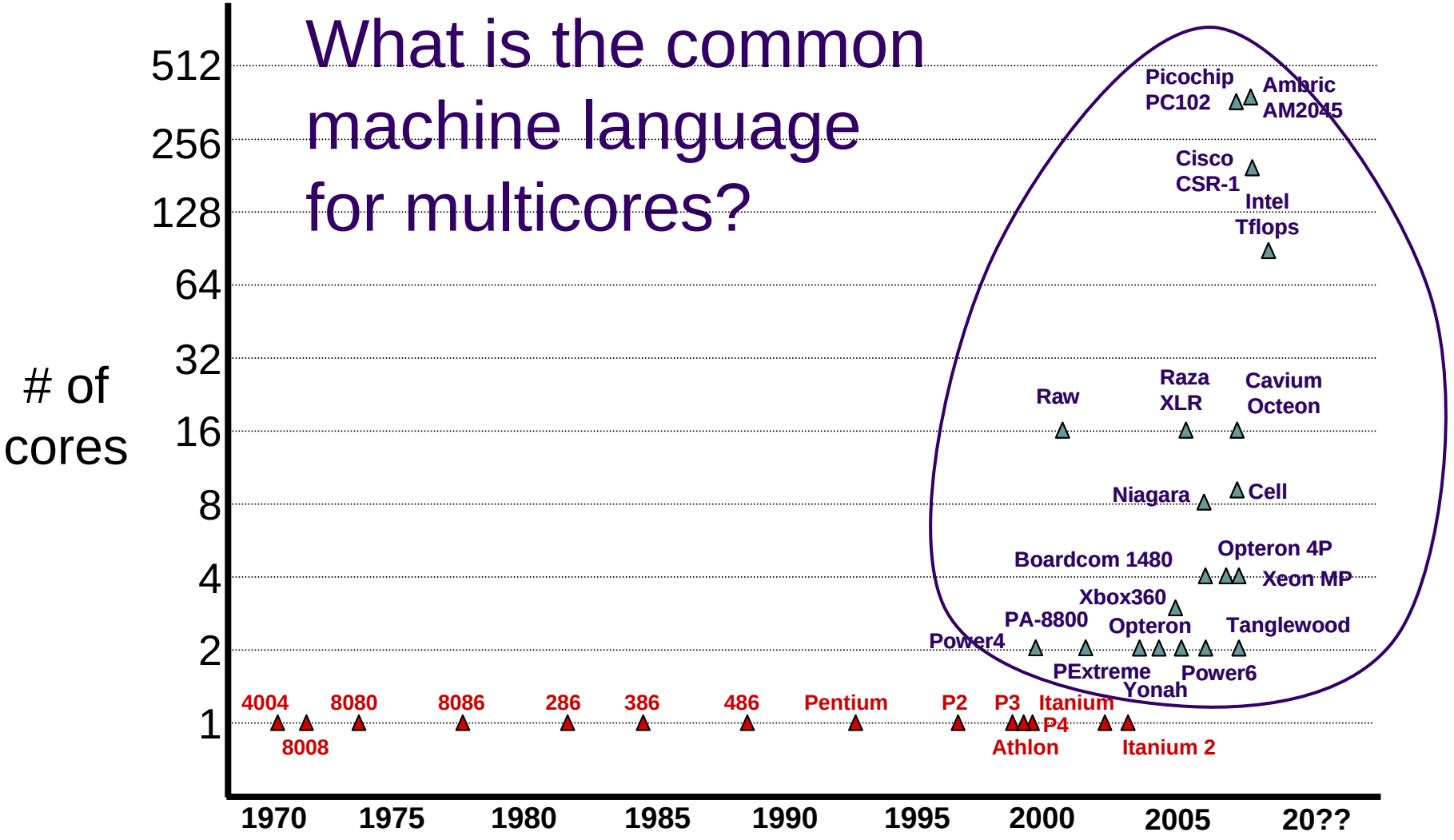


Common Machine Languages

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:

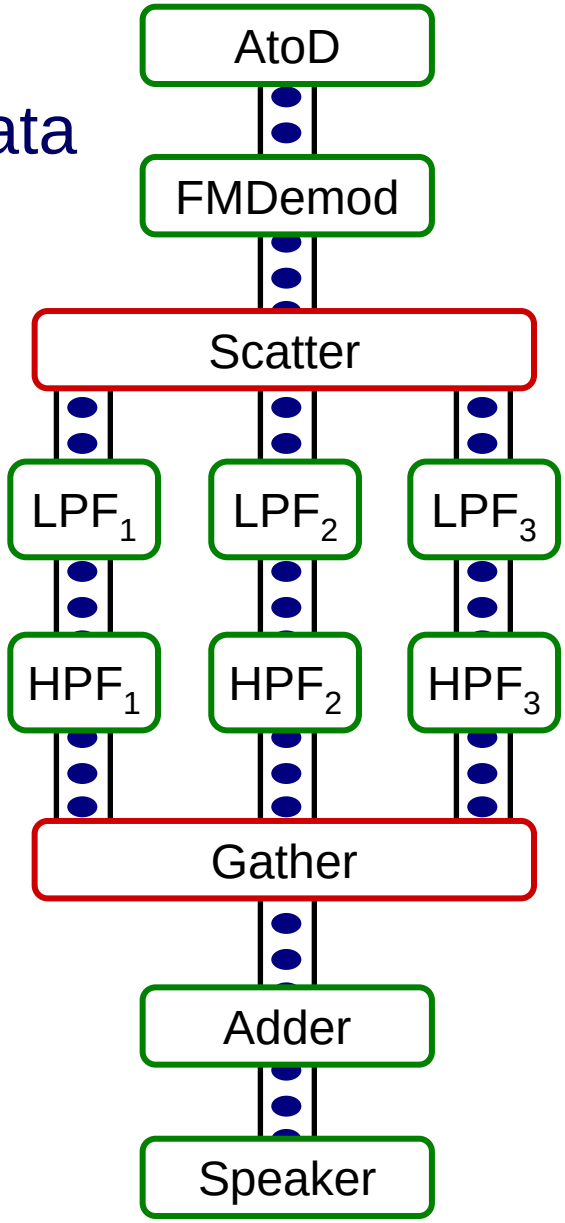
Common Properties
Multiple flows of control
Multiple local memories

Differences:
Number and capabilities of cores
Communication Model
Synchronization Model

Need common machine language(s) for multicores

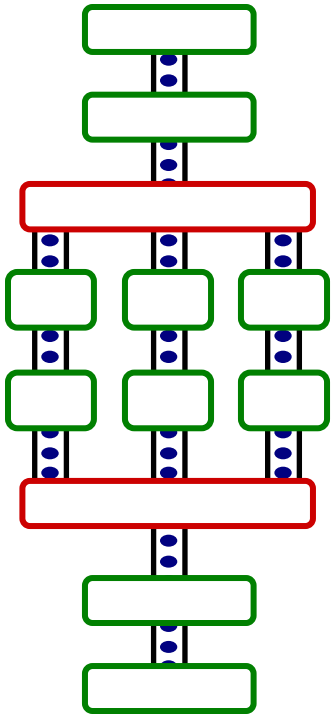
Streaming as a Common Machine Language

- 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

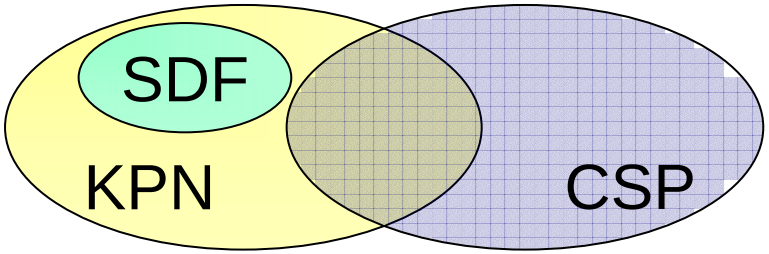
- Many different ways to represent streaming
  - Do senders/receivers block?
  - How much buffering is allowed on channels?
  - Is computation deterministic?
  - Can you avoid deadlock?



- 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

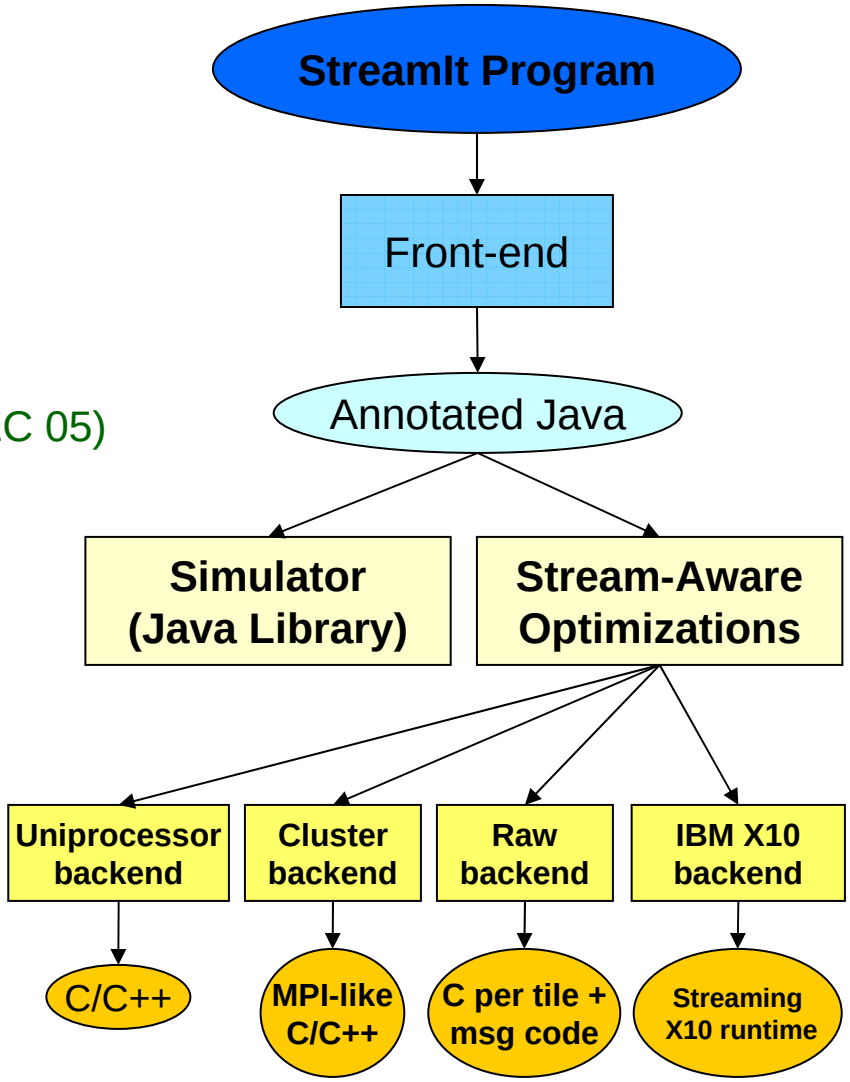
The StreamIt Language

- 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

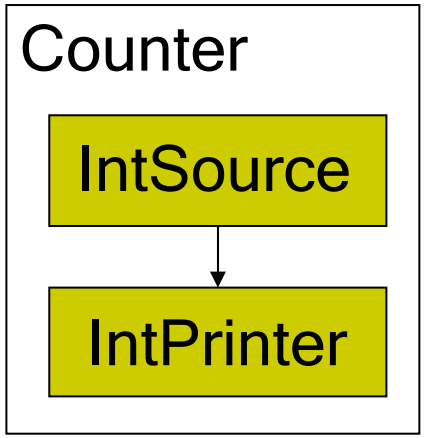
The StreamIt Project

- **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

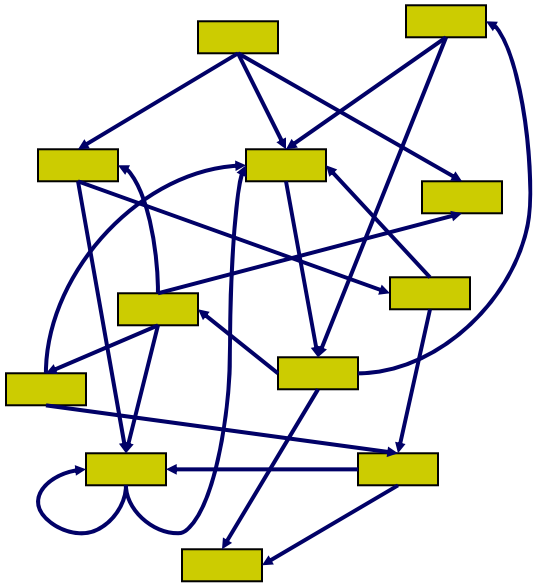
```
void->void pipeline Counter() {
    add IntSource();
    add IntPrinter();
}
void->int filter IntSource() {
    int x;
    init { x = 0; }
    work push 1 { push (x++); }
}
int->void filter IntPrinter() {
    work pop 1 { print(pop()); }
}
```



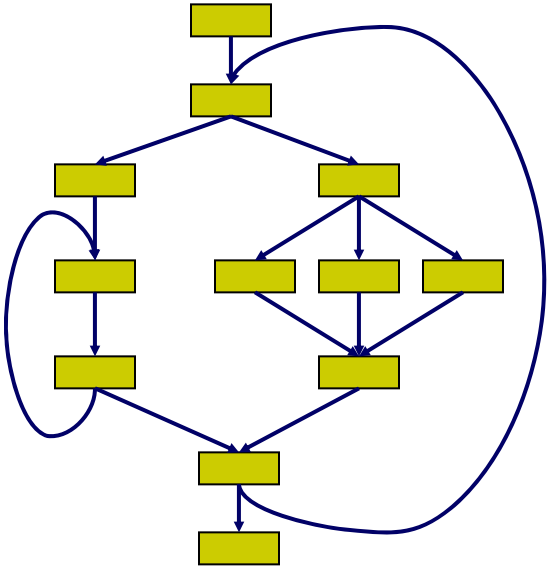

```
% strc Counter.str -o counter
% ./counter -i 4
0
1
2
3
```

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

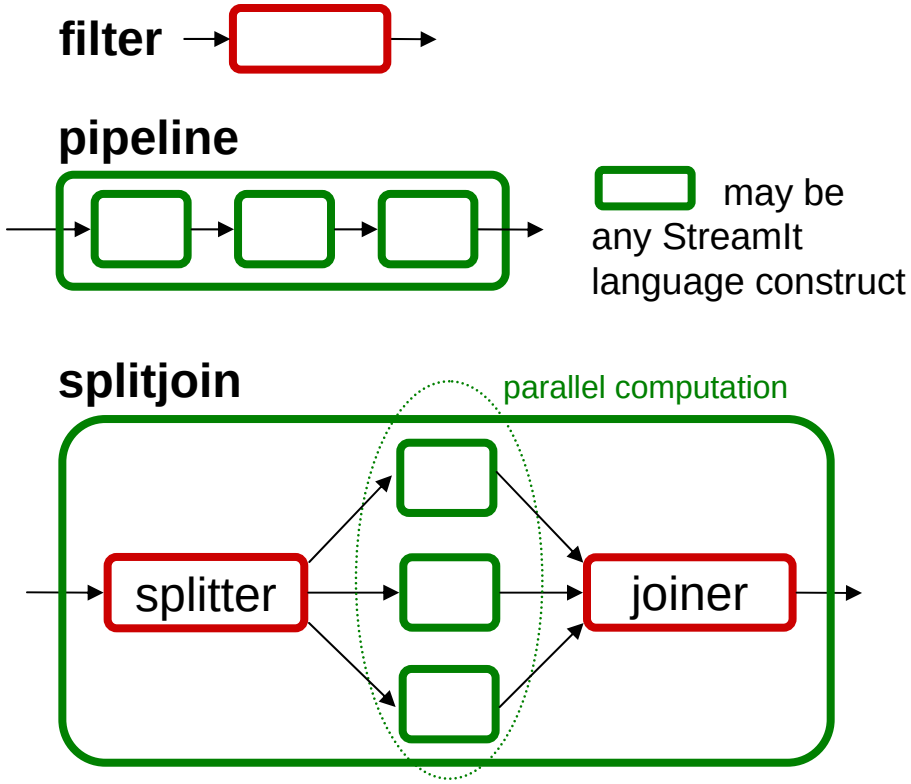


unstructured



structured

Structured Streams



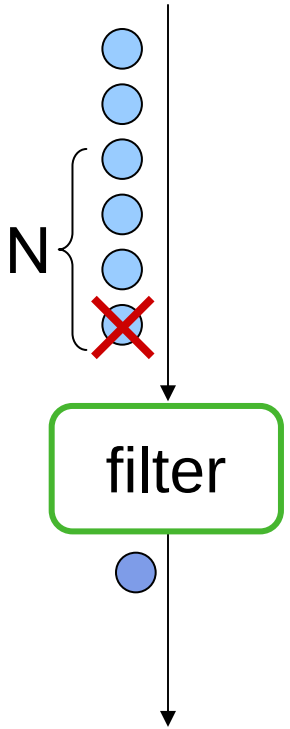
- Each structure is single-input, single-output
- Hierarchical and composable

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

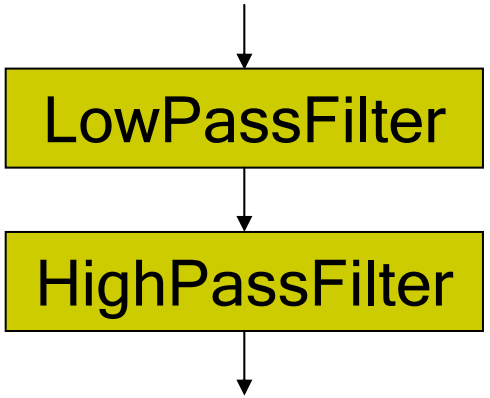
```
void FIR(
  int* src,
  int* dest,
  int* srcIndex,
  int* destIndex,
  int srcBufferSize,
  int destBufferSize,
  int N) {

  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

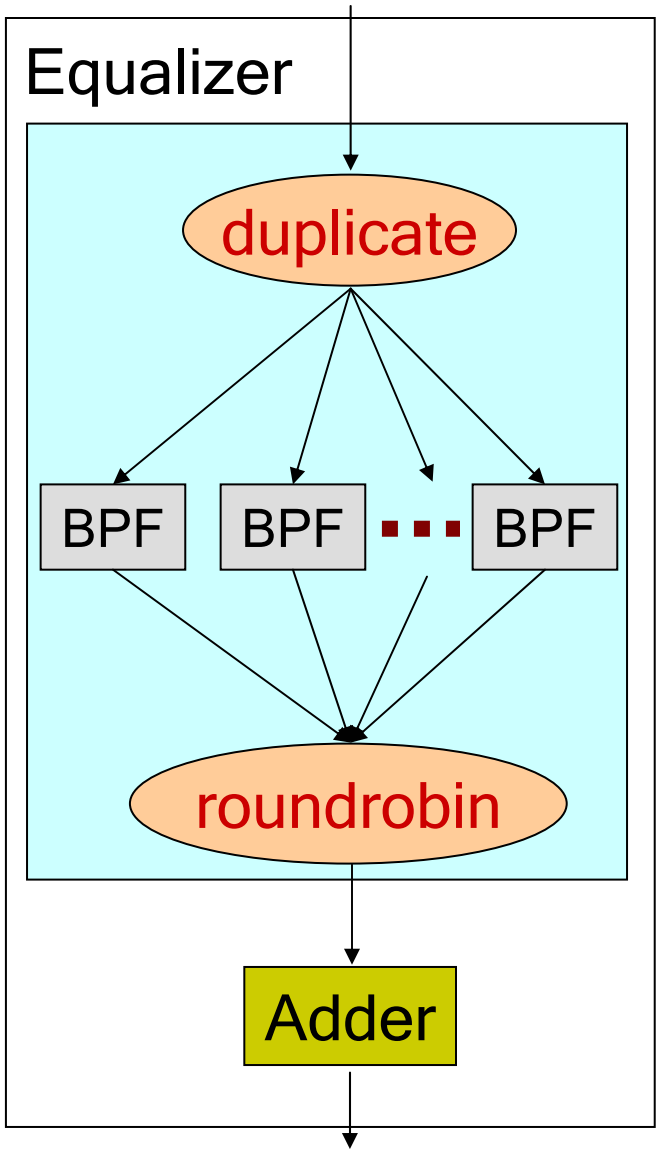
Pipeline Example: Band Pass Filter

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



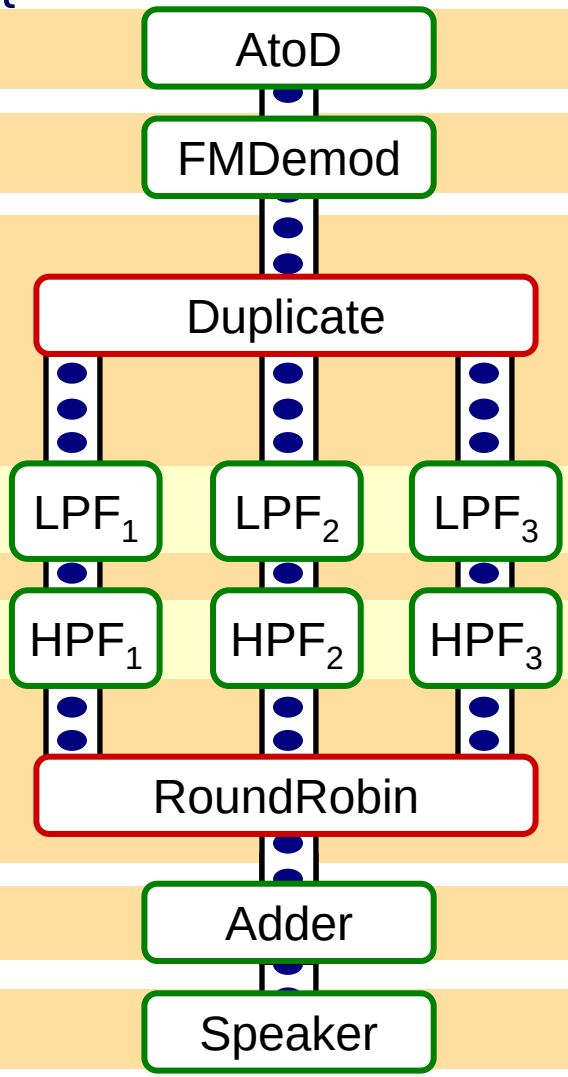
SplitJoin Example: Equalizer

```
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

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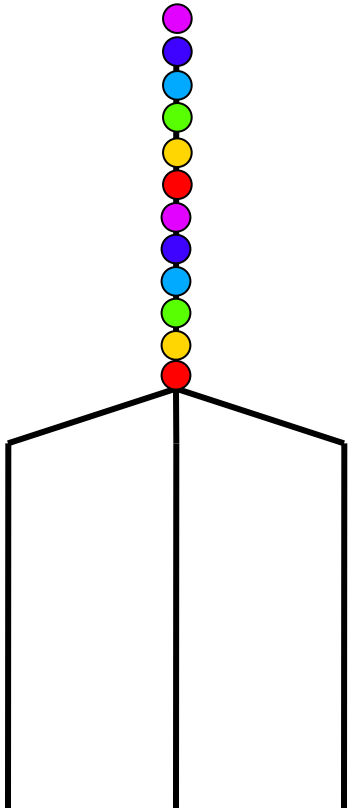
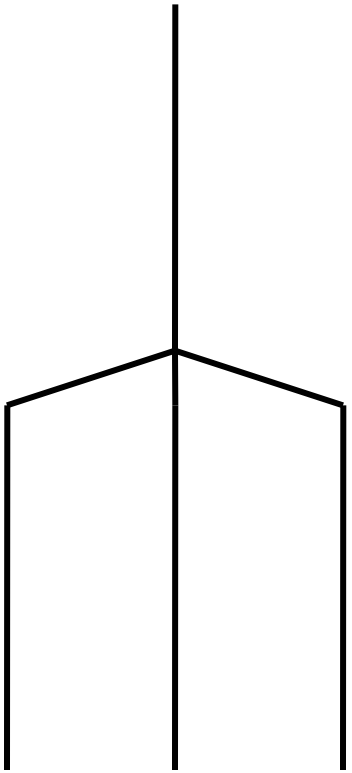
SplitJoins are Beautiful

split duplicate



split roundrobin(N)



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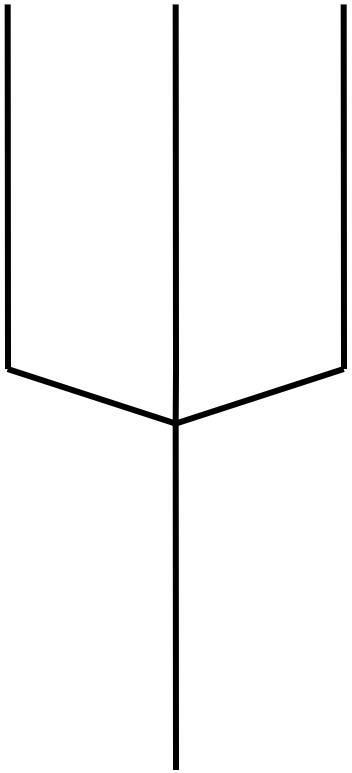

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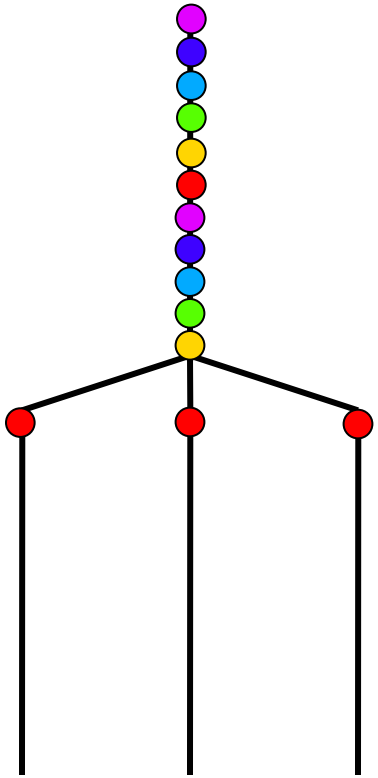

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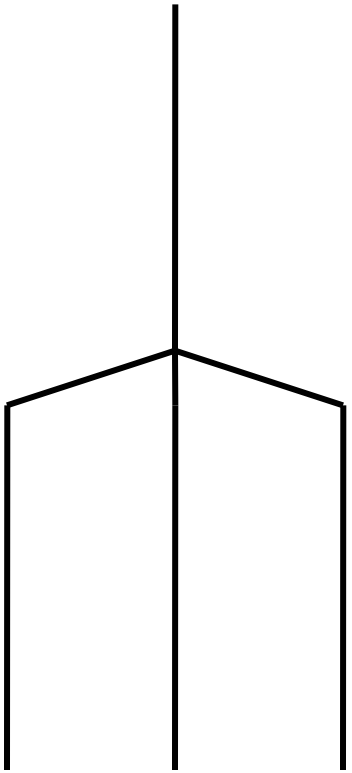

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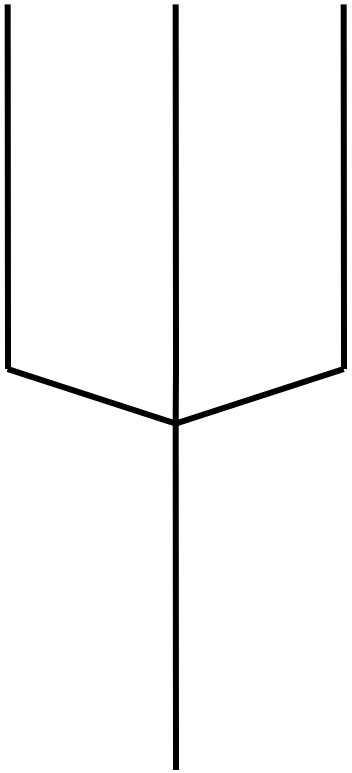

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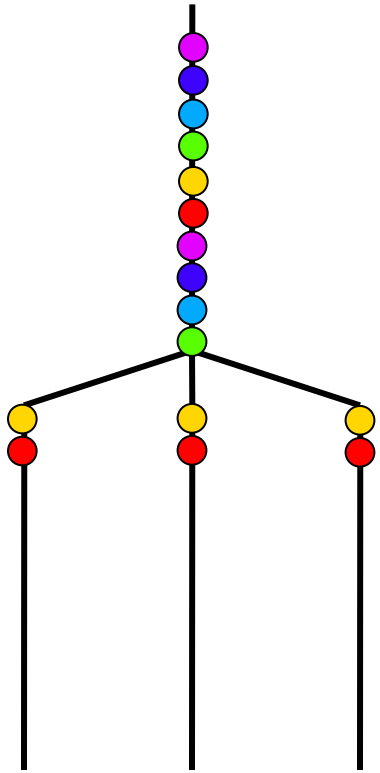

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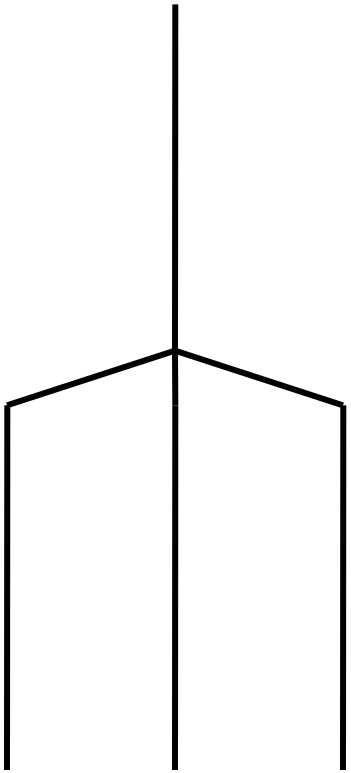

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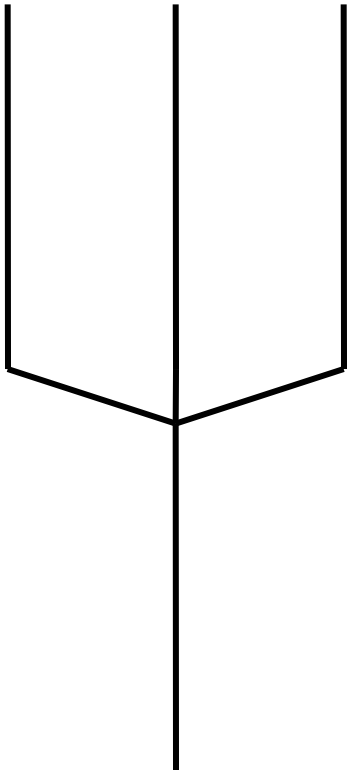

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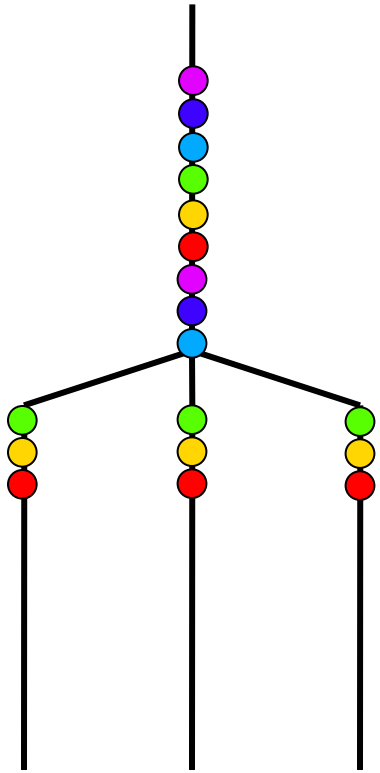

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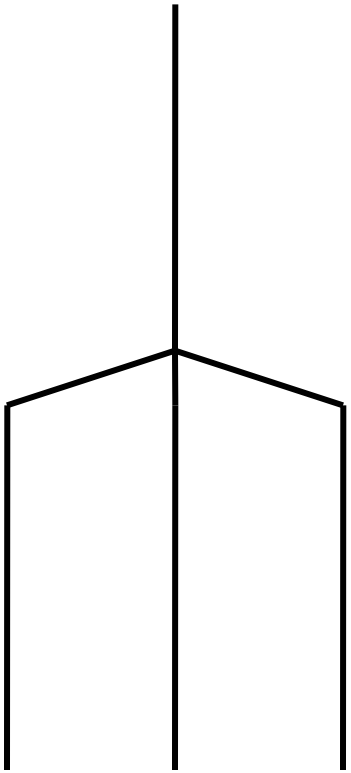

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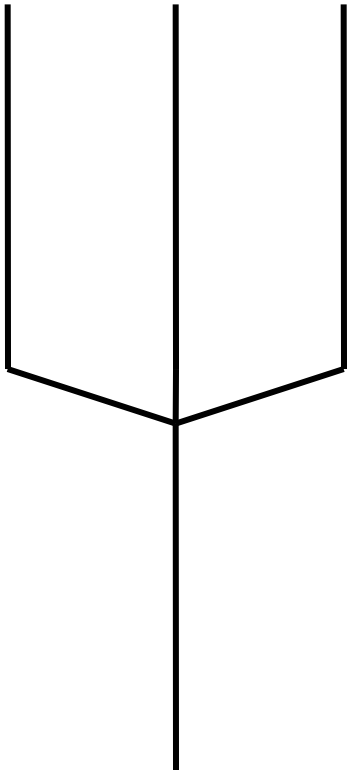

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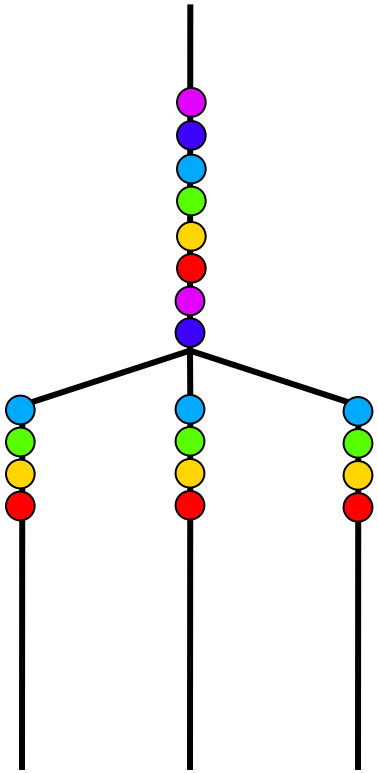

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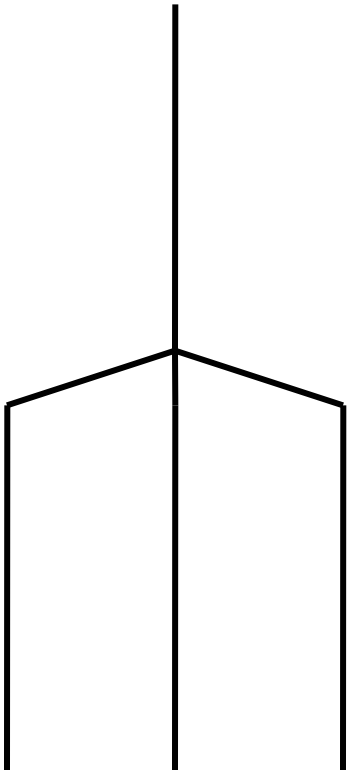

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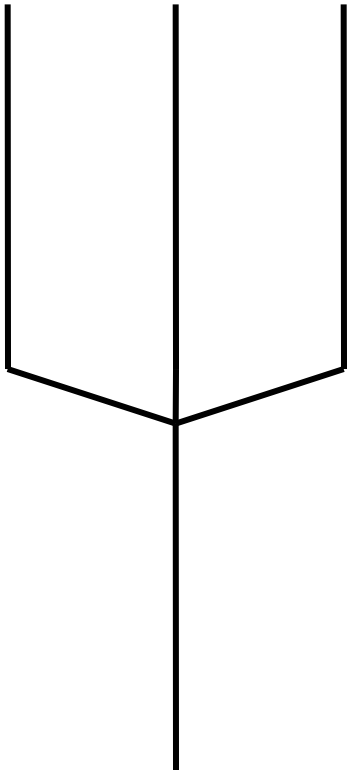

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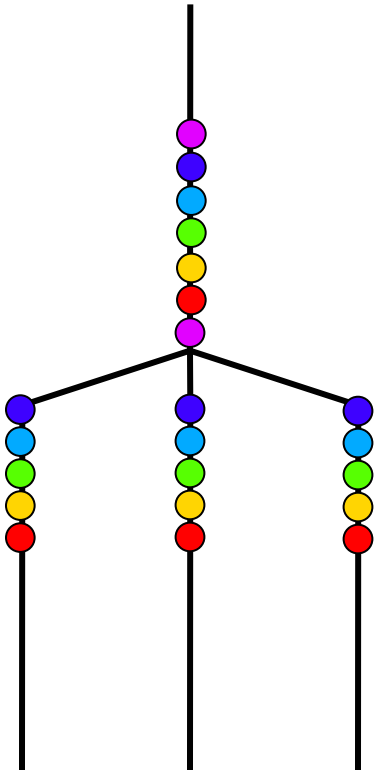

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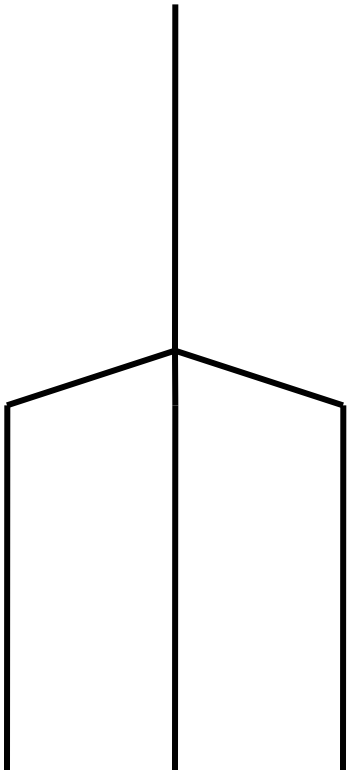

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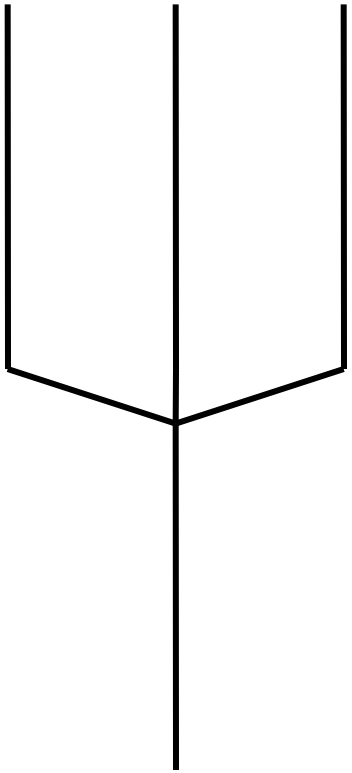

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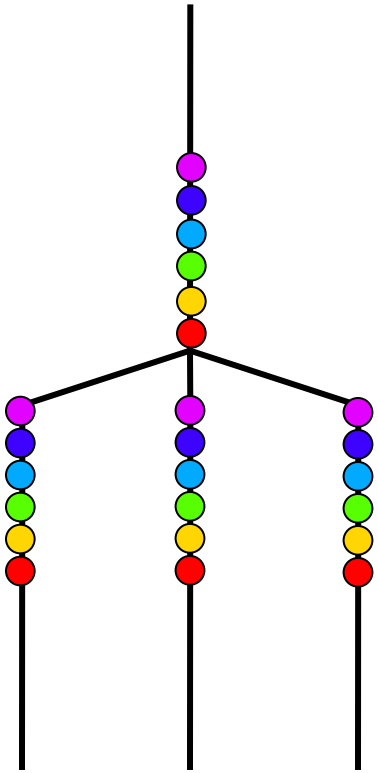

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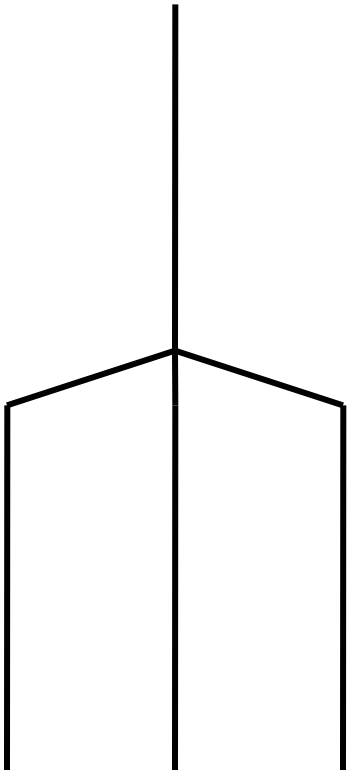

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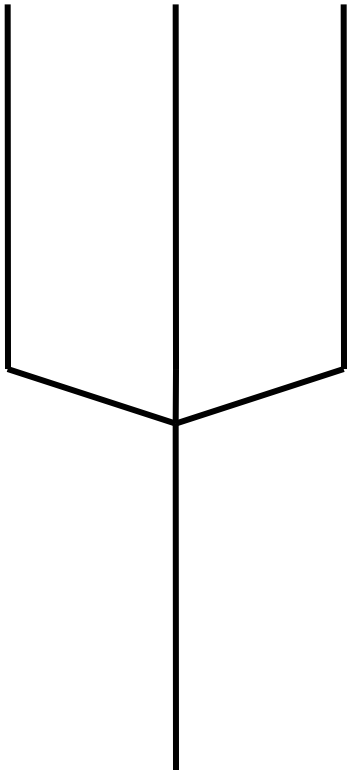

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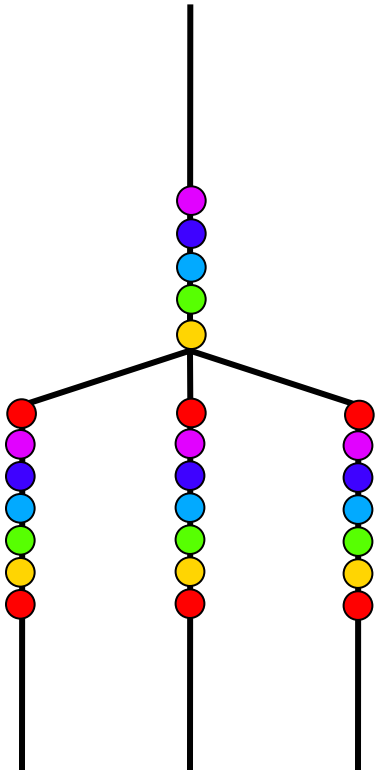

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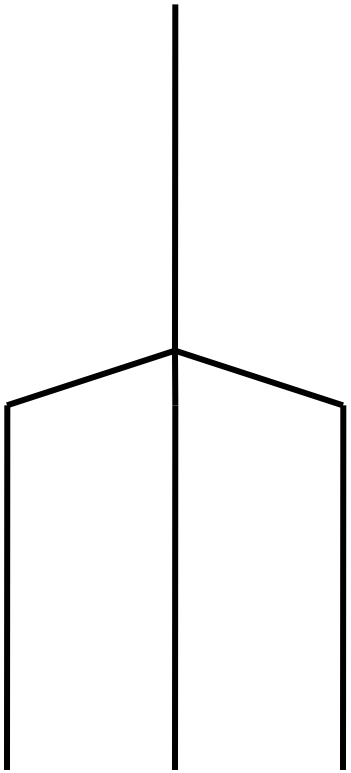

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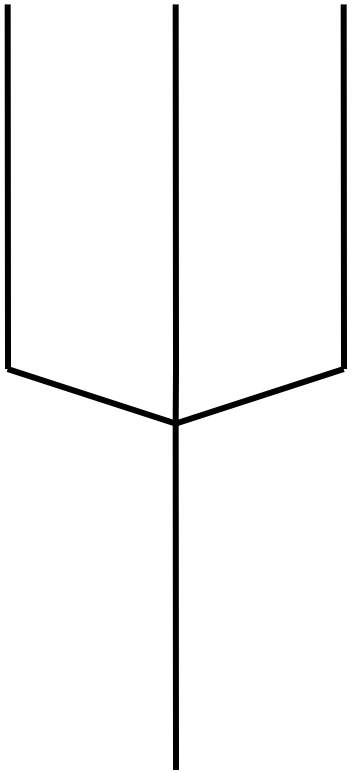

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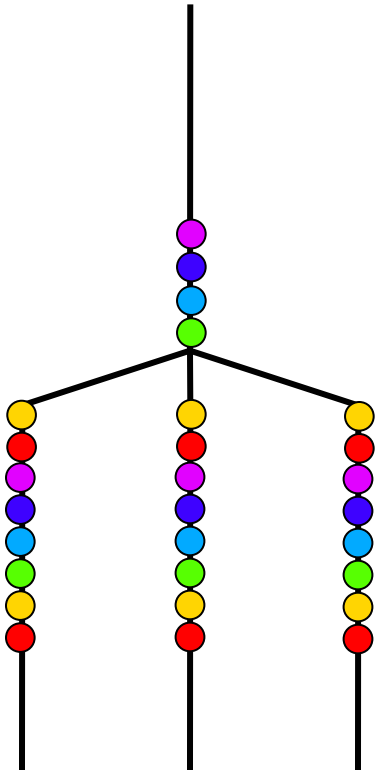

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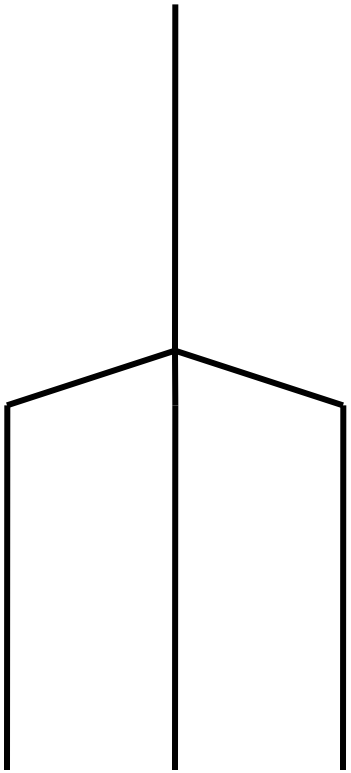

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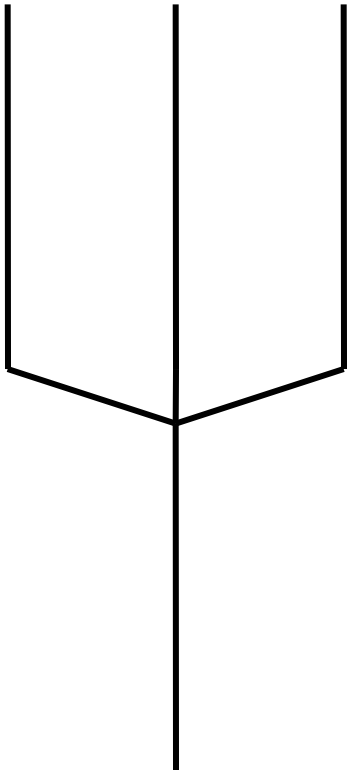

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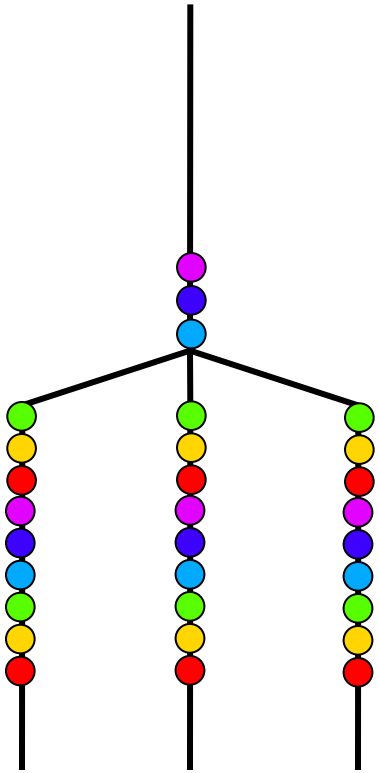
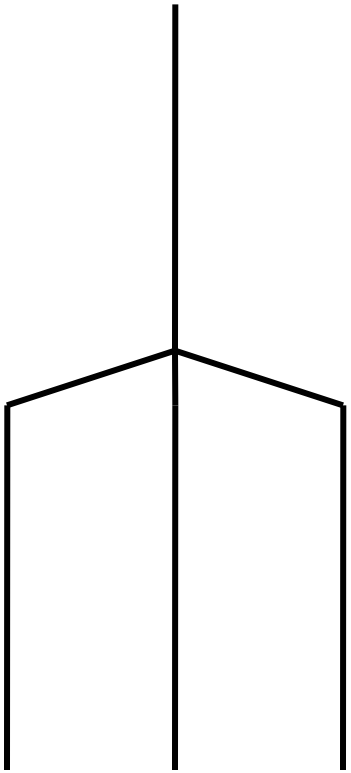


split roundrobin(N)



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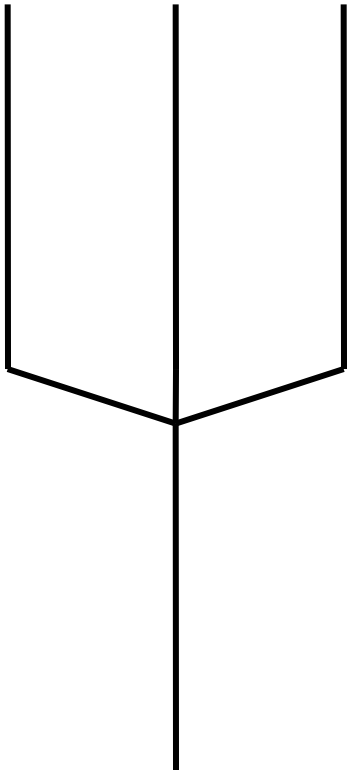

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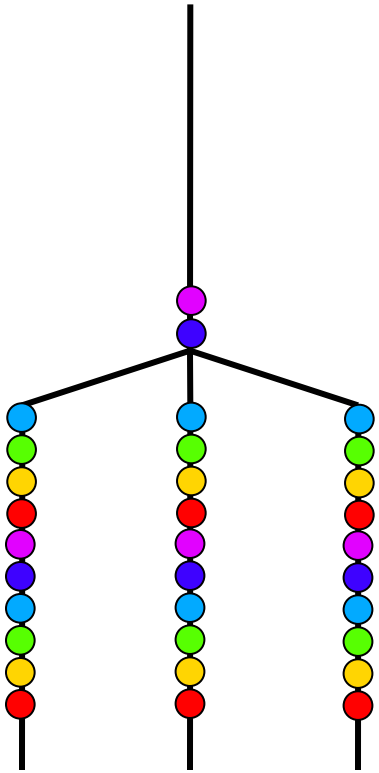

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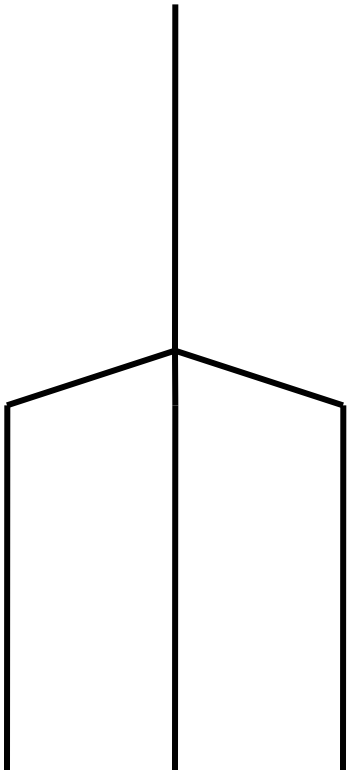

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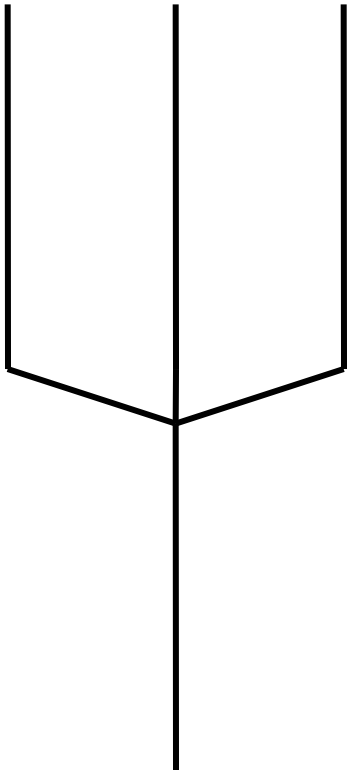

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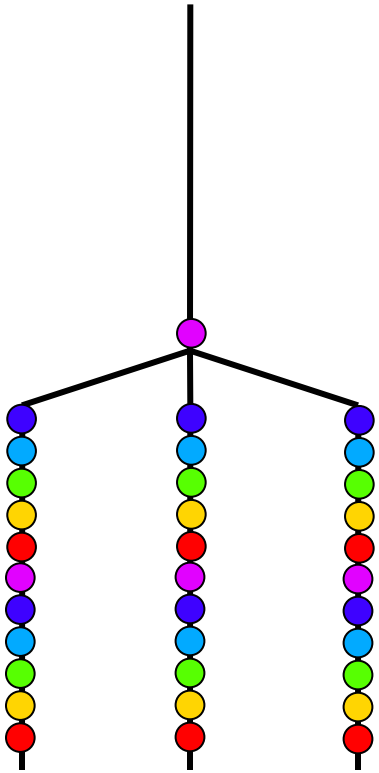

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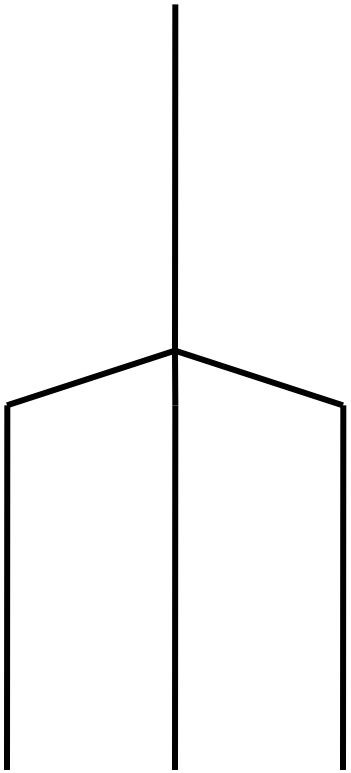

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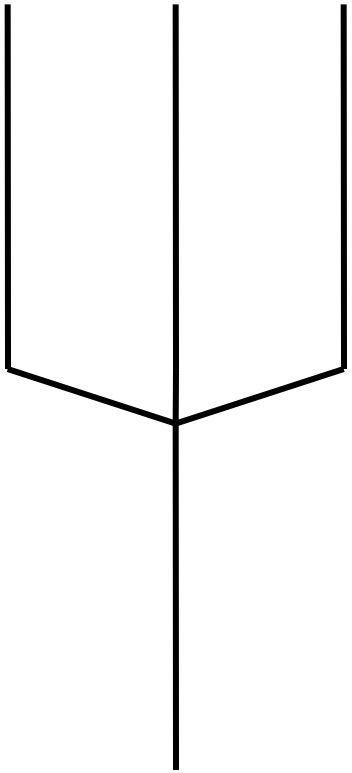

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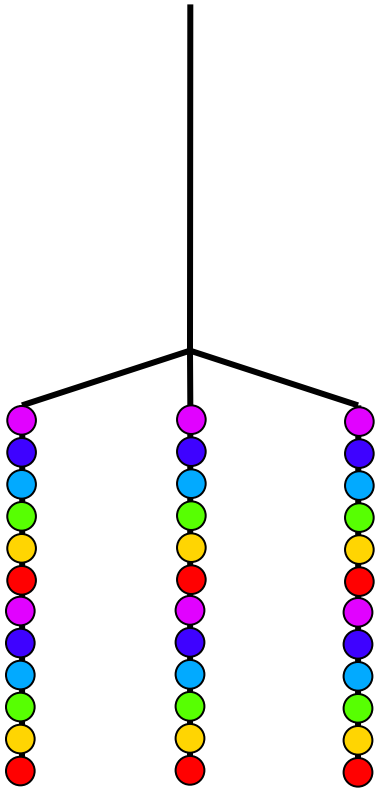

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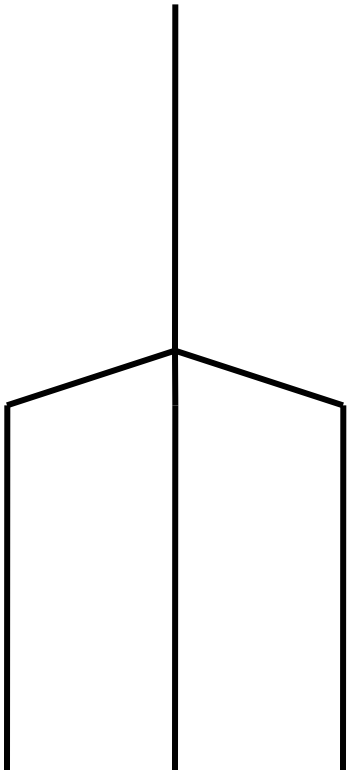

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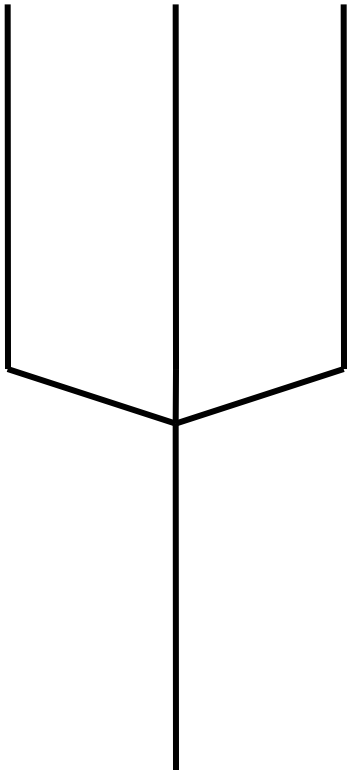

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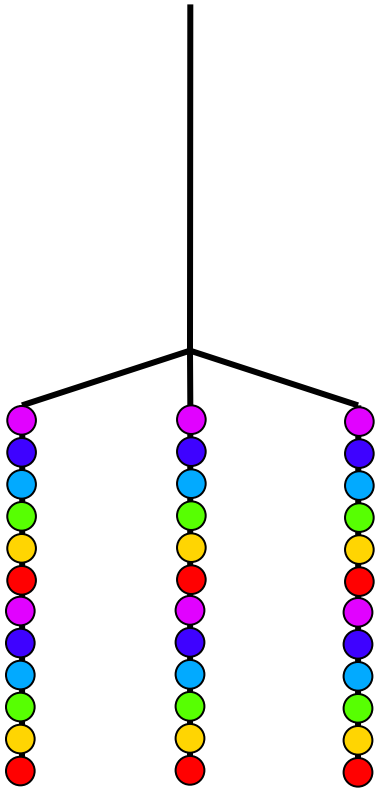

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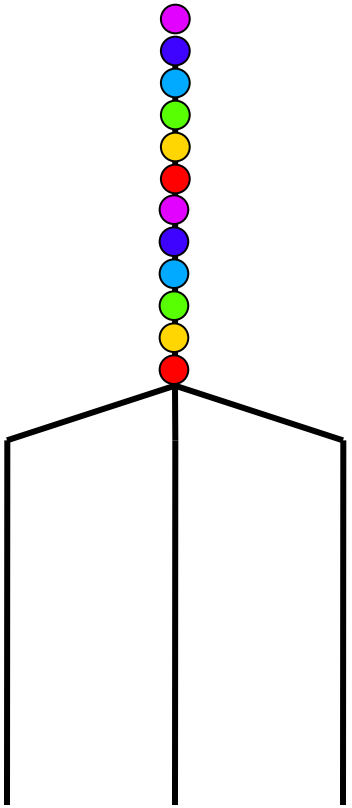

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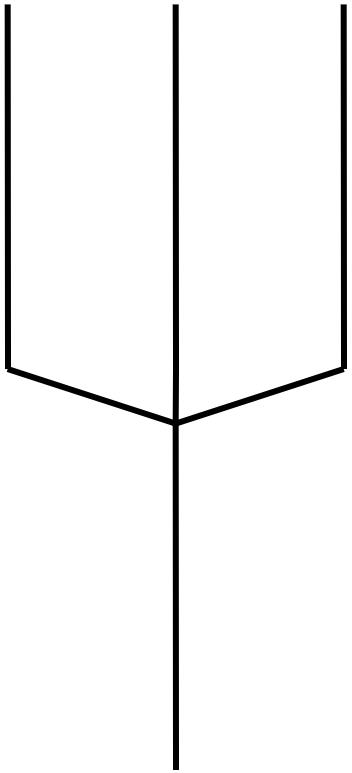

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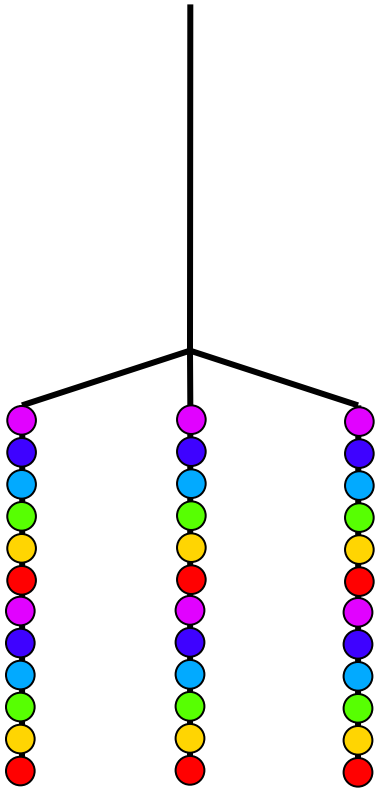

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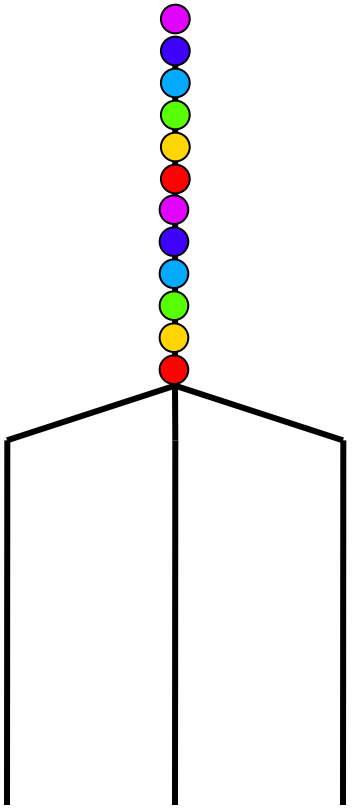

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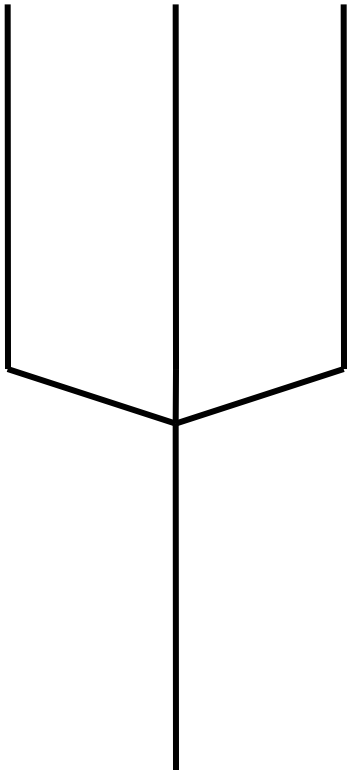

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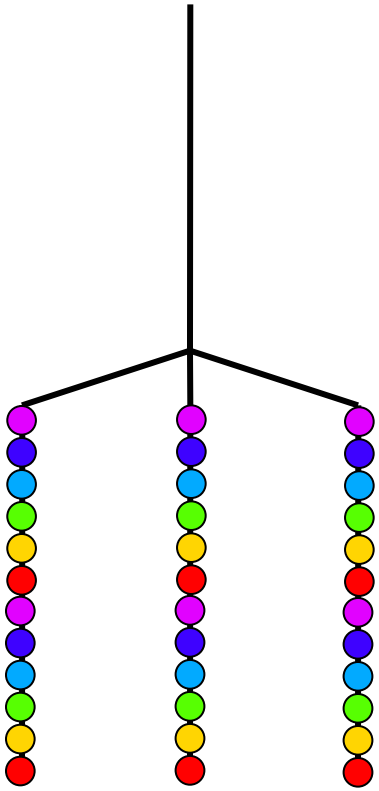

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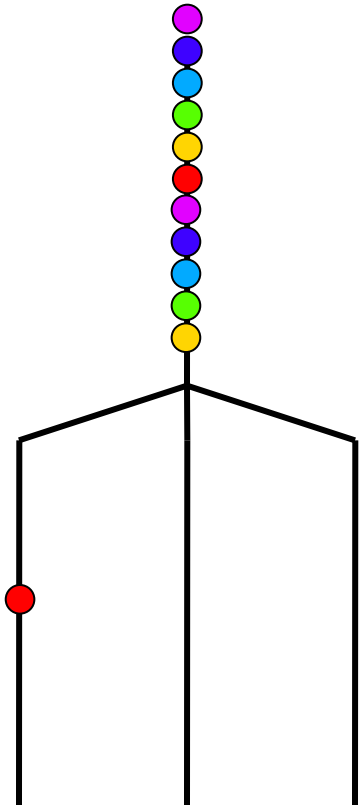

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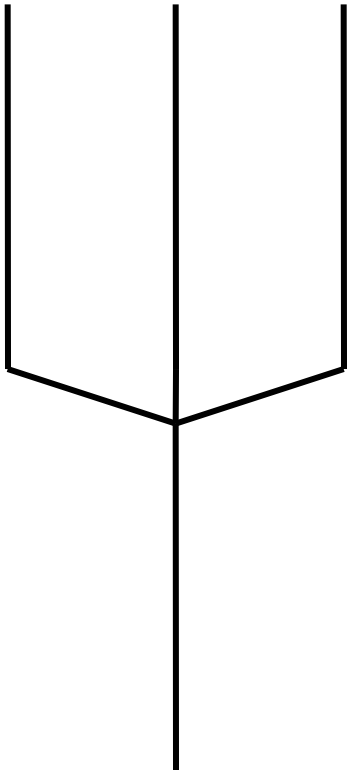

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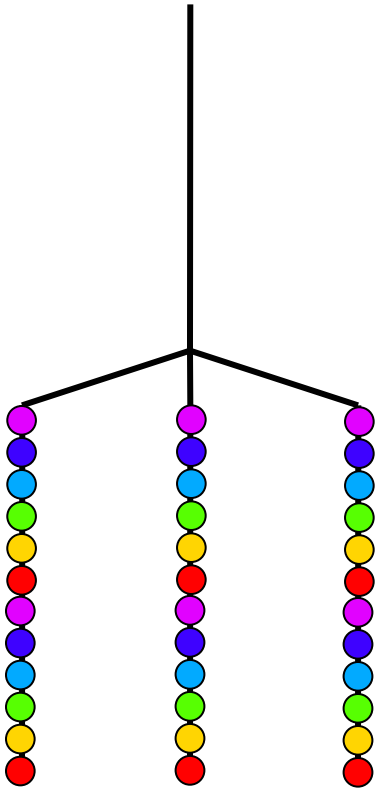

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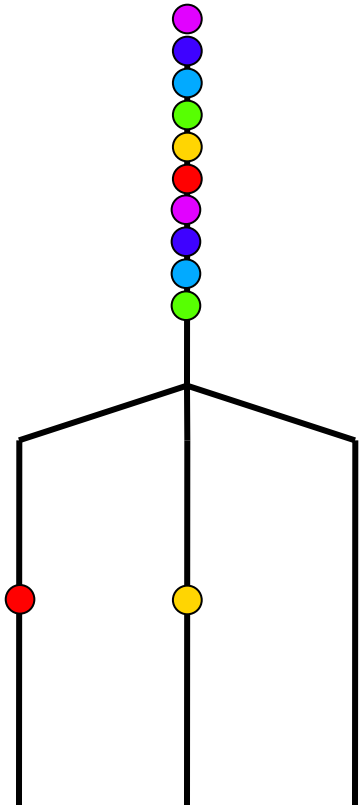

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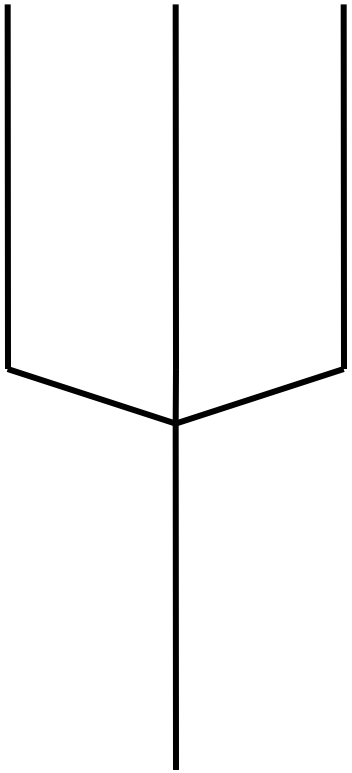

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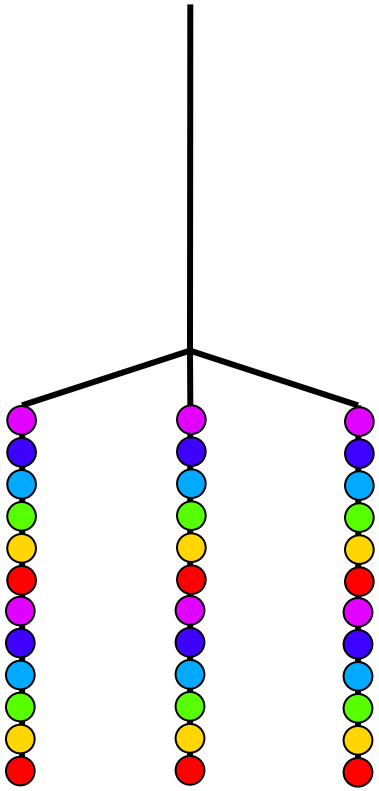

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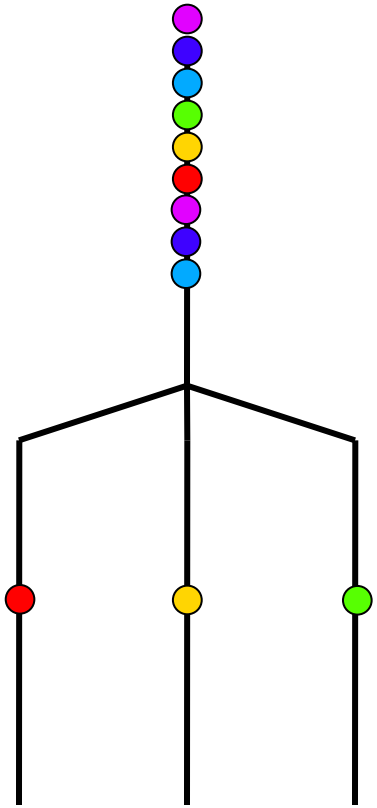

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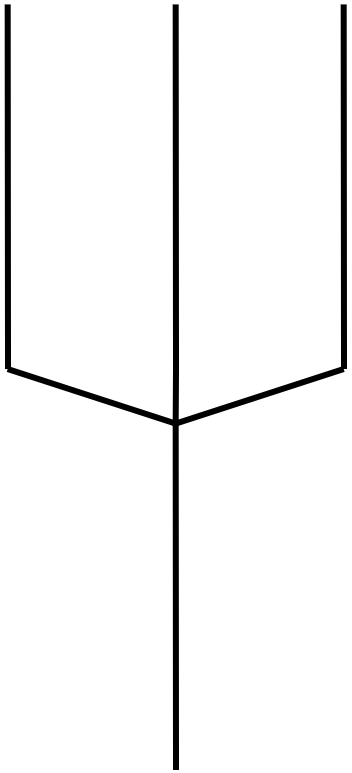

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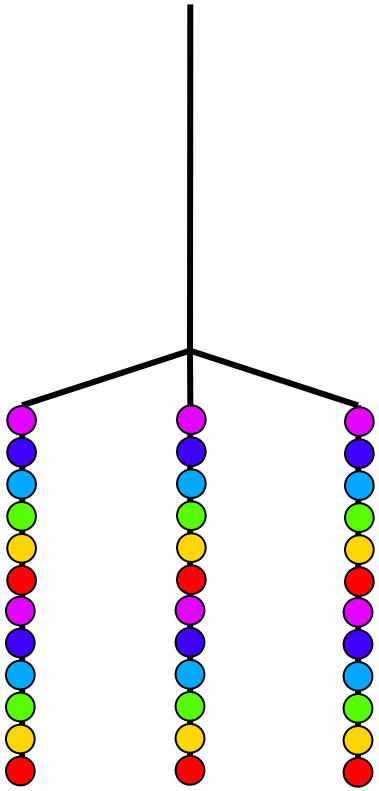

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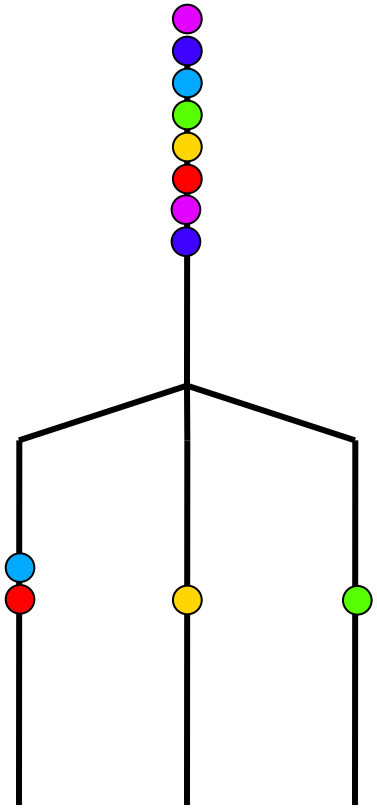

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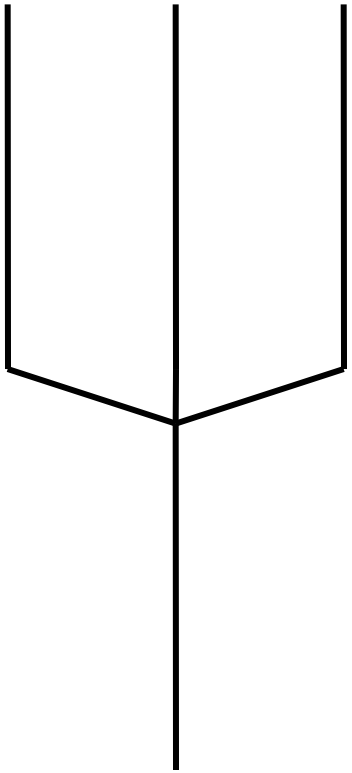

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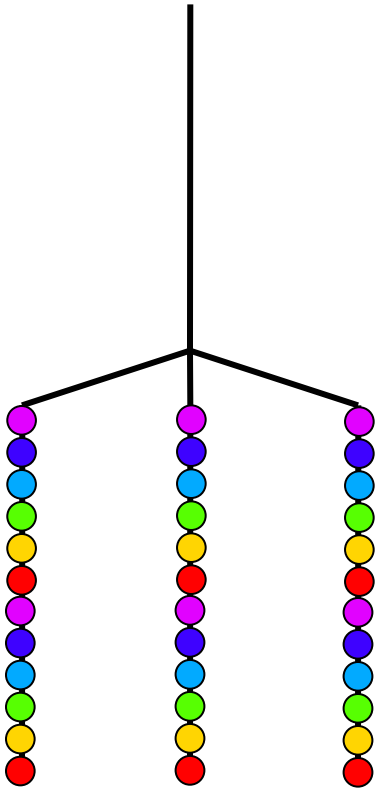

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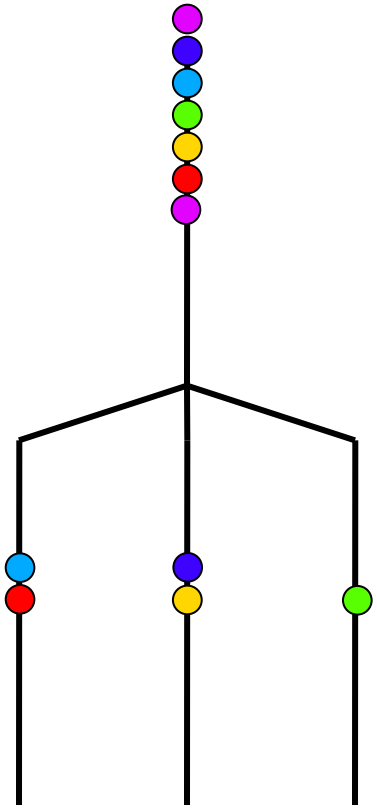

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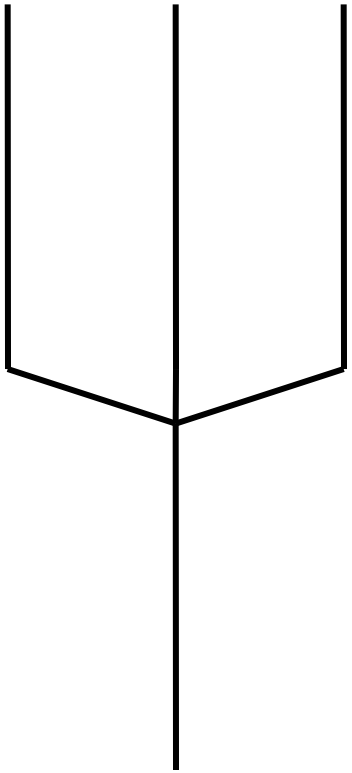

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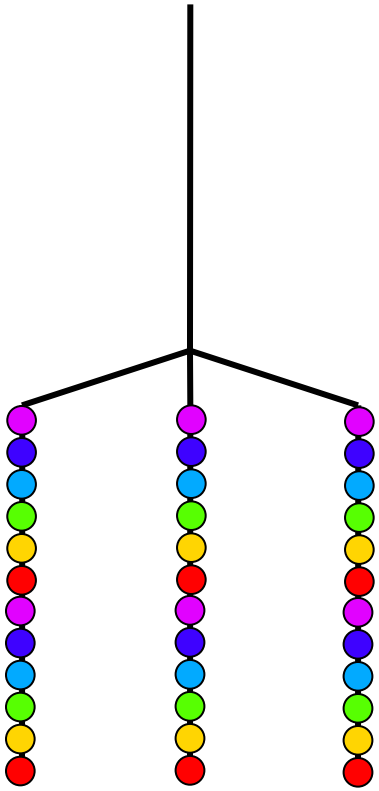

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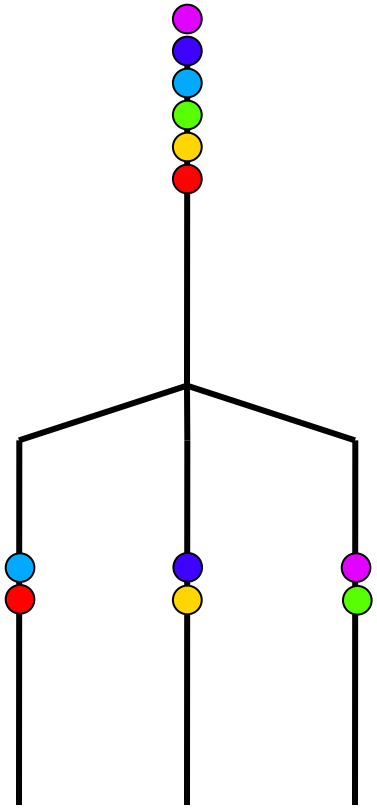

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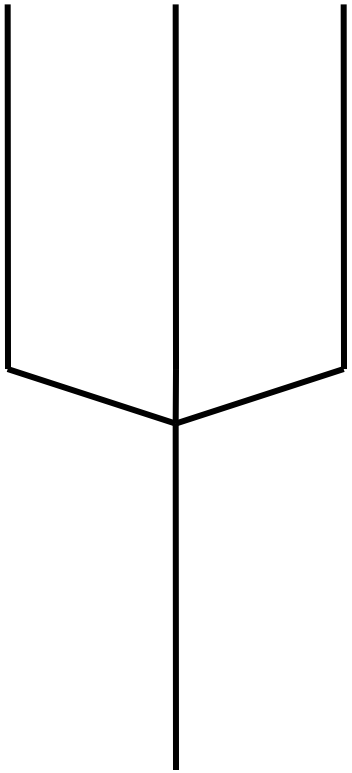

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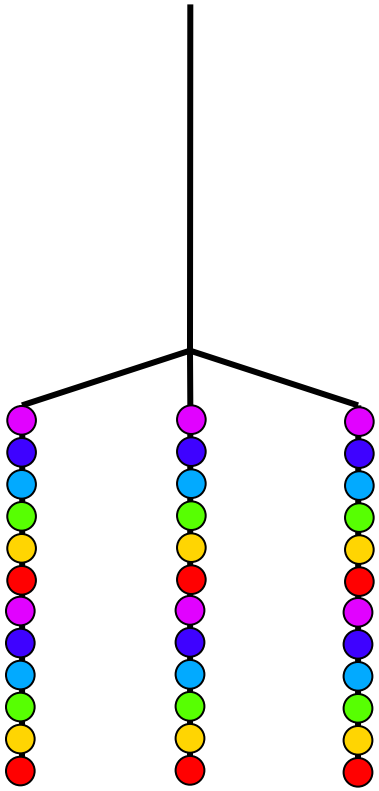

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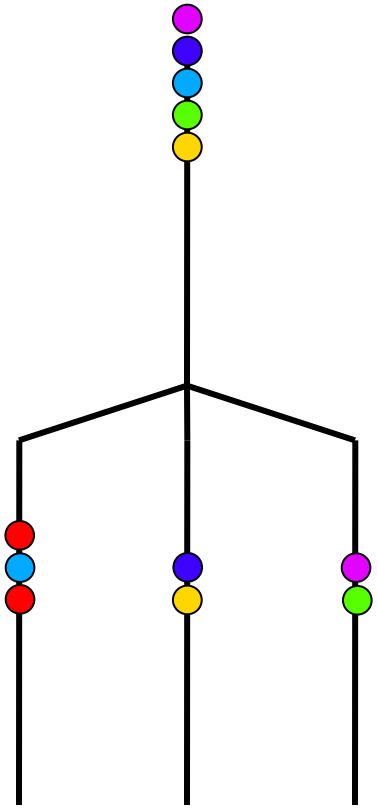

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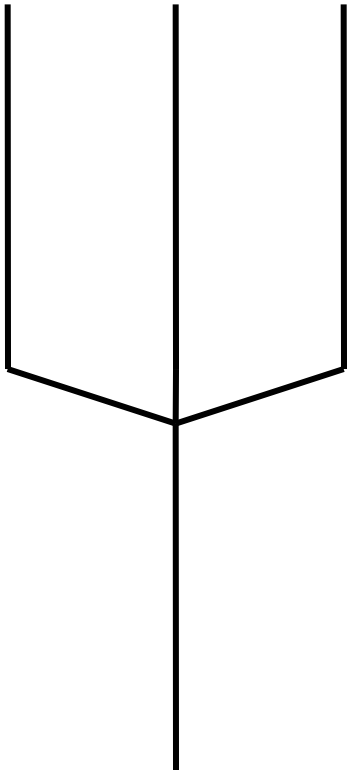

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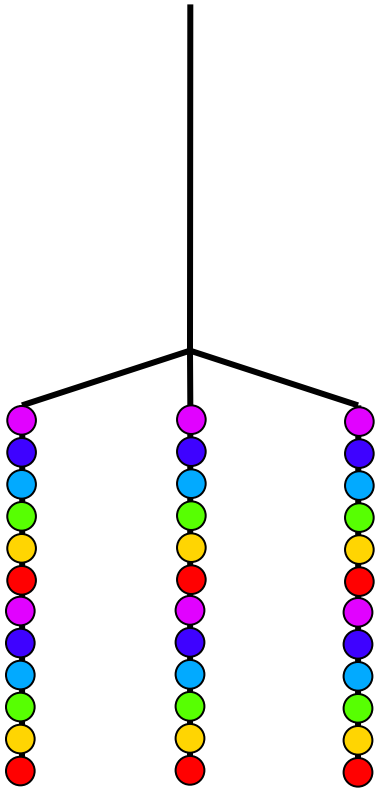

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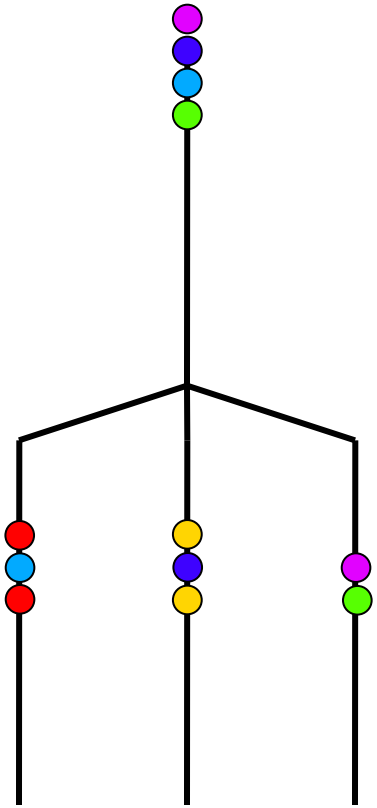

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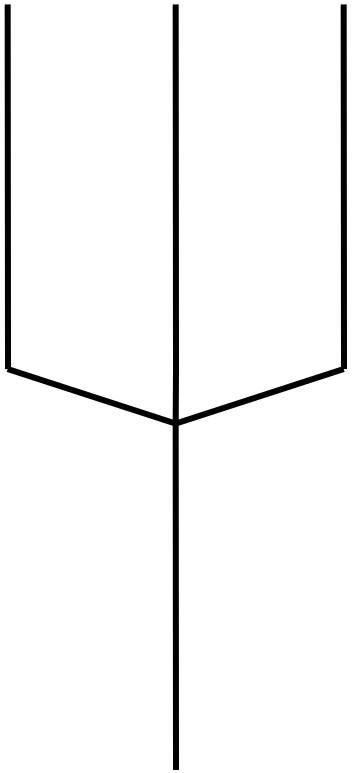

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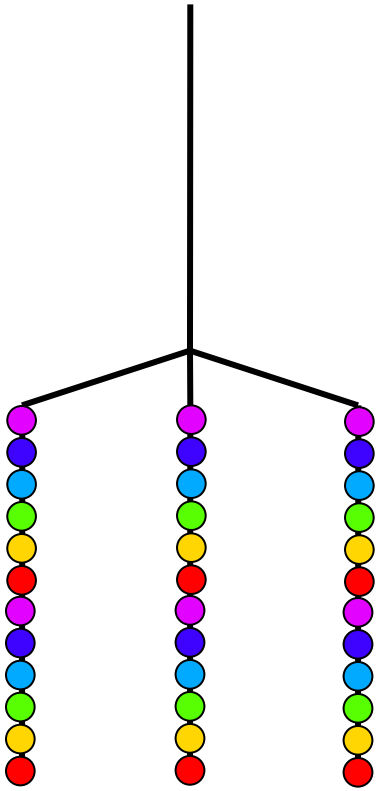

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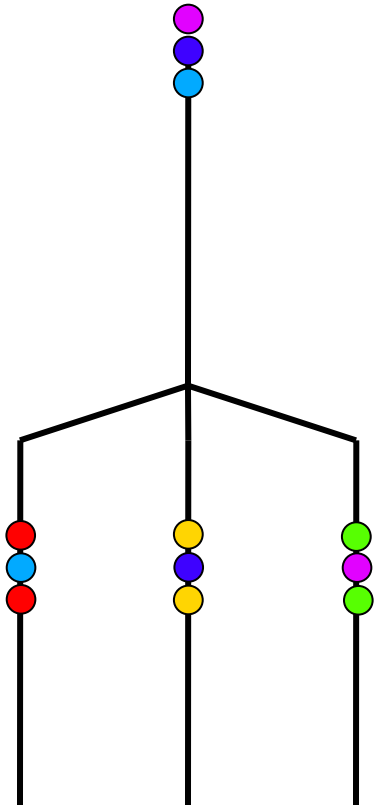

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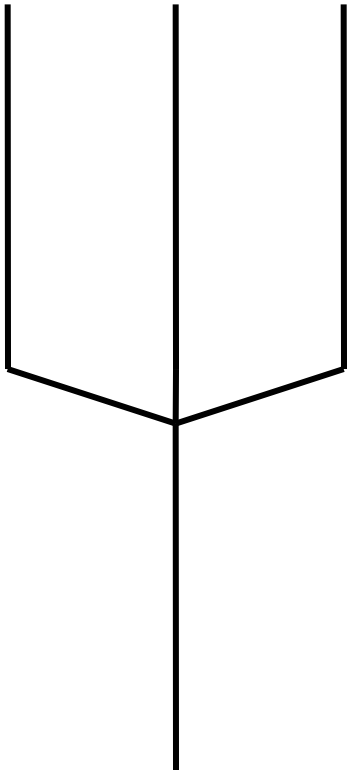

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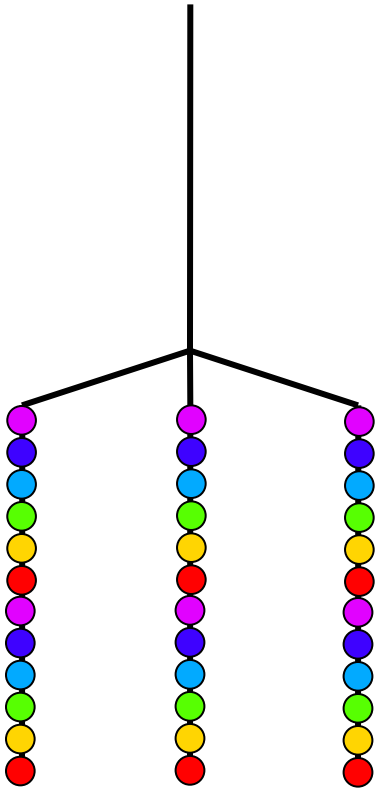

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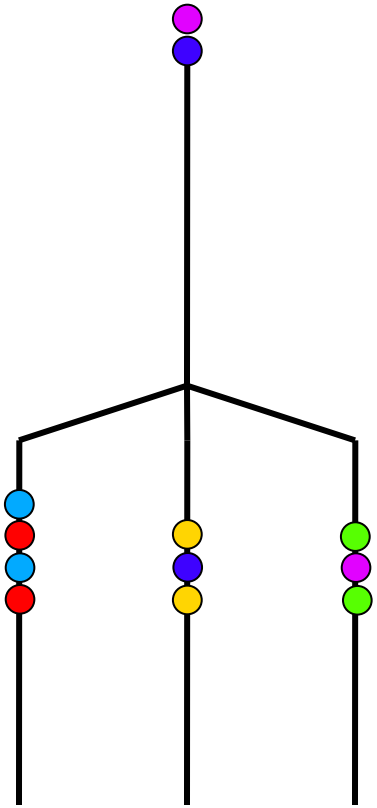

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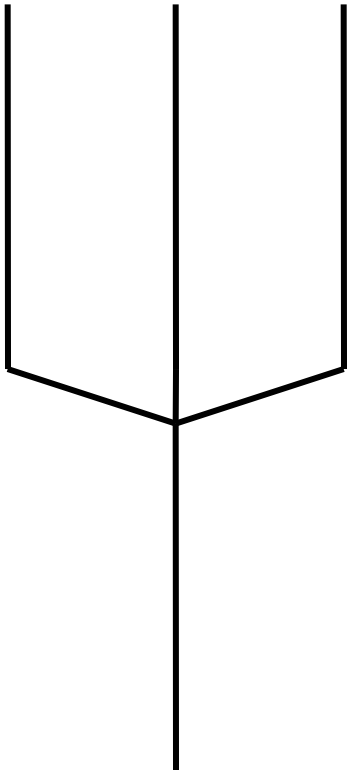

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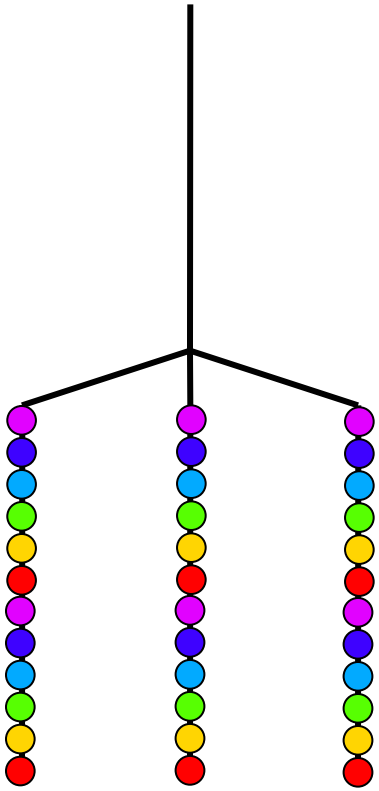

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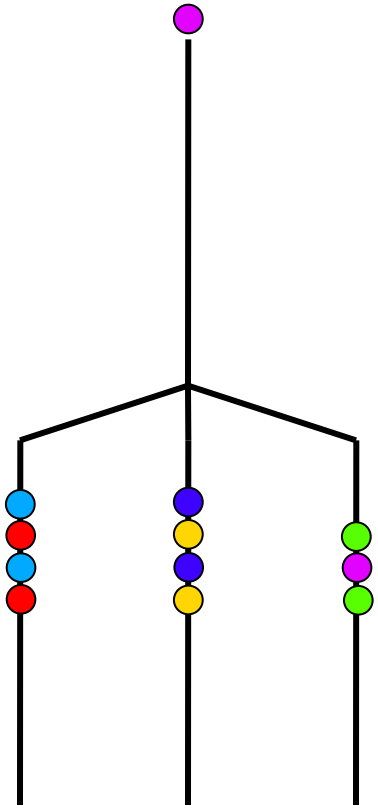

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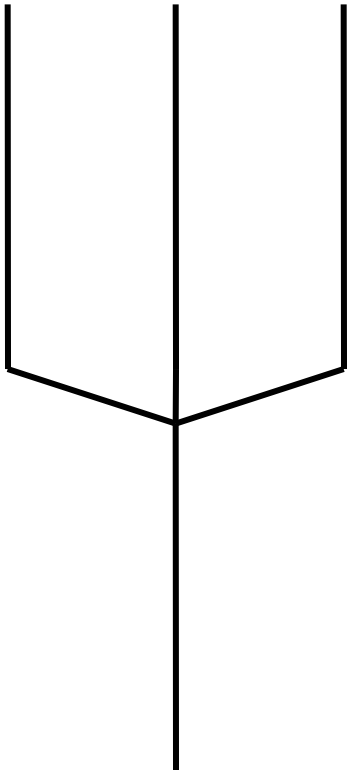

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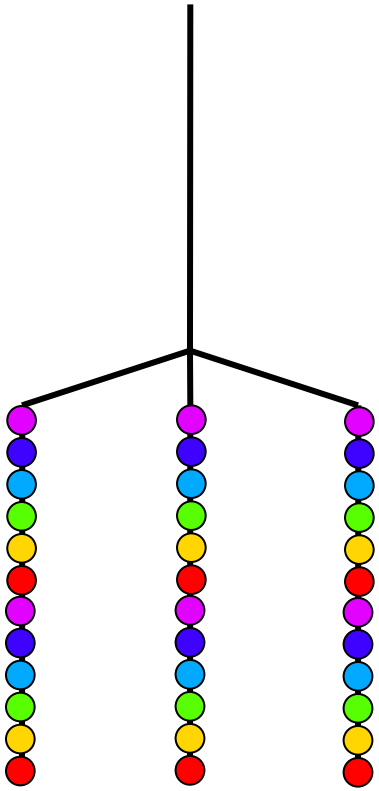

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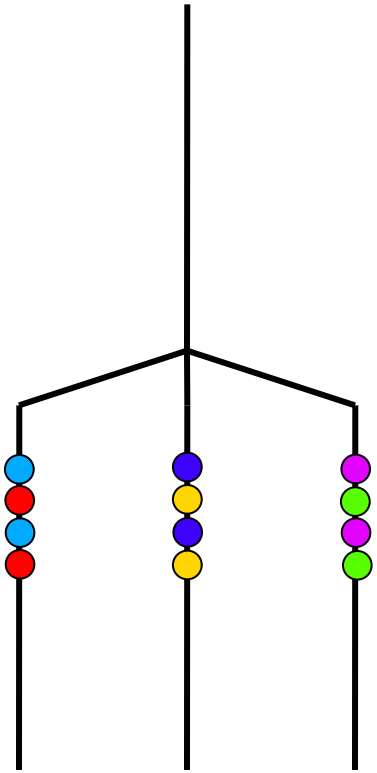

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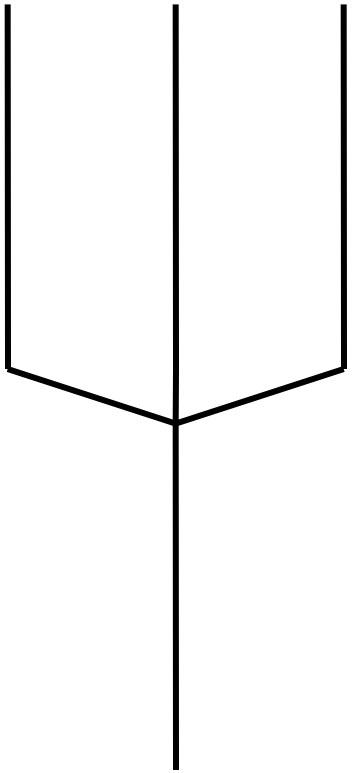

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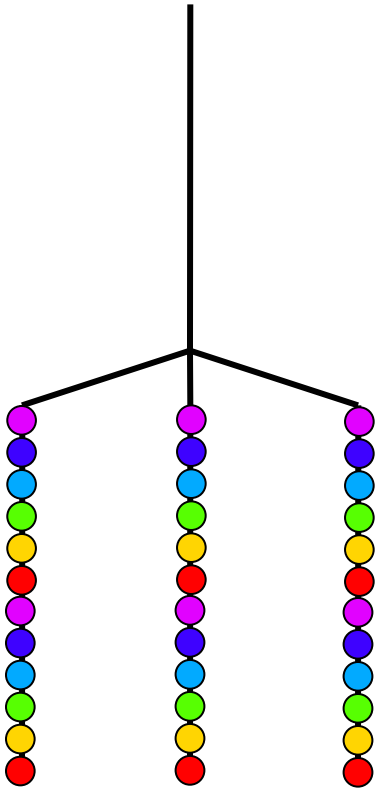

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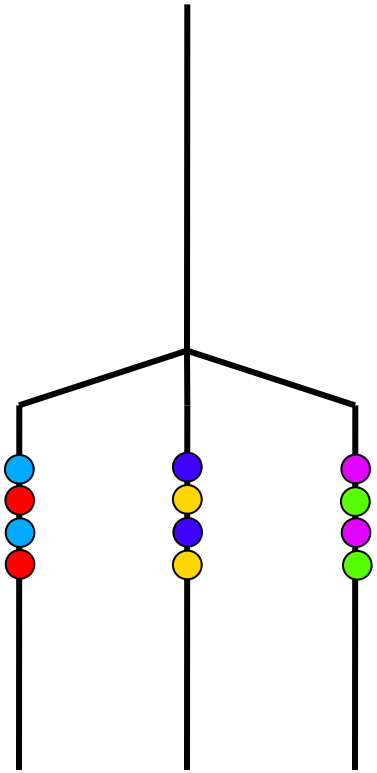

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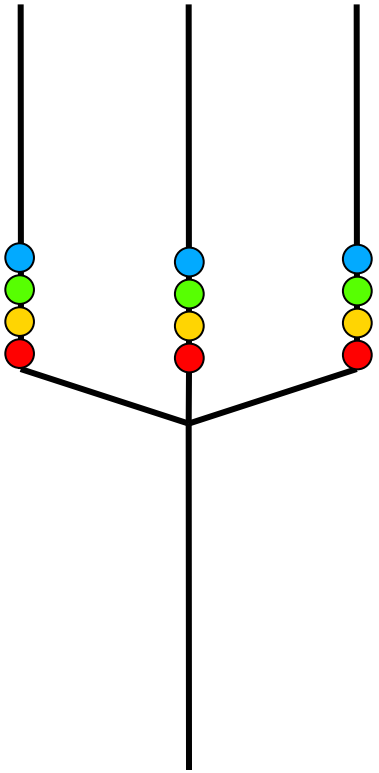

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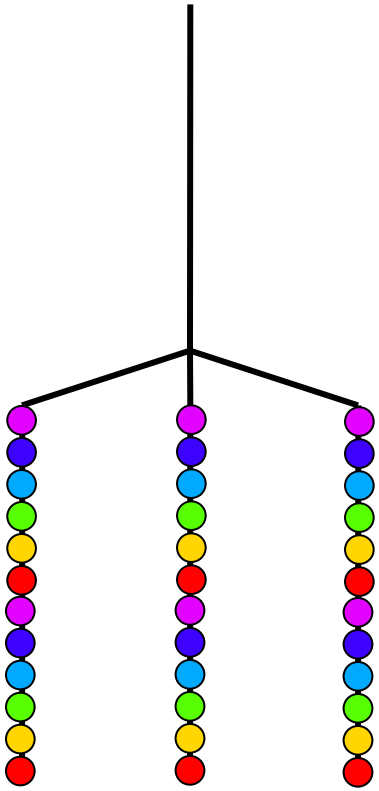

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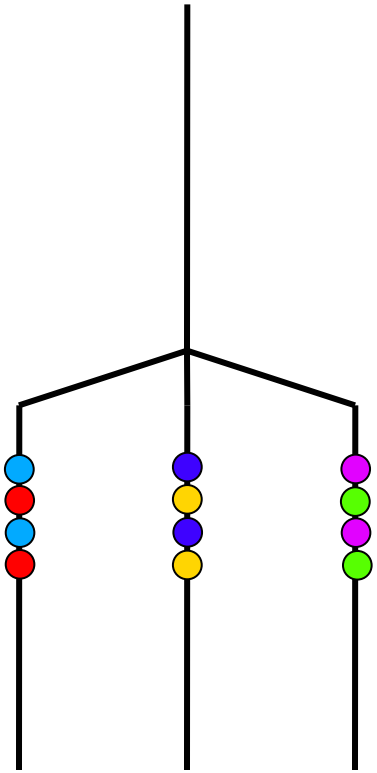

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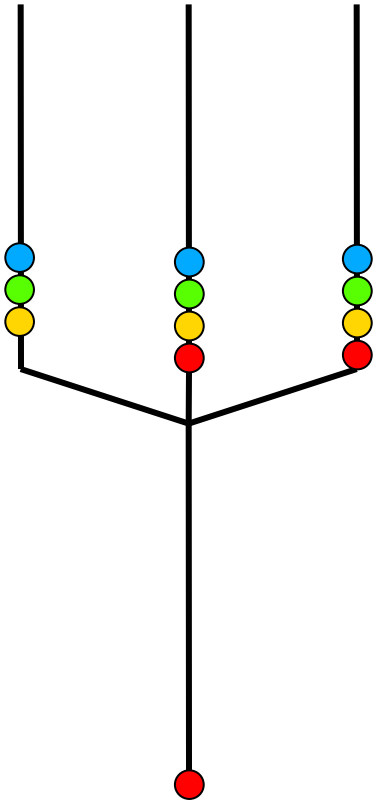

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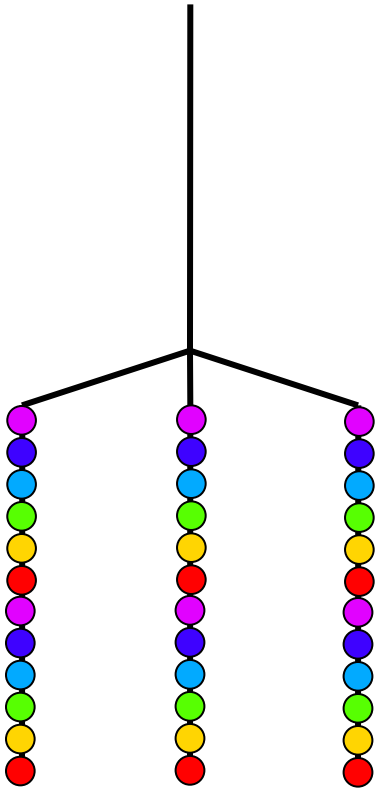

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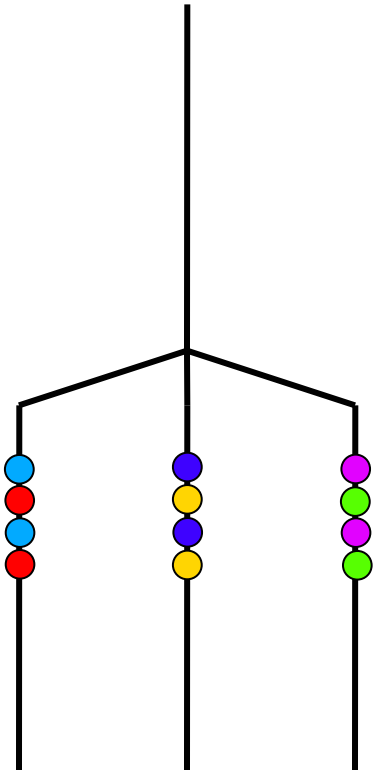

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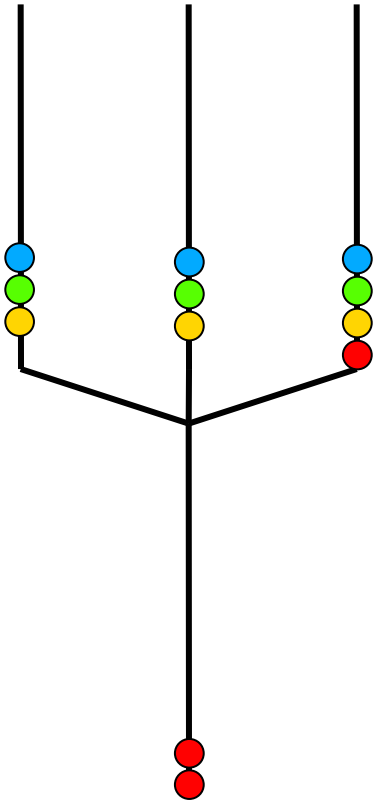

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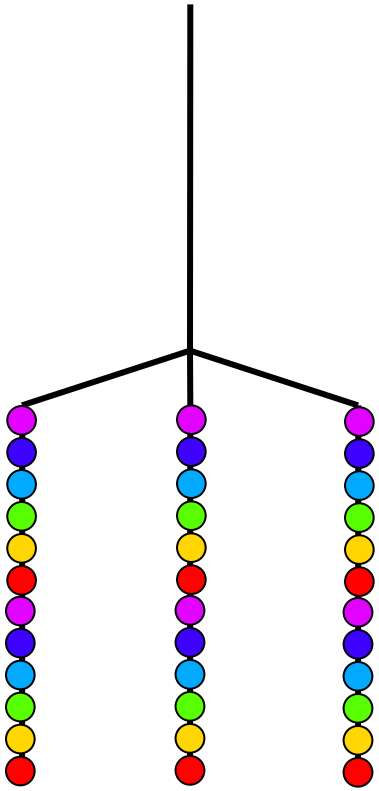

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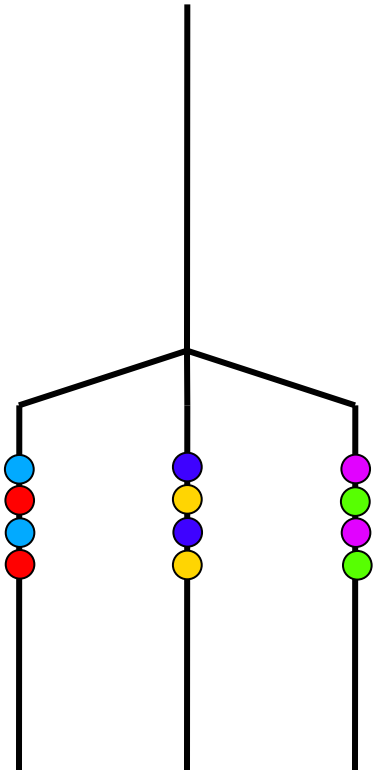

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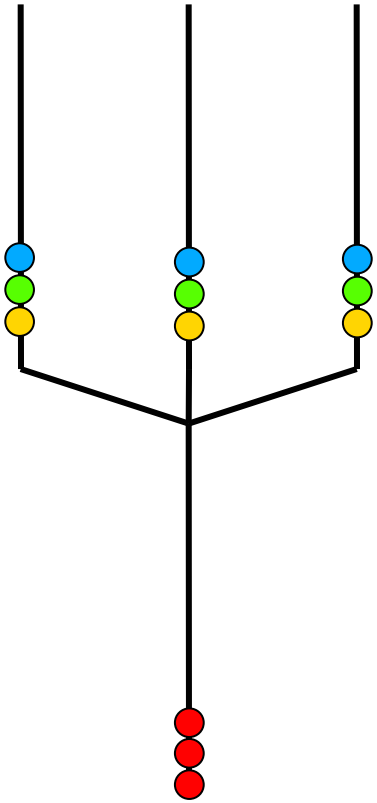

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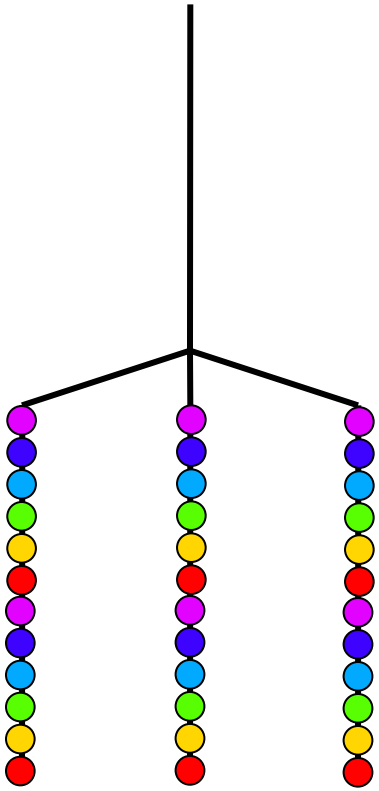

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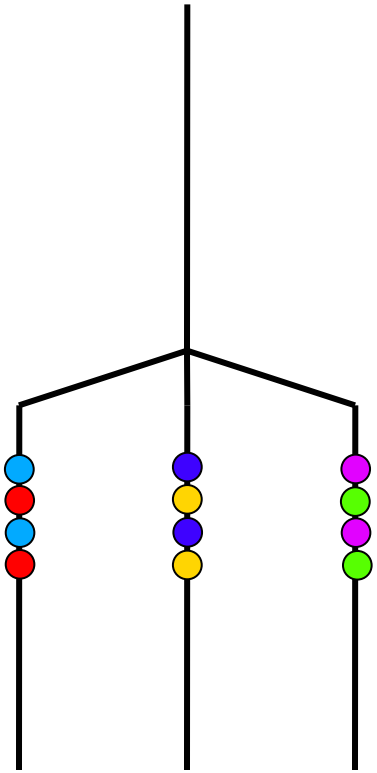

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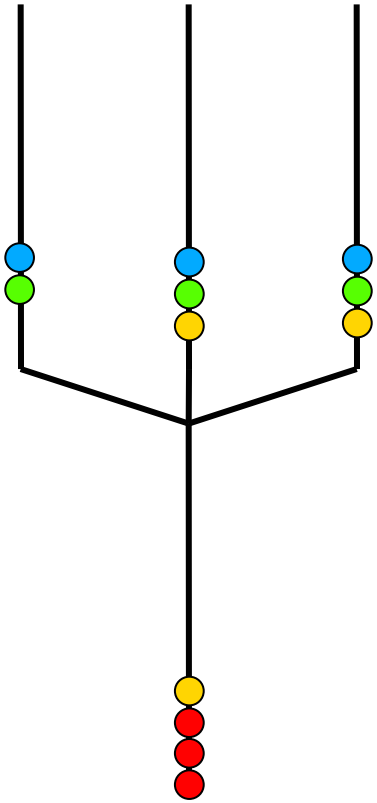

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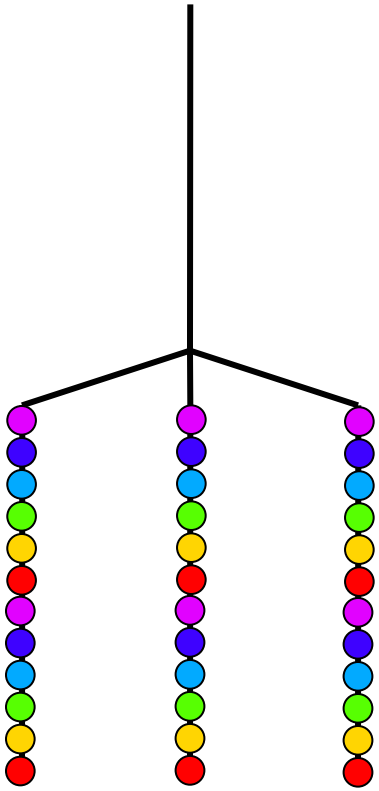

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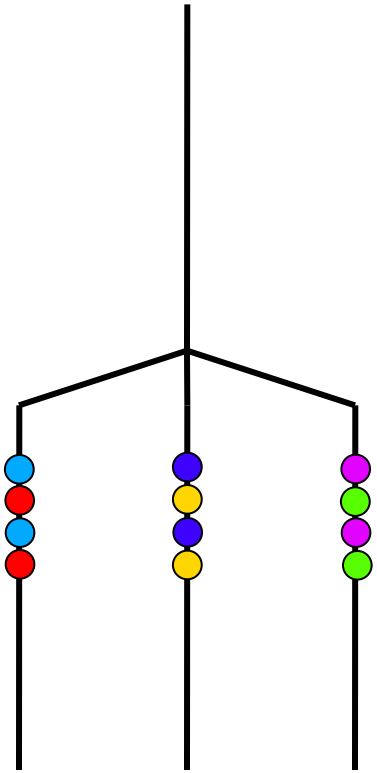

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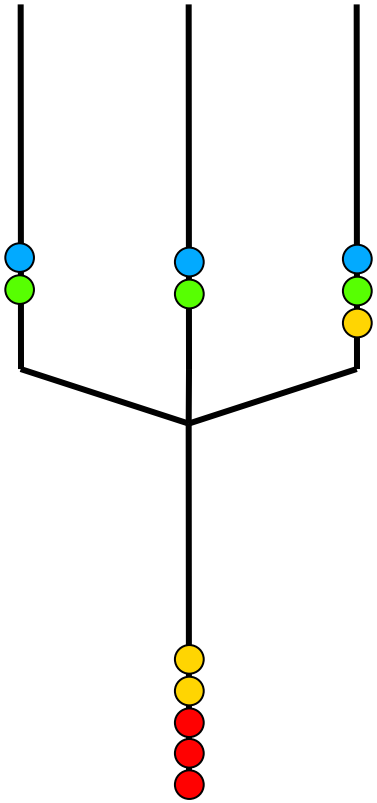

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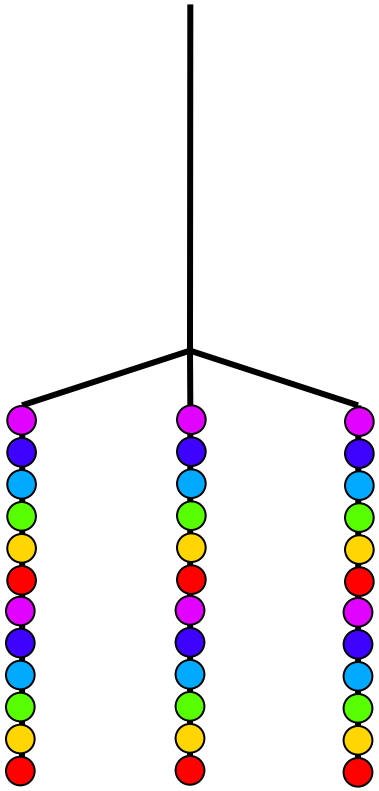

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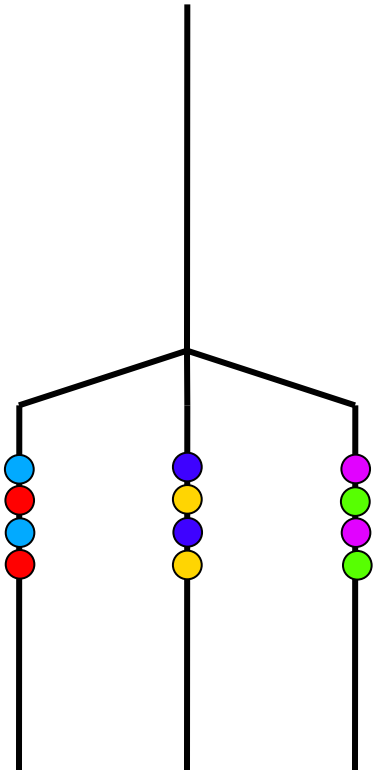

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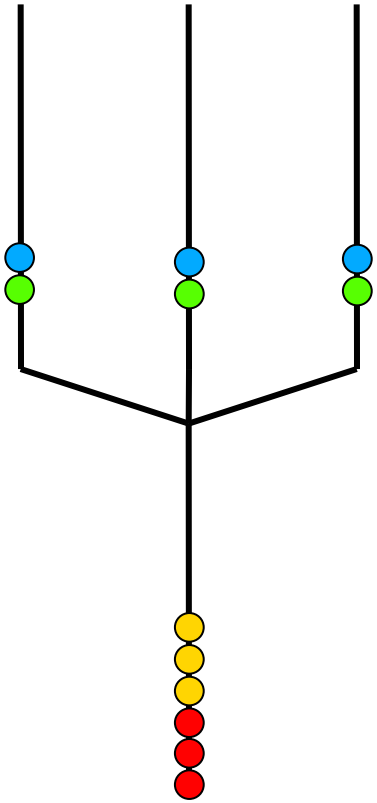

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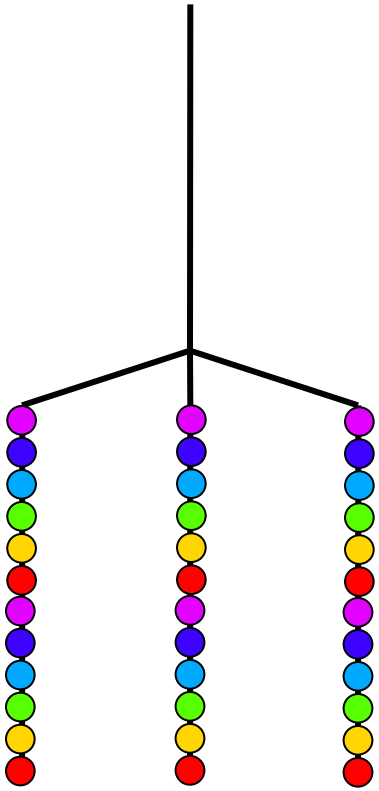

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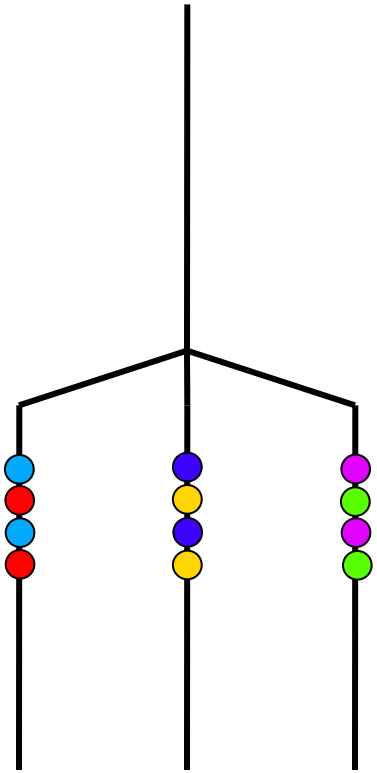

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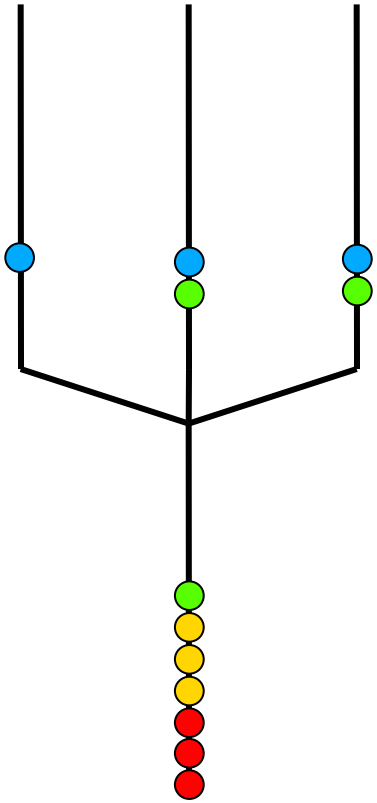

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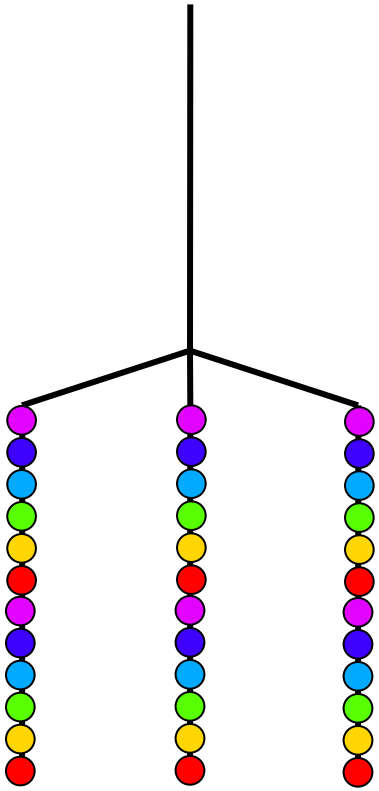

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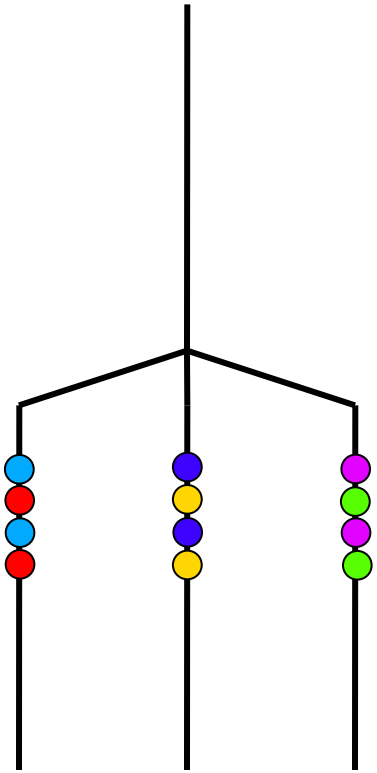

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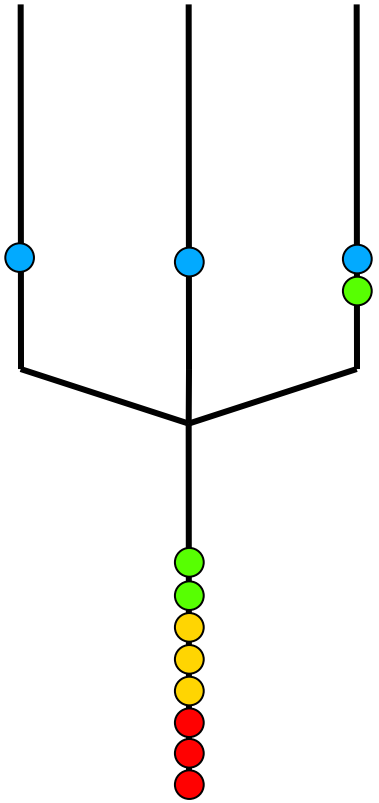

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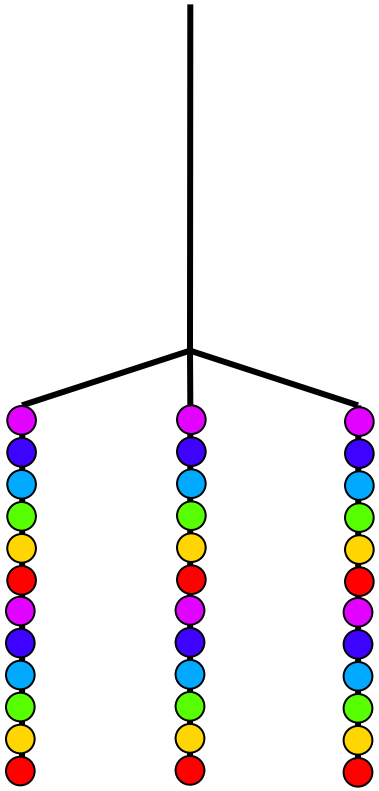

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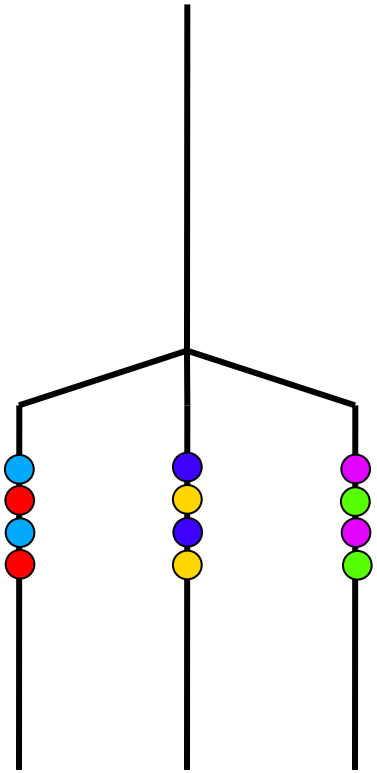

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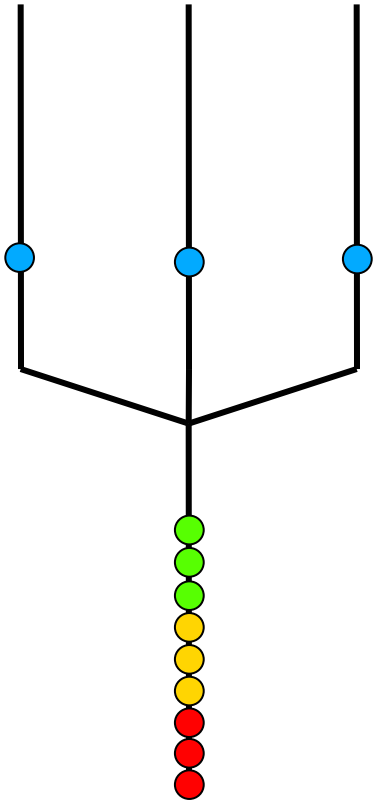

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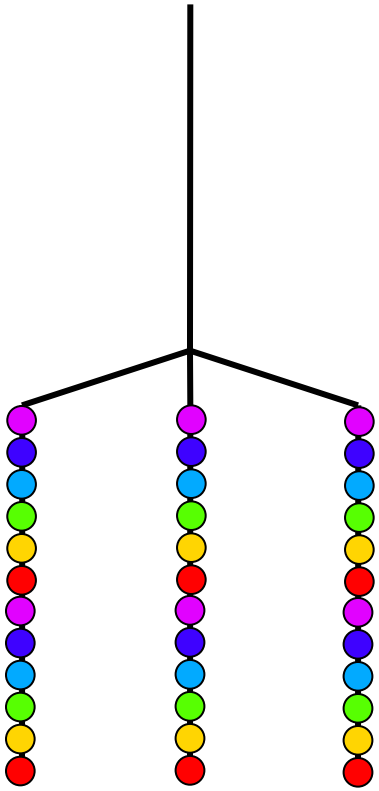

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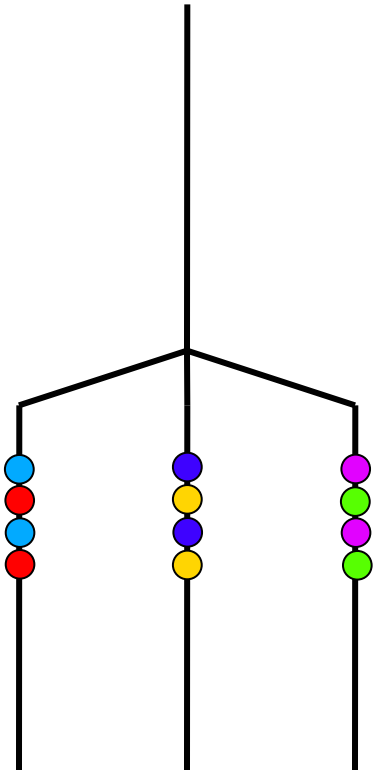

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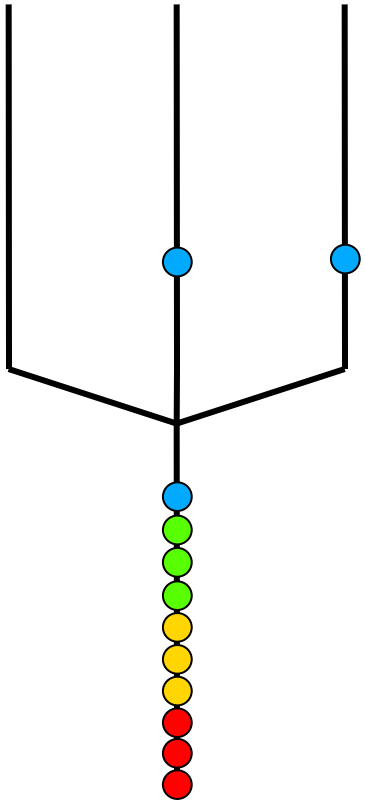

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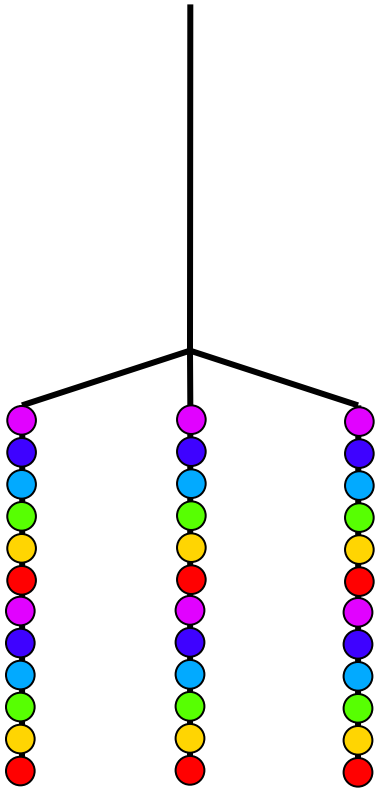

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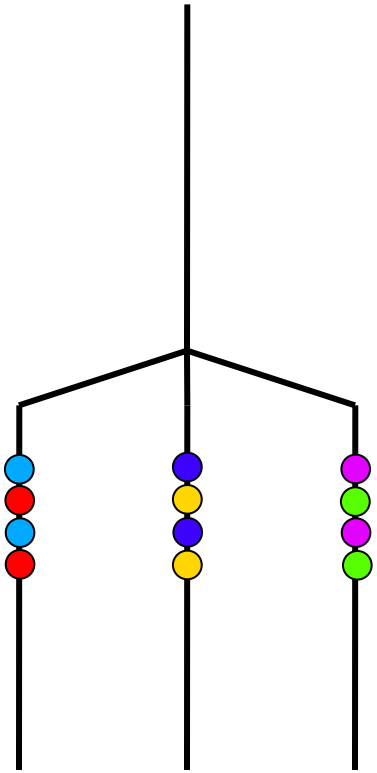

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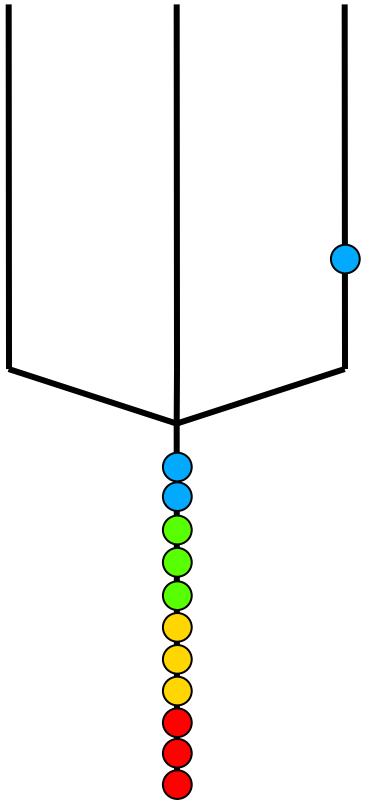

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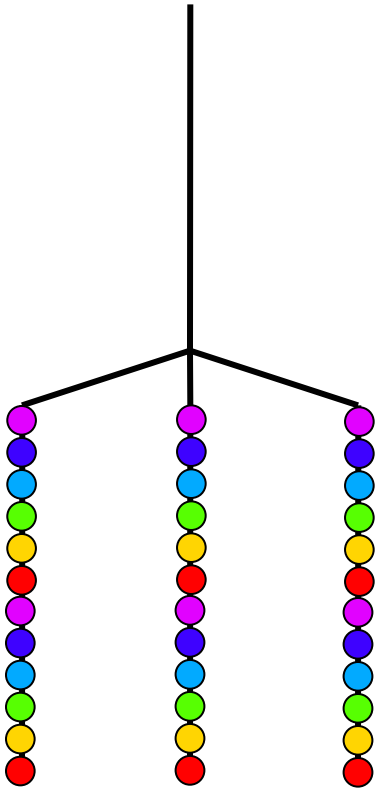

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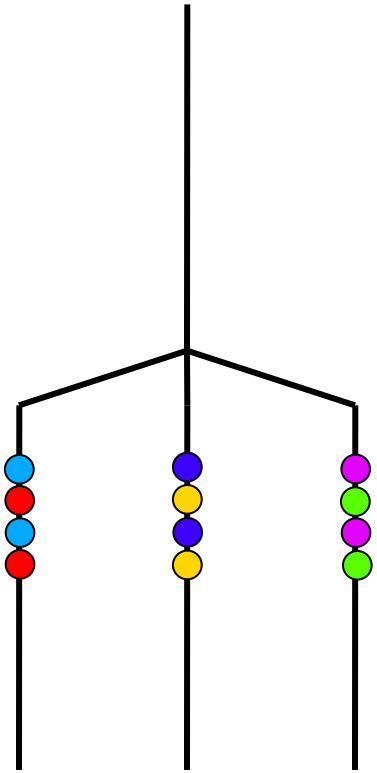

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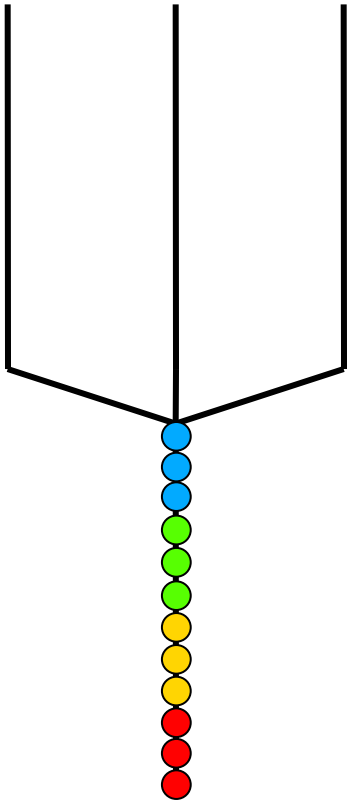

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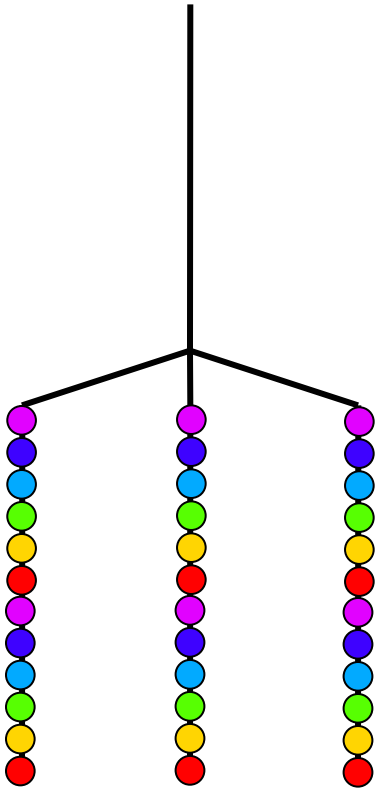

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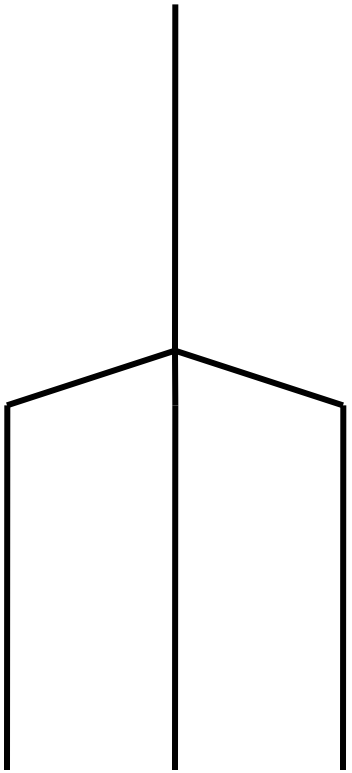

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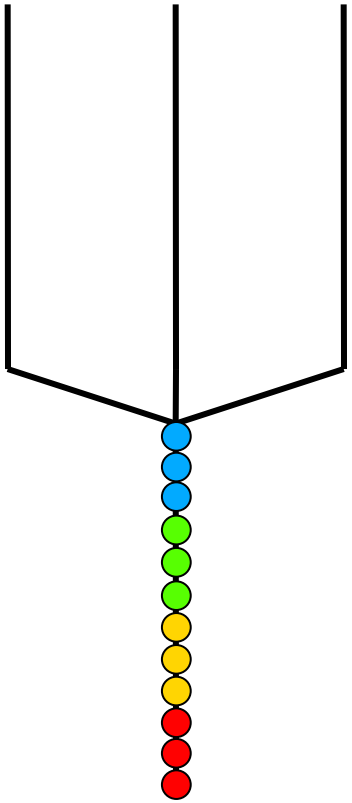

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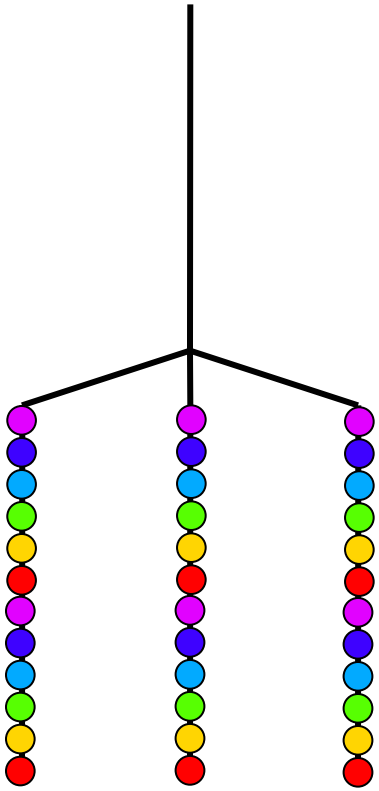

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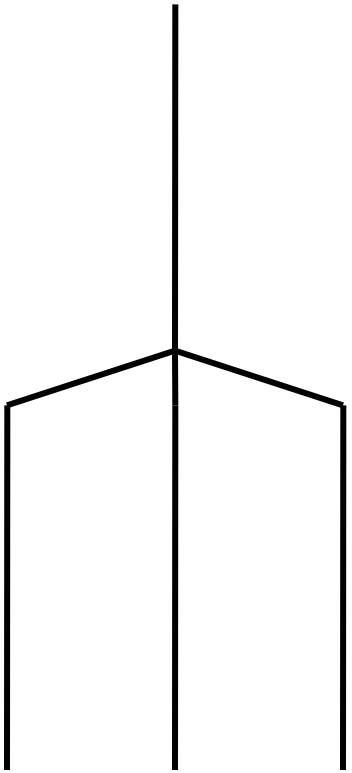

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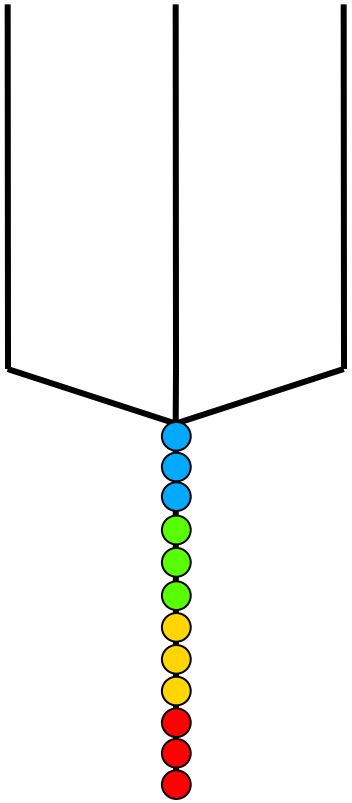

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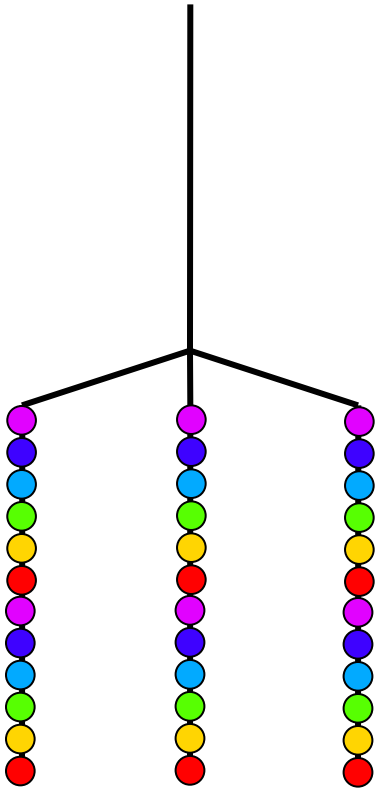

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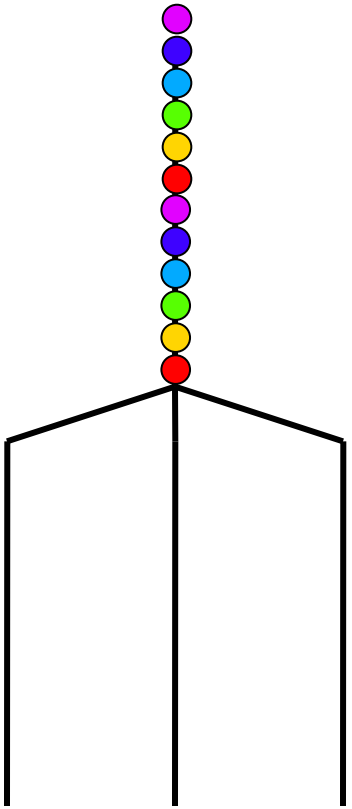

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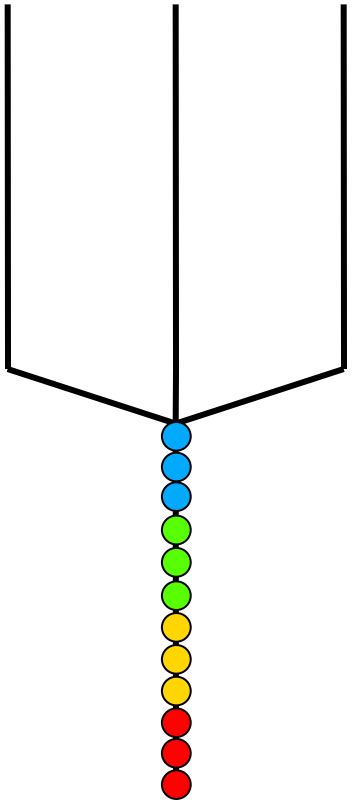

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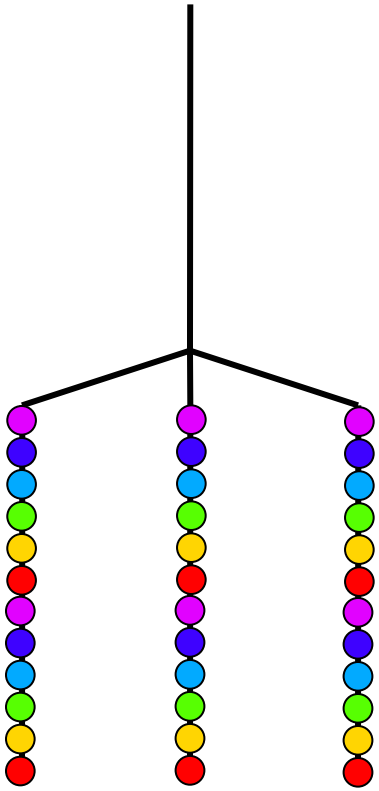

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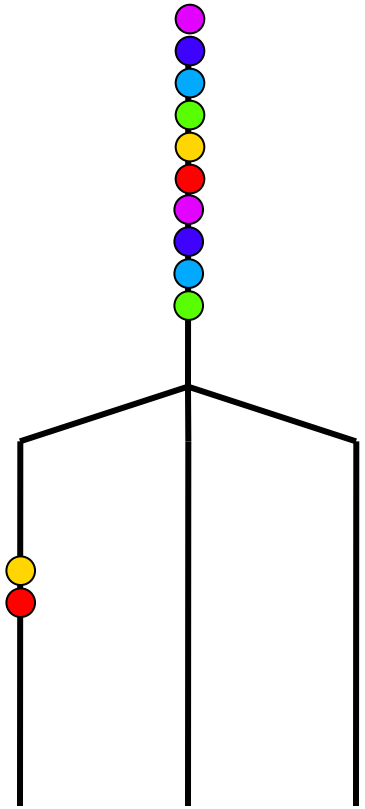

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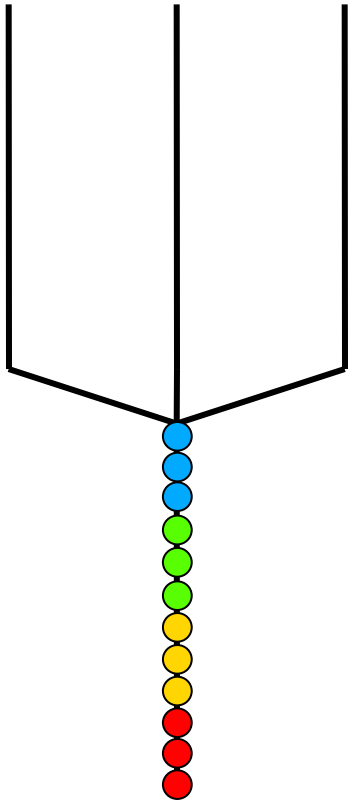

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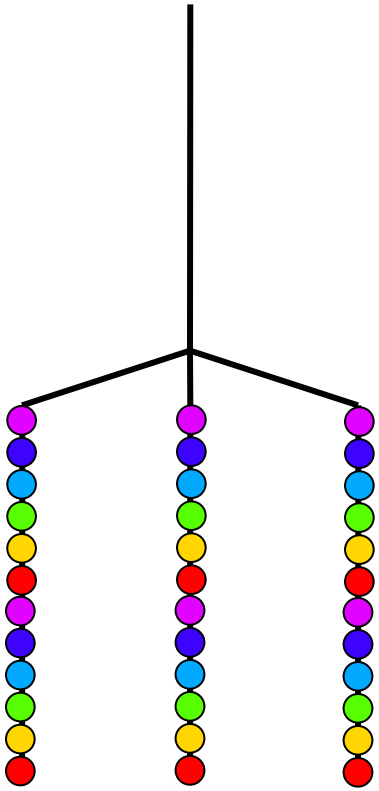

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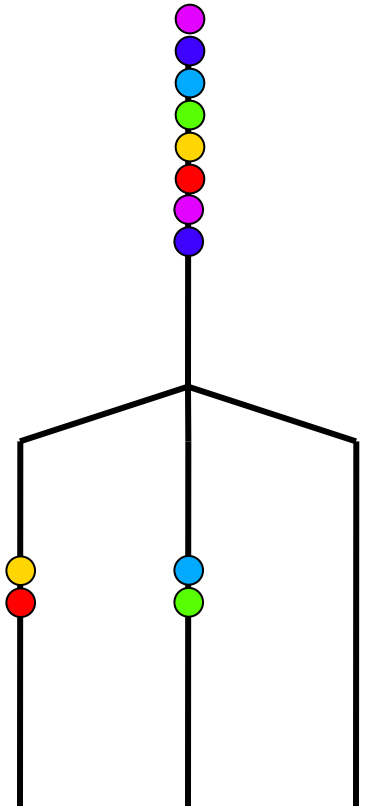

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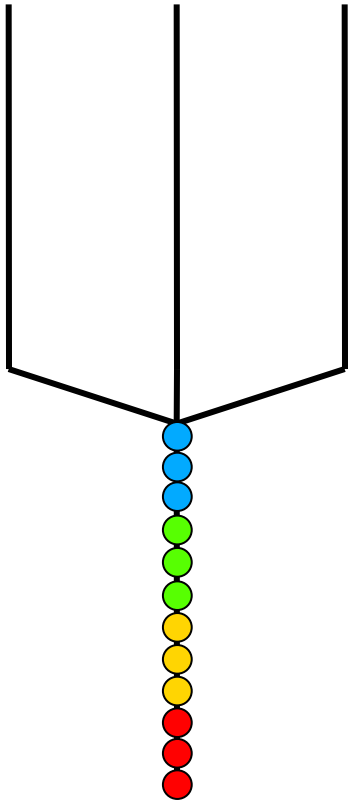

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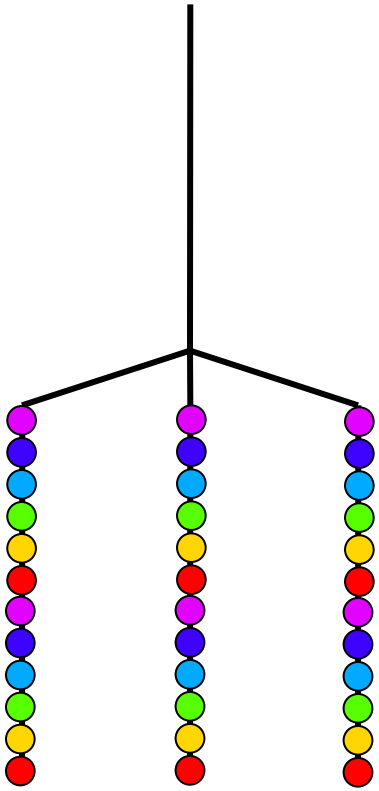

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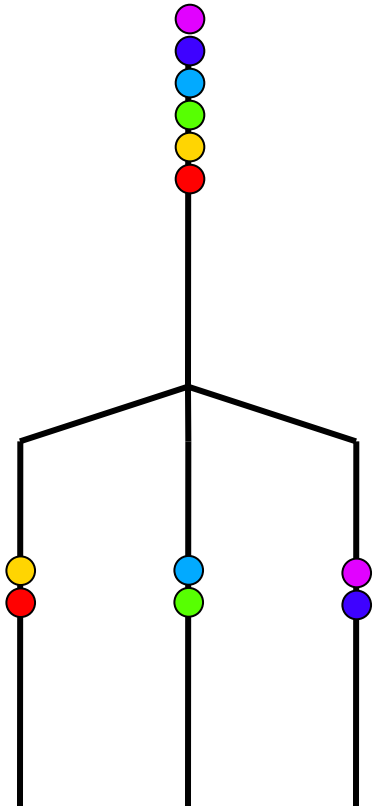

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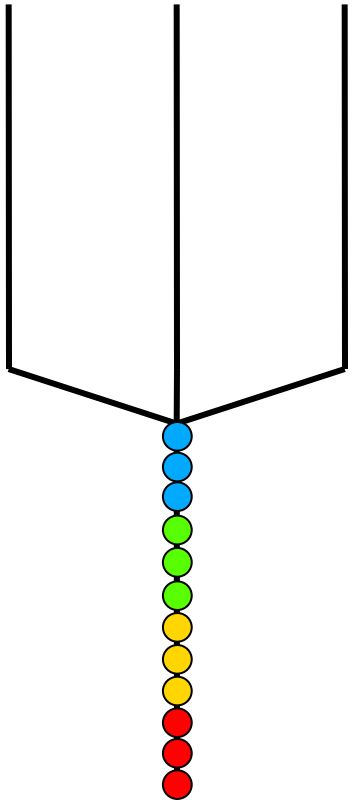

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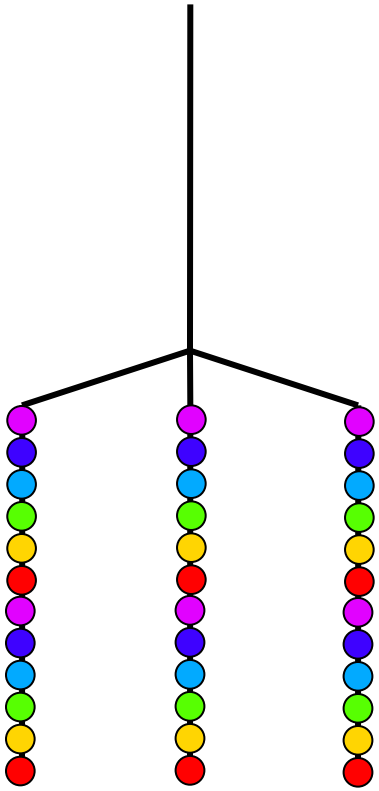

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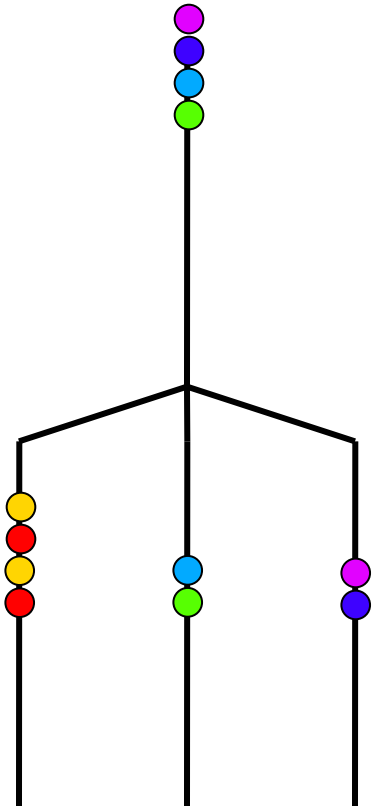

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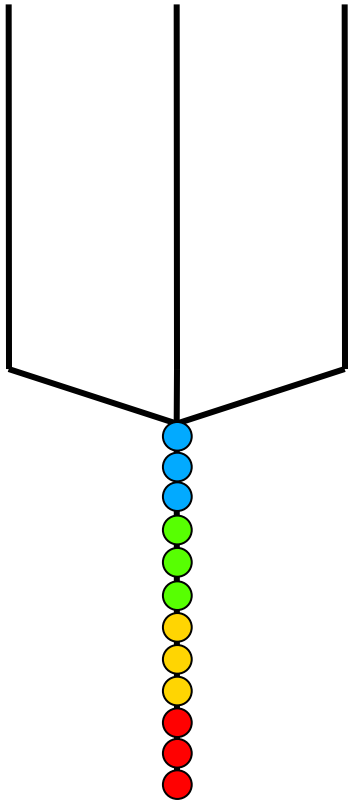

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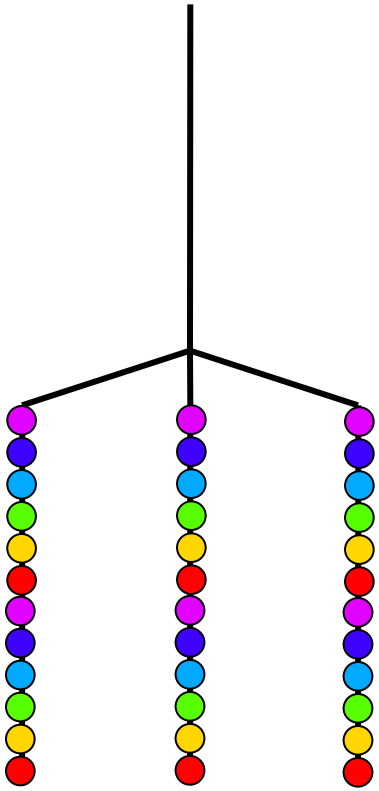

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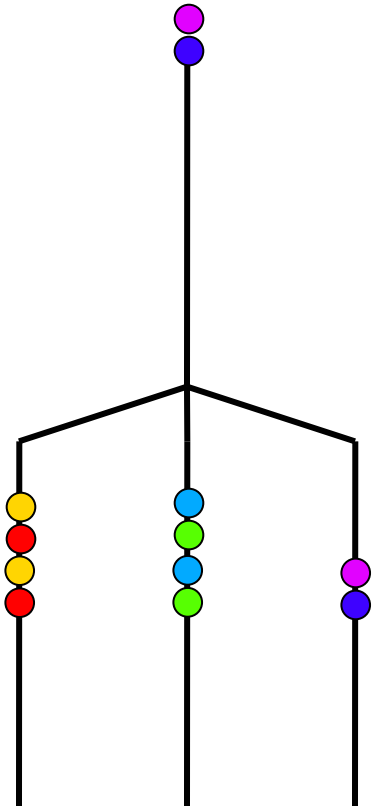

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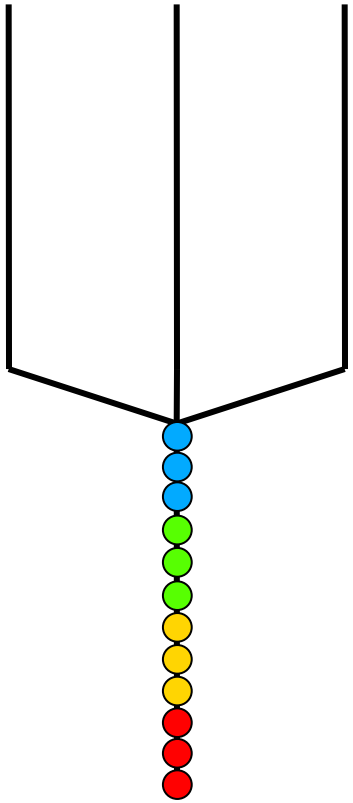
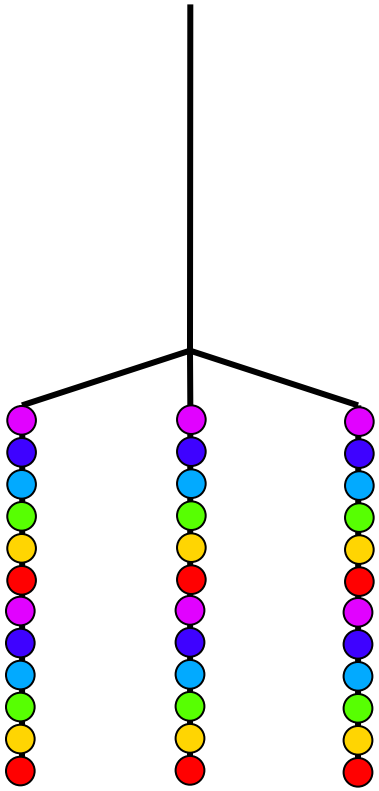
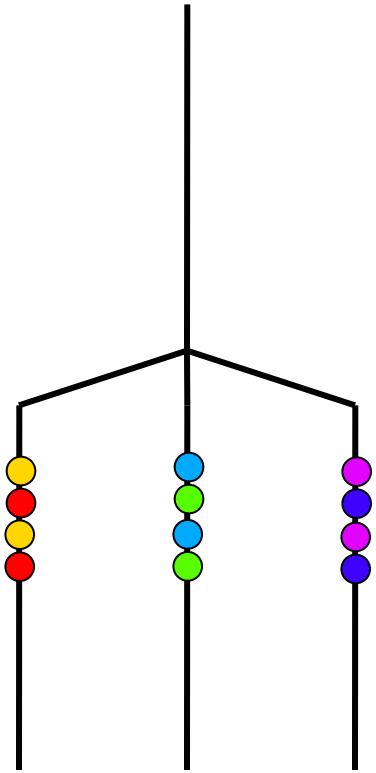


SplitJoins are Beautiful

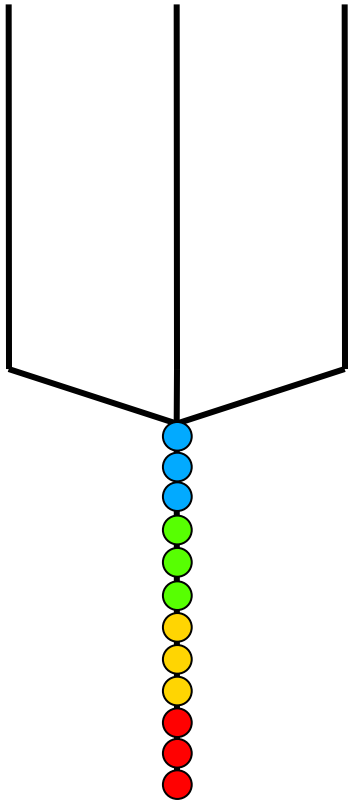
split duplicate



split roundrobin(2)



join roundrobin(1)



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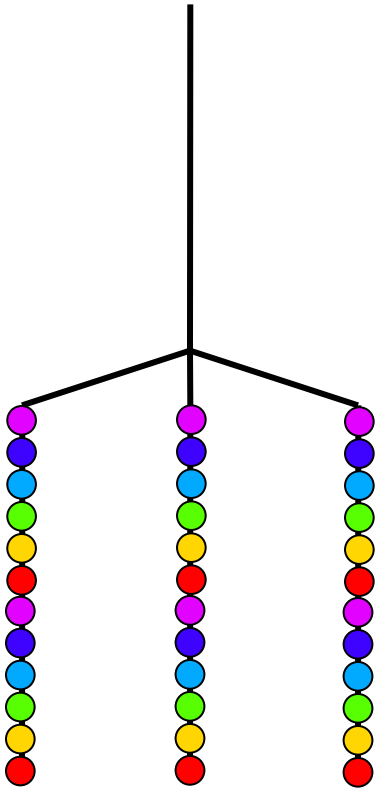

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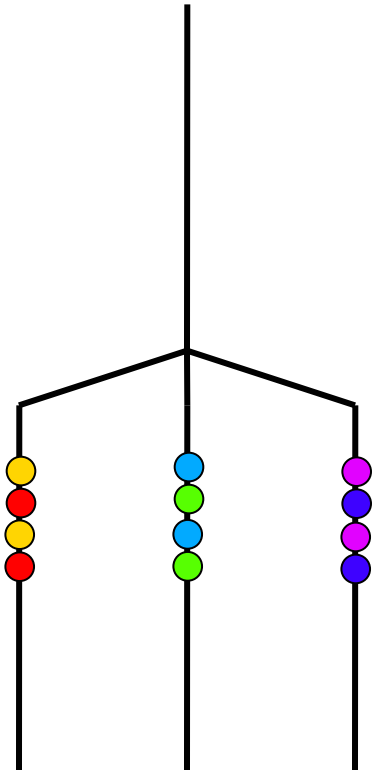

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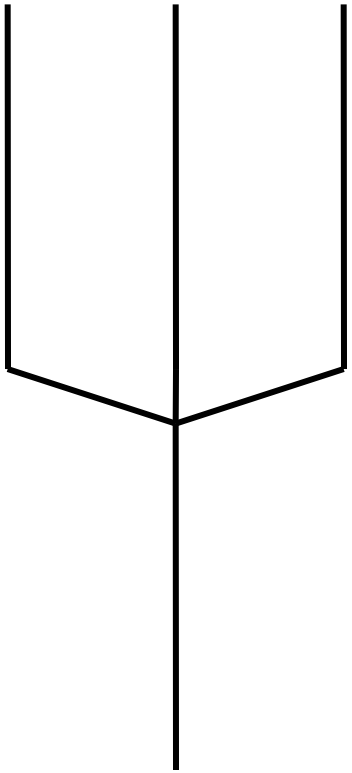

SplitJoins are Beautiful

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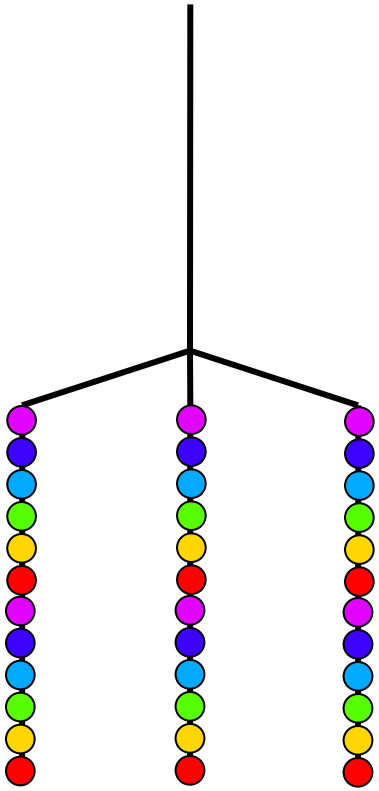
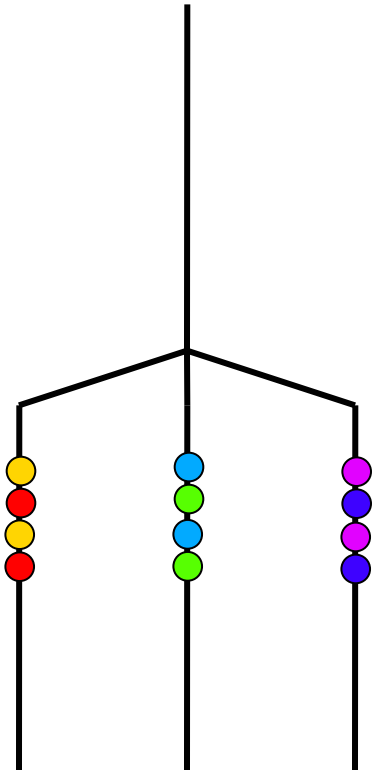
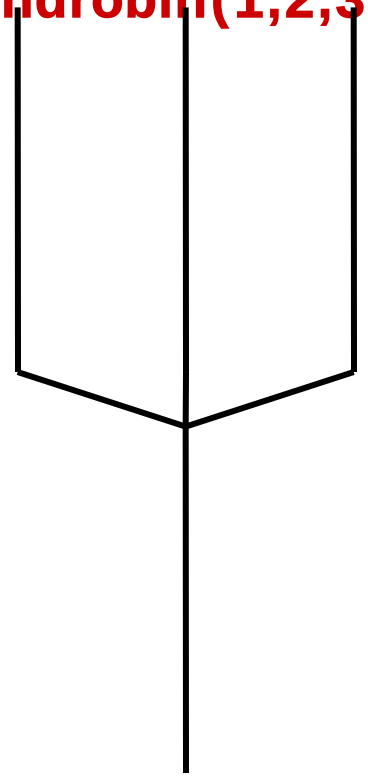


split roundrobin(2)



join roundrobin(1,2,3)



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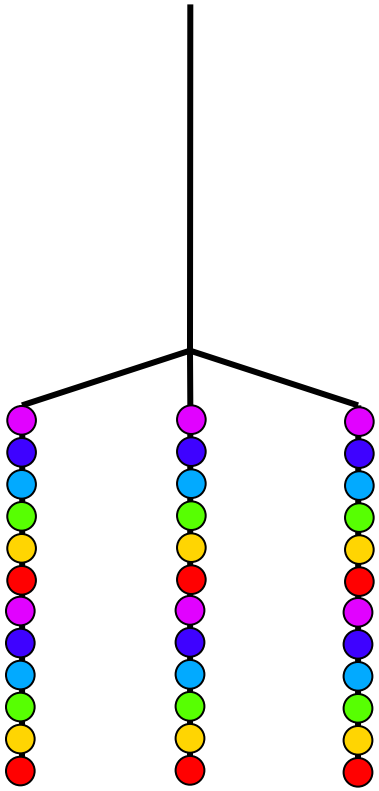
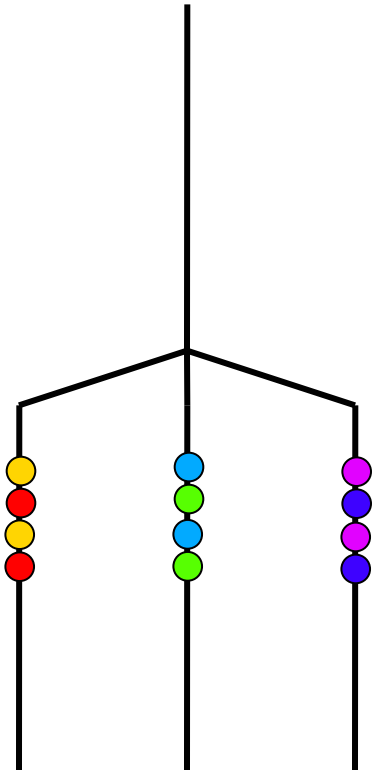
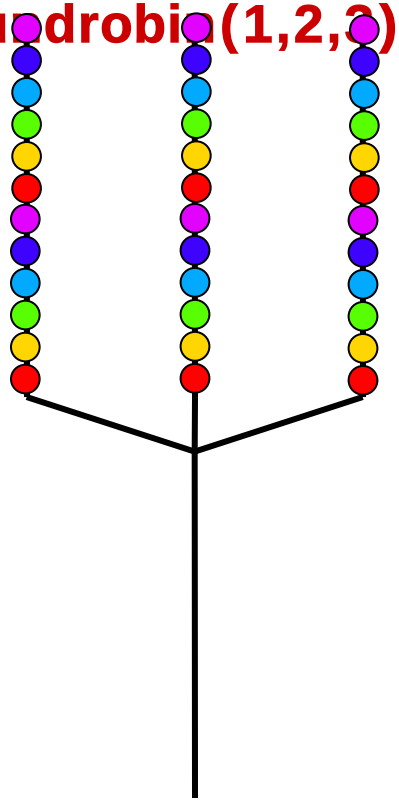
split duplicate



split roundrobin(2)

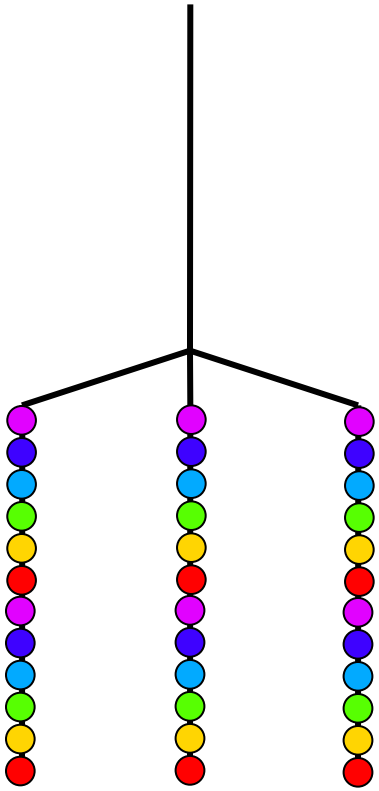


join roundrobin(1,2,3)

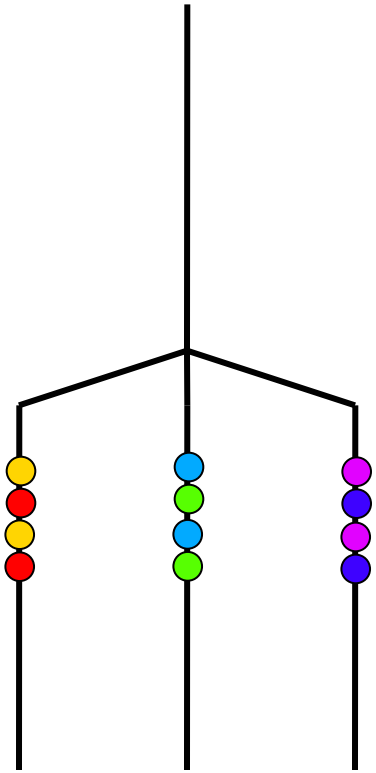


SplitJoins are Beautiful

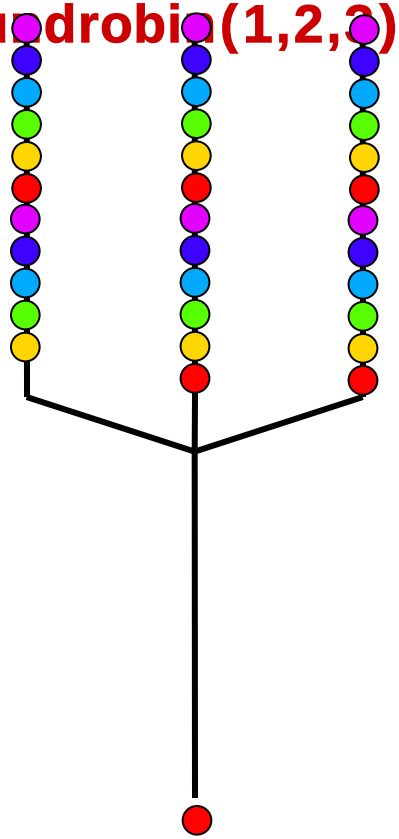
split duplicate



split roundrobin(2)

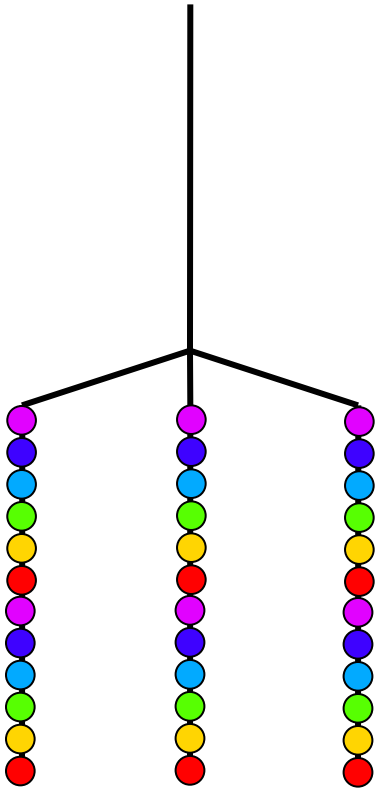


join roundrobin(1,2,3)



SplitJoins are Beautiful

split duplicate



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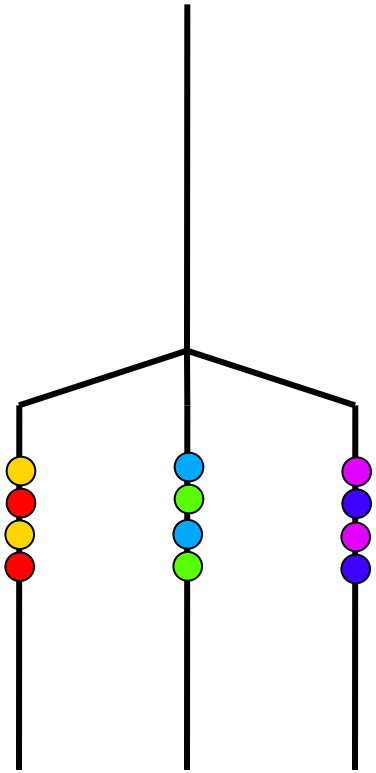
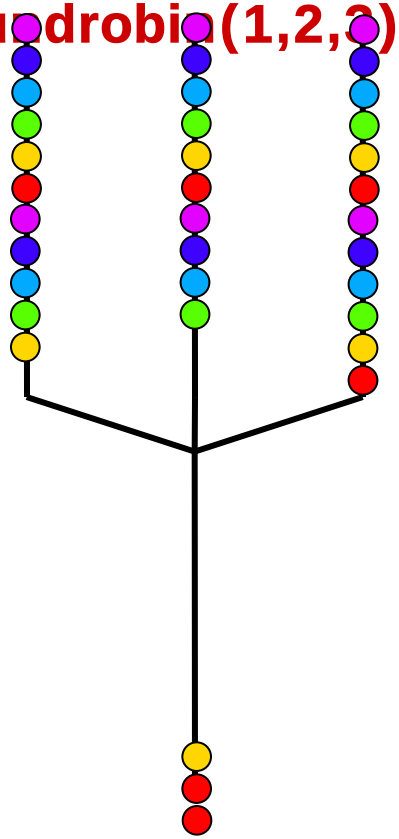
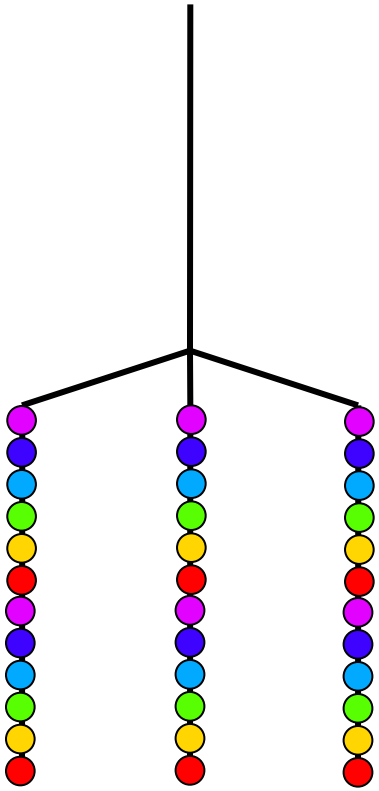


join roundrobin(1,2,3)

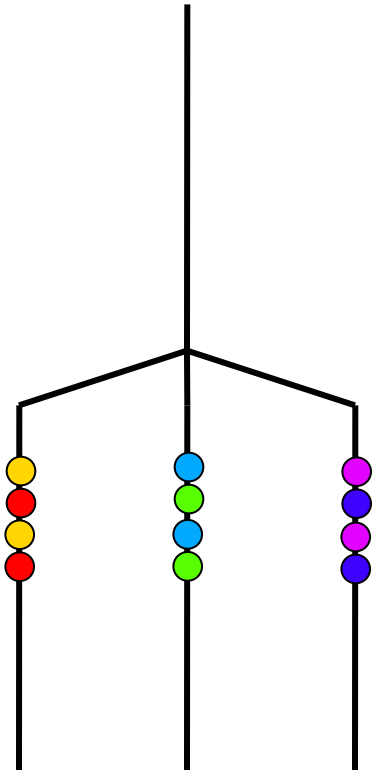


SplitJoins are Beautiful

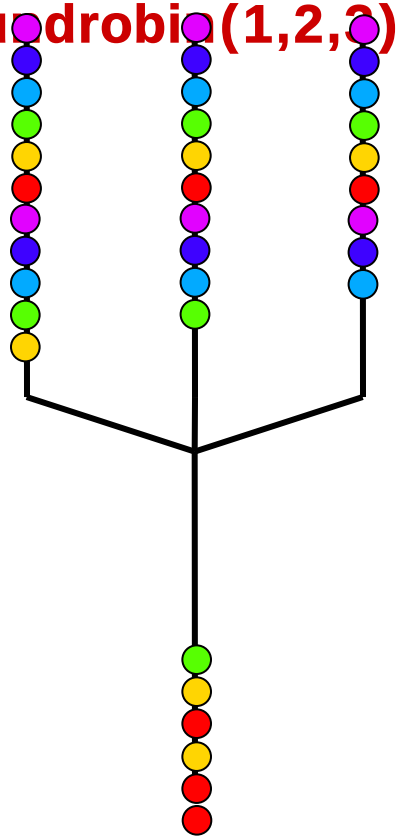
split duplicate



split roundrobin(2)

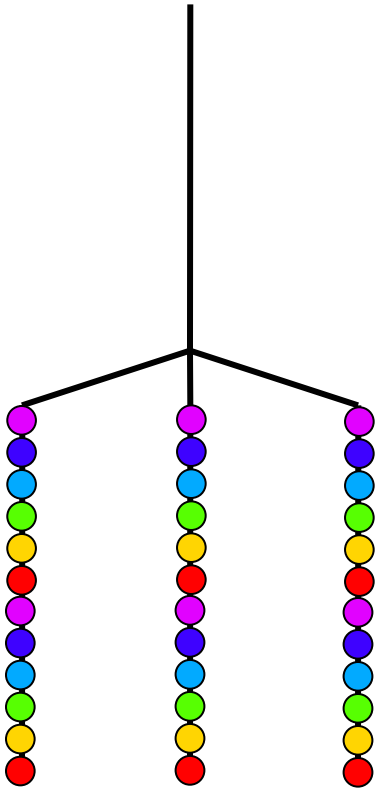


join roundrobin(1,2,3)

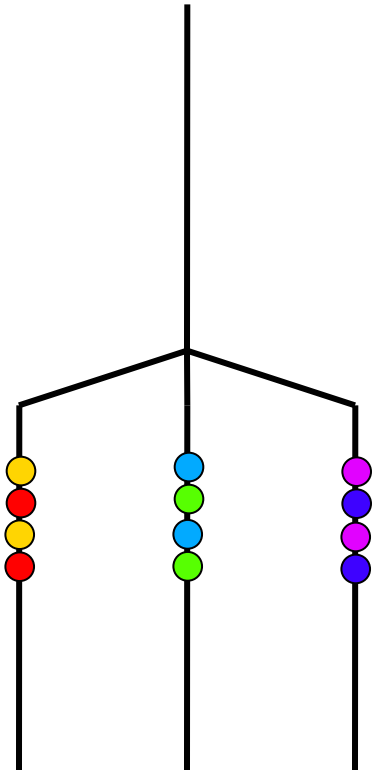


SplitJoins are Beautiful

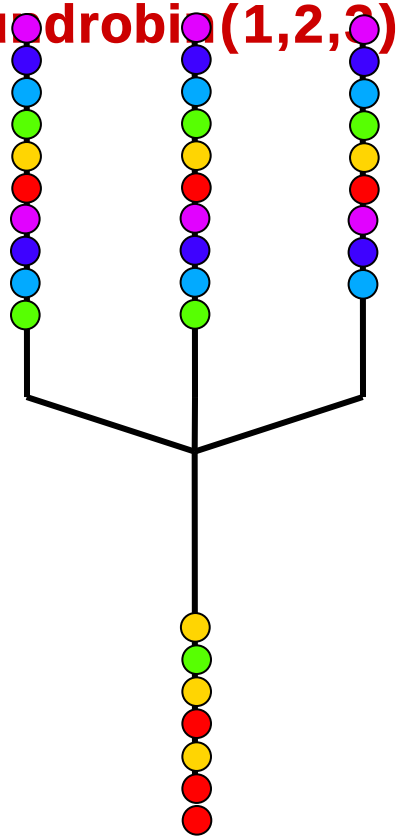
split duplicate



split roundrobin(2)

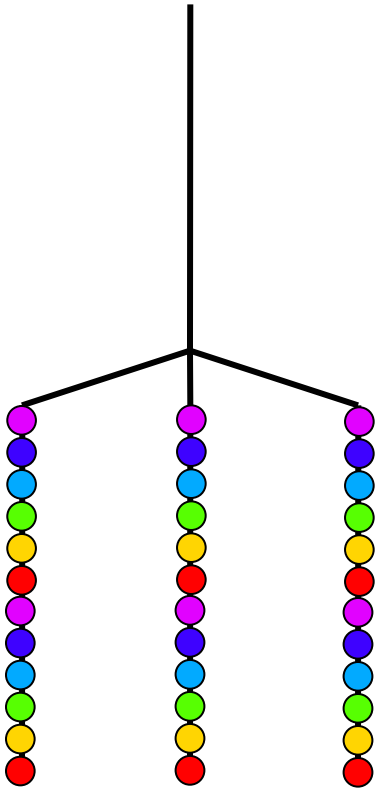


join roundrobin(1,2,3)



SplitJoins are Beautiful

split duplicate



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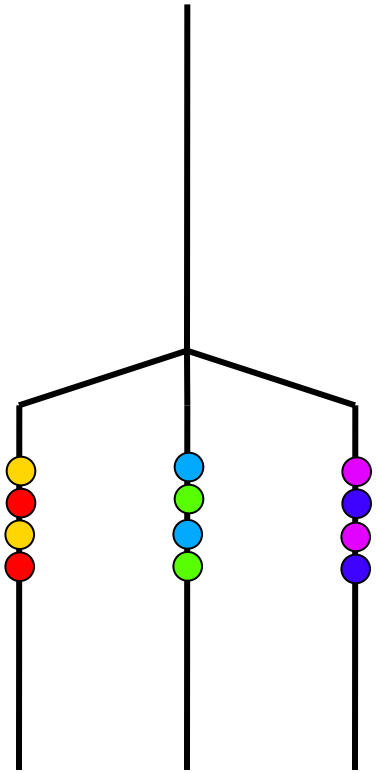
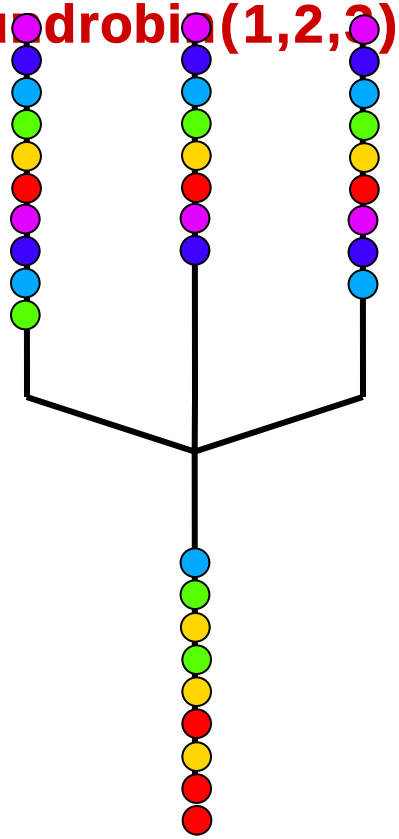


join roundrobin(1,2,3)



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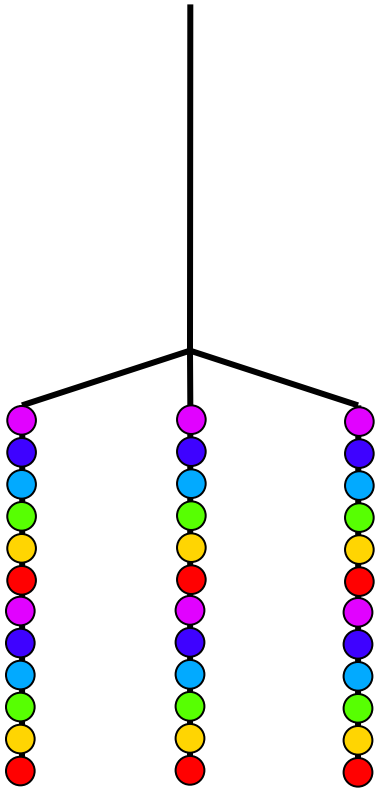

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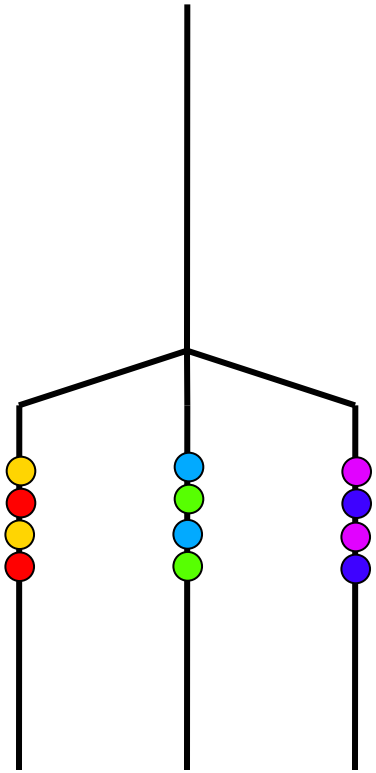
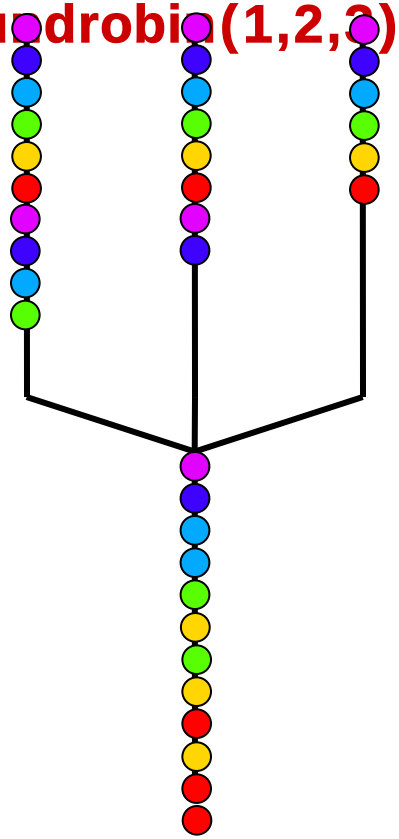
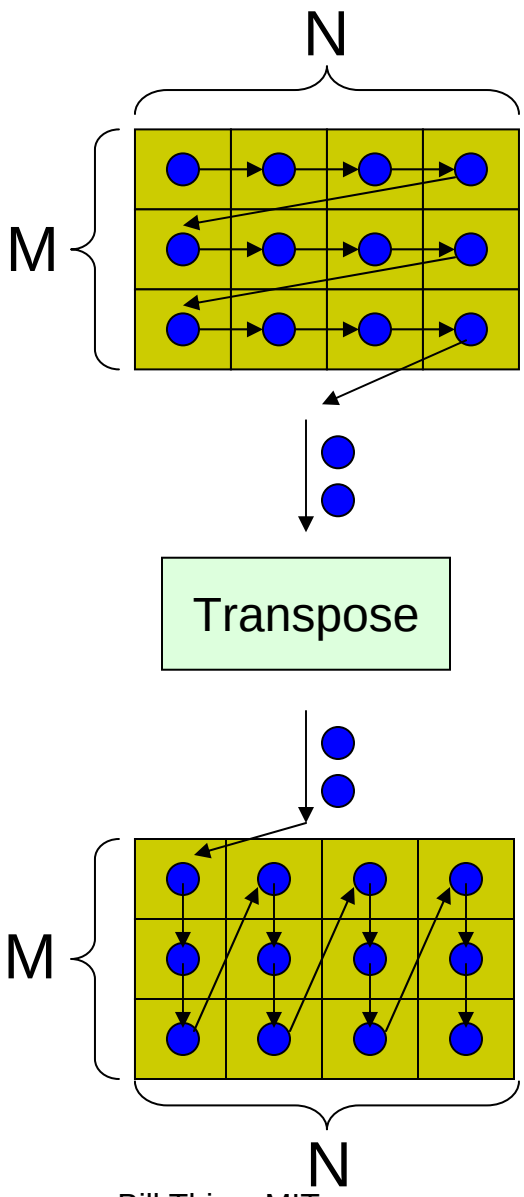


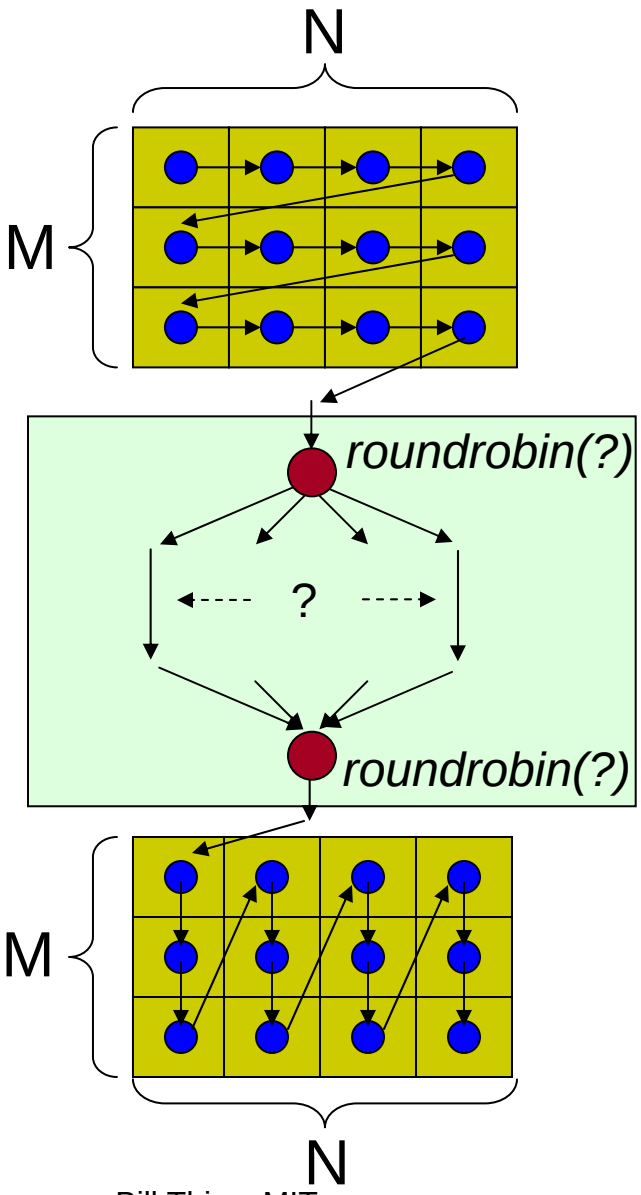
join roundrobin(1,2,3)



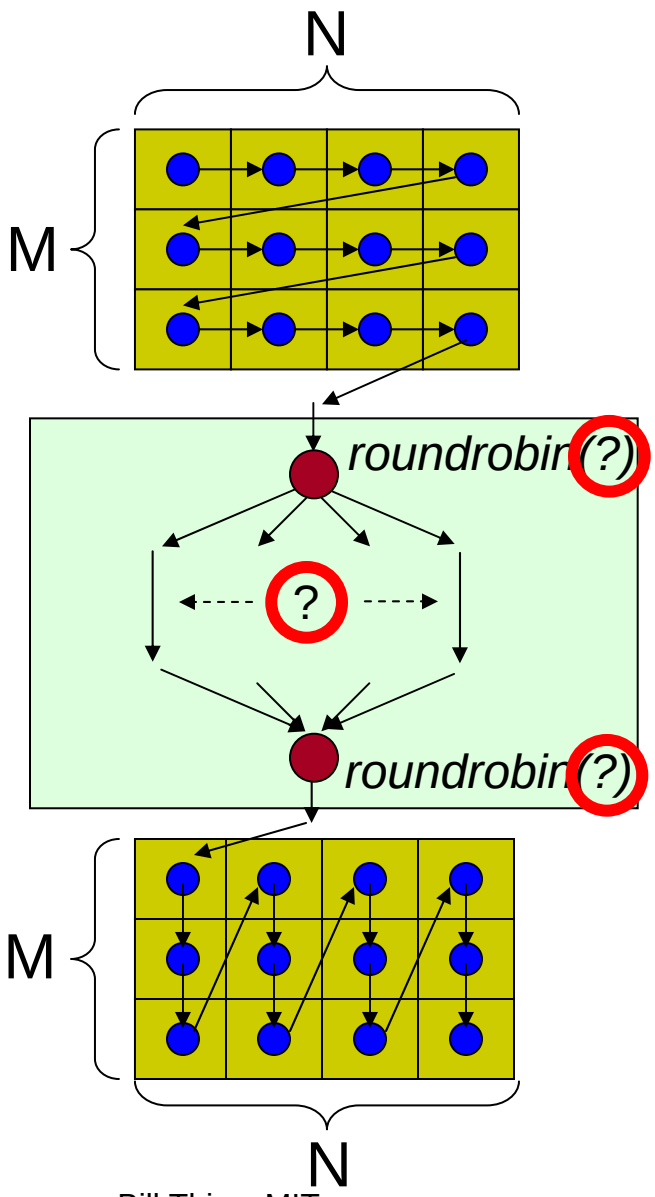
Matrix Transpose



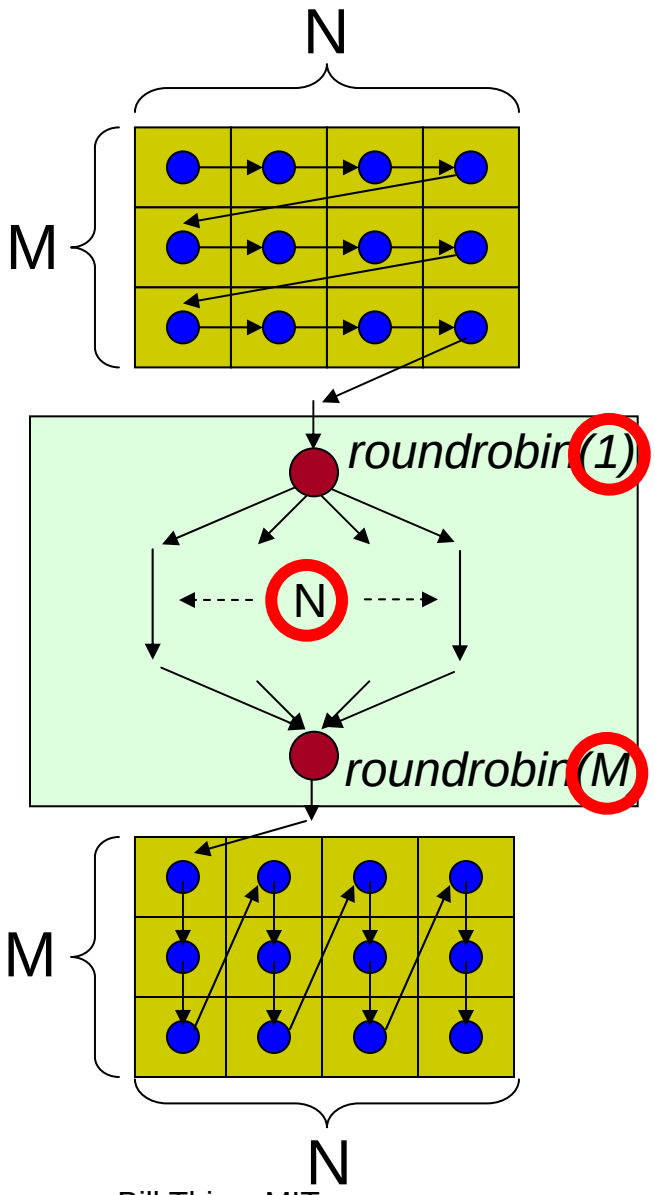
Matrix Transpose



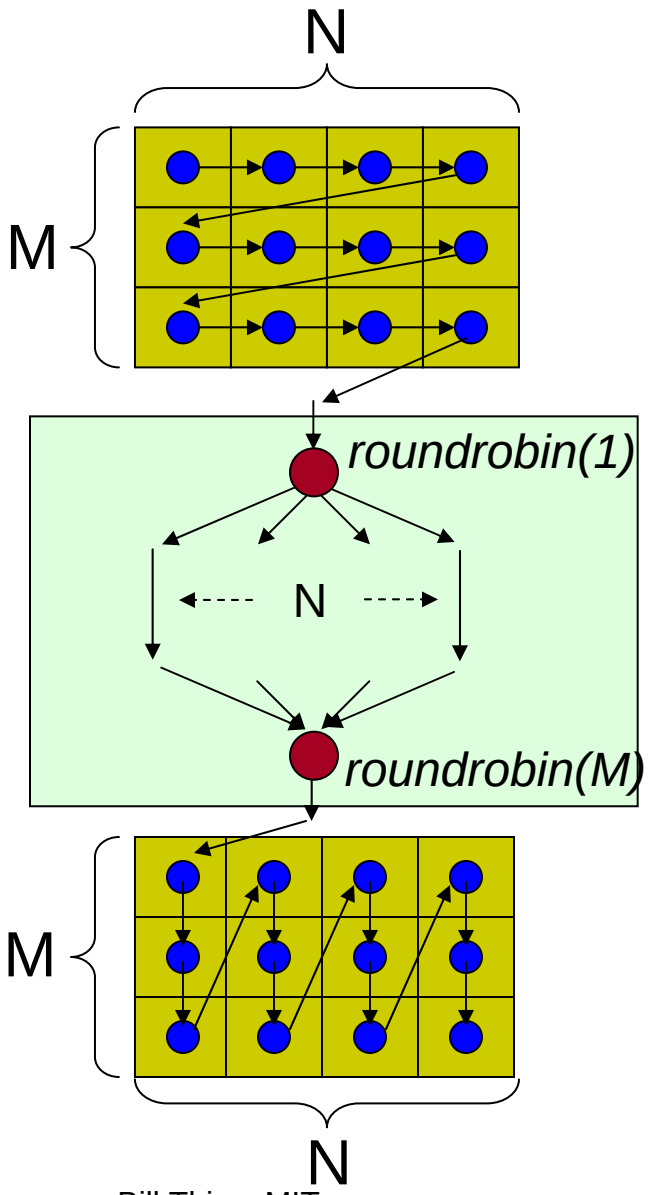
Matrix Transpose



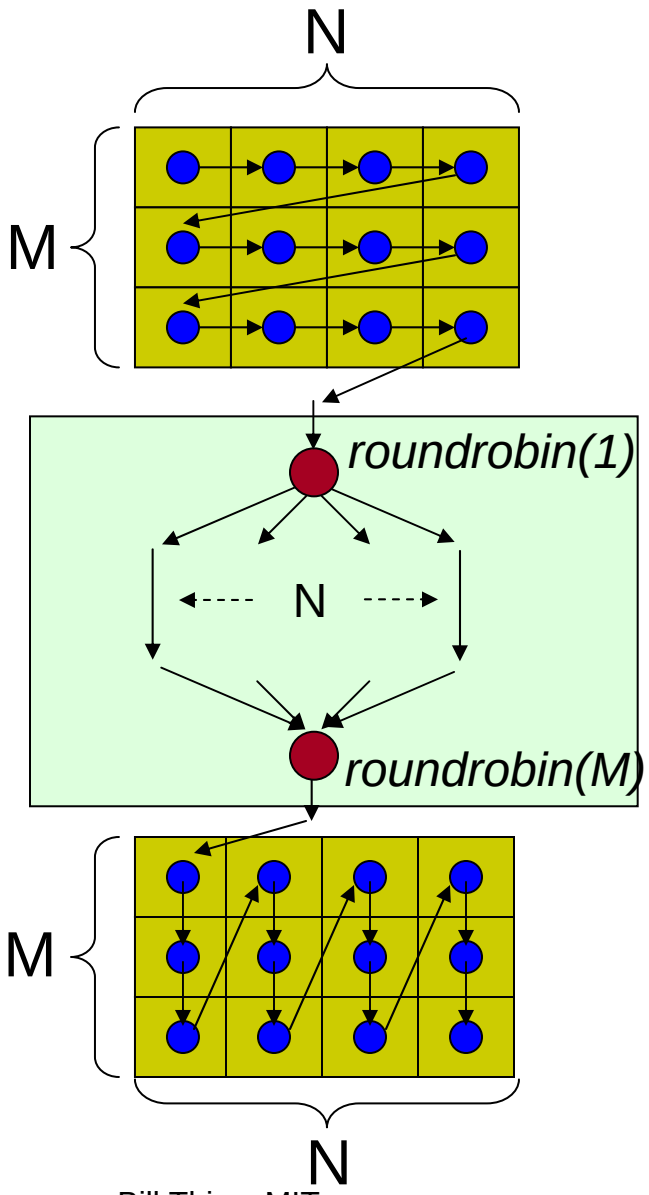
Matrix Transpose



Matrix Transpose



Matrix Transpose

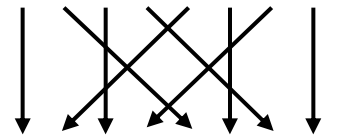



```
float->float splitjoin Transpose (int M,
                                  int N) {
    split roundrobin(1);
    for (int i = 0; i<N; i++) {
        add Identity<float>;
    }
    join roundrobin(M);
}
```

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
```



```
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01010101
```

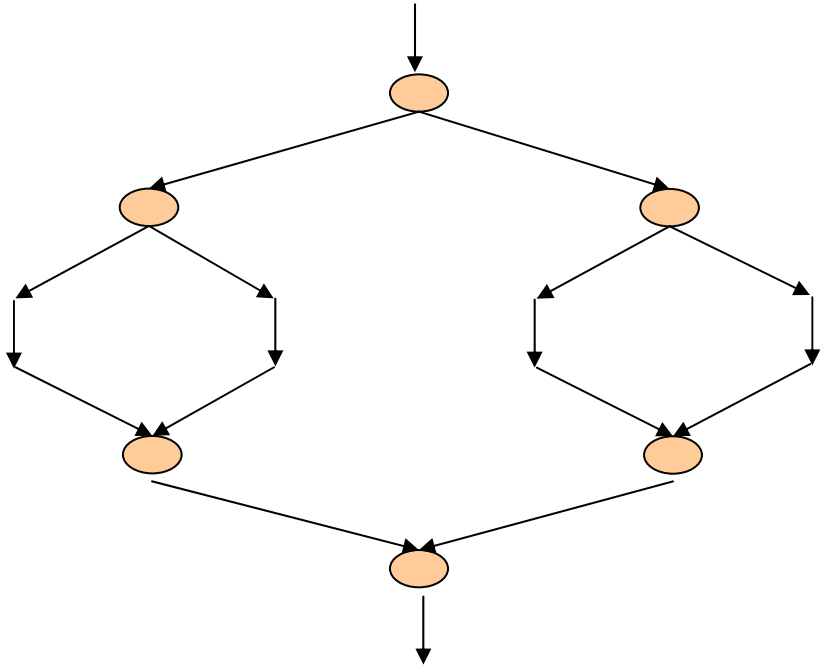

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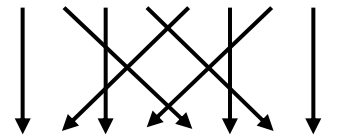

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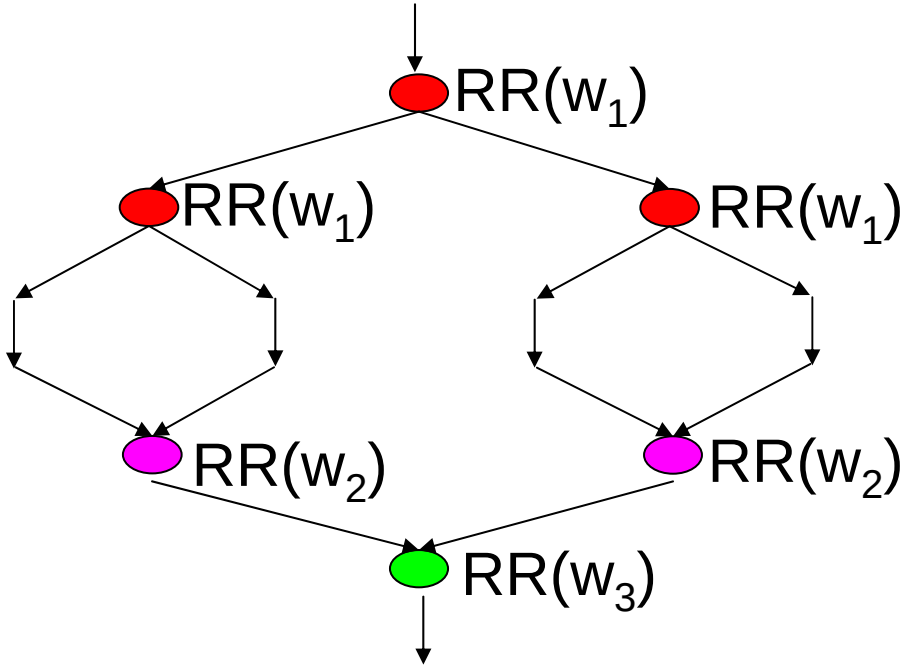

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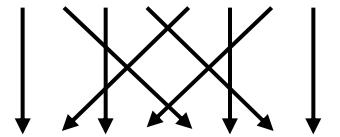
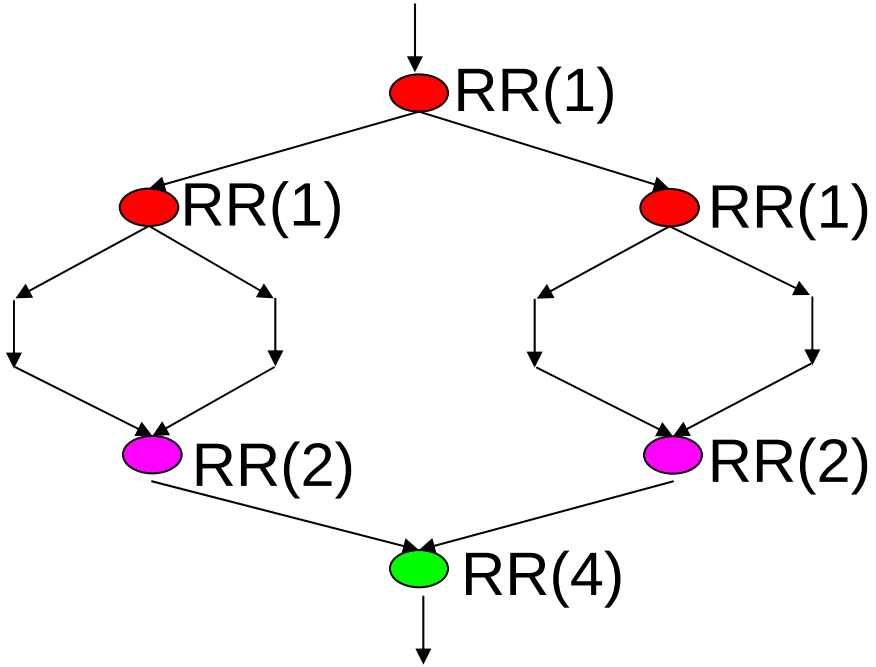
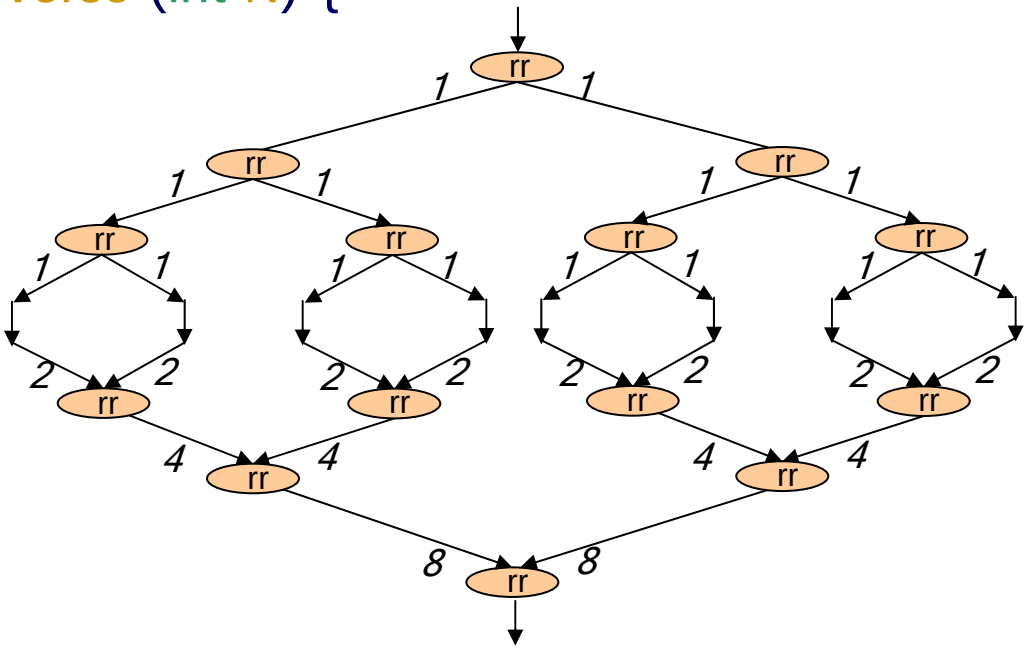


```
00001111
00110011
01010101
```



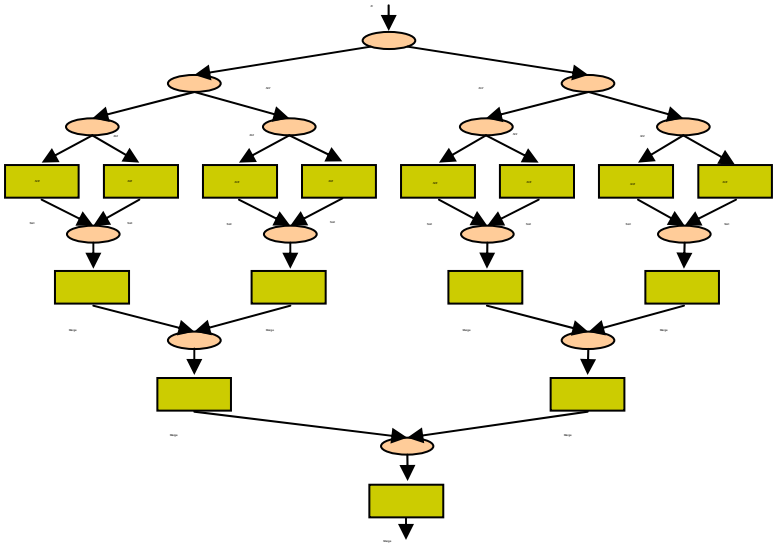
Bit-reversed ordering

```
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);
        }
    }
}
```

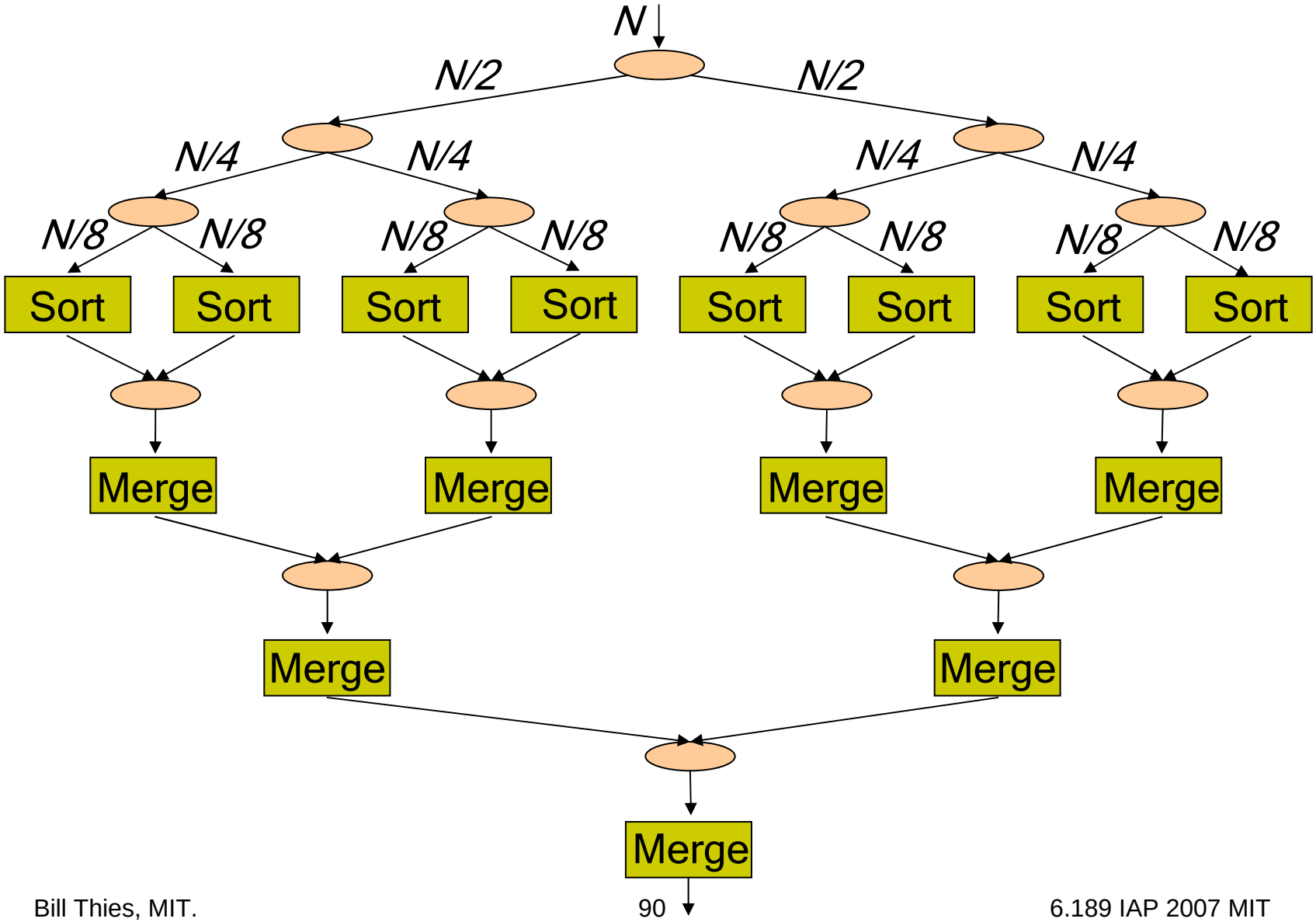


N-Element Merge Sort

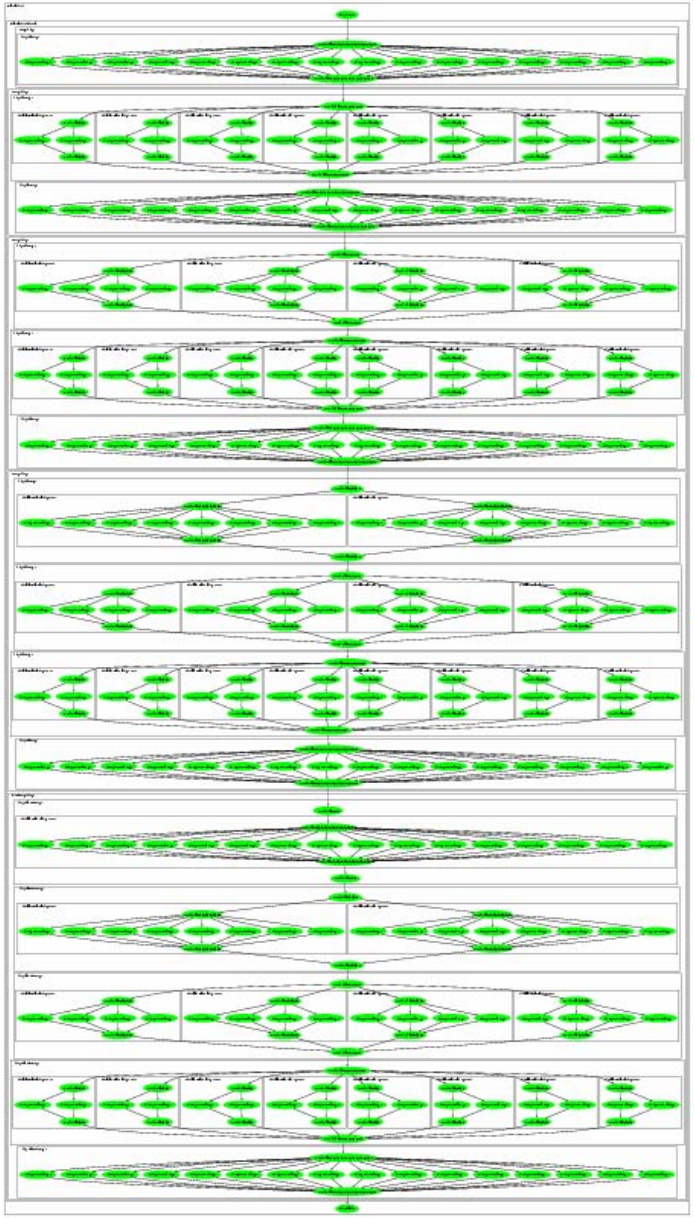
```
int->int pipeline MergeSort (int N) {
    if (N==2) {
        add Sort(N);
    } else {
        add splitjoin {
            split roundrobin(N/2);
            add MergeSort(N/2);
            add MergeSort(N/2);
            join roundrobin(N/2);
        }
    }
    add Merge(N);
}
```



N-Element Merge Sort (3-level)



Bitonic Sort



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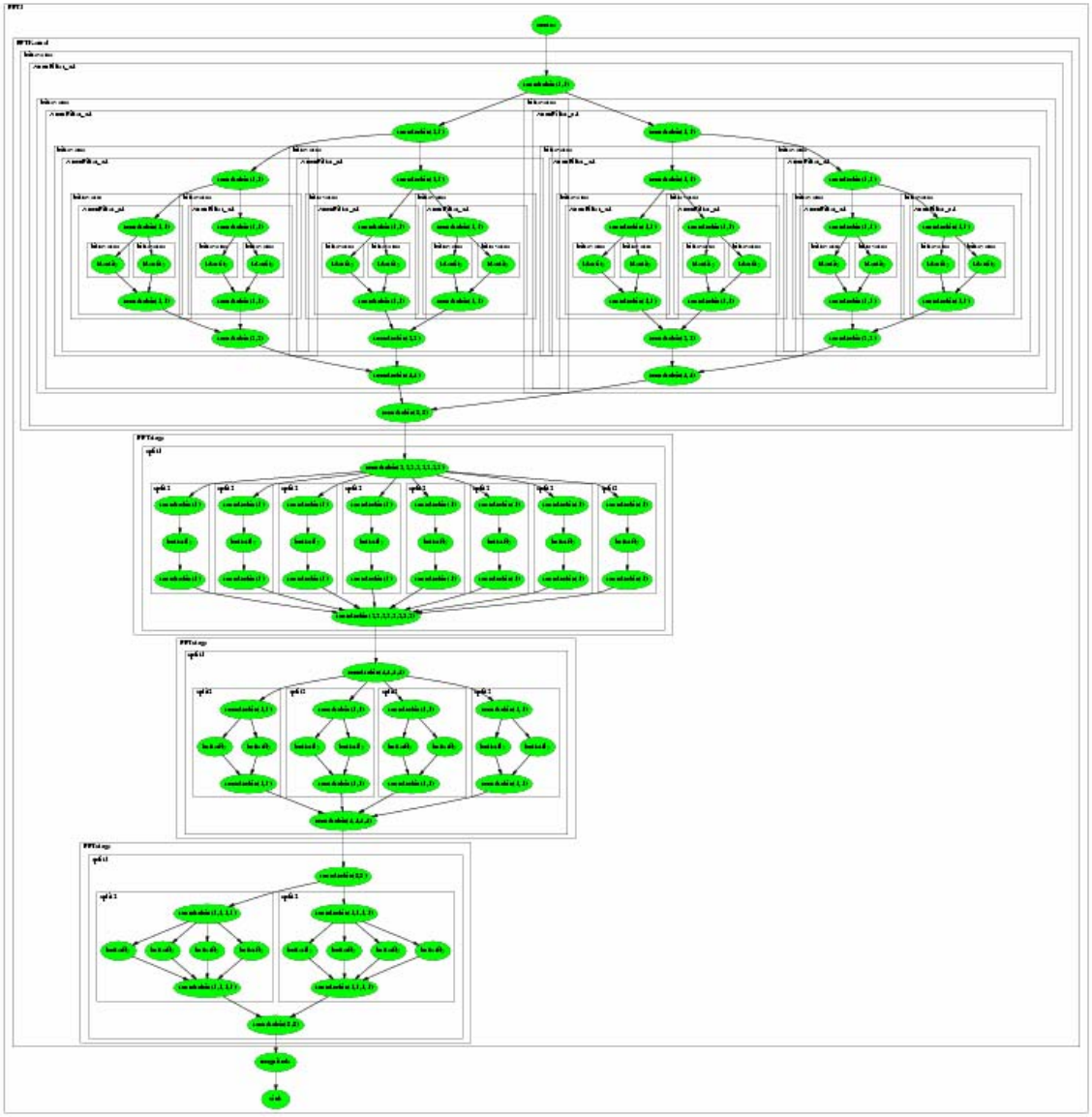
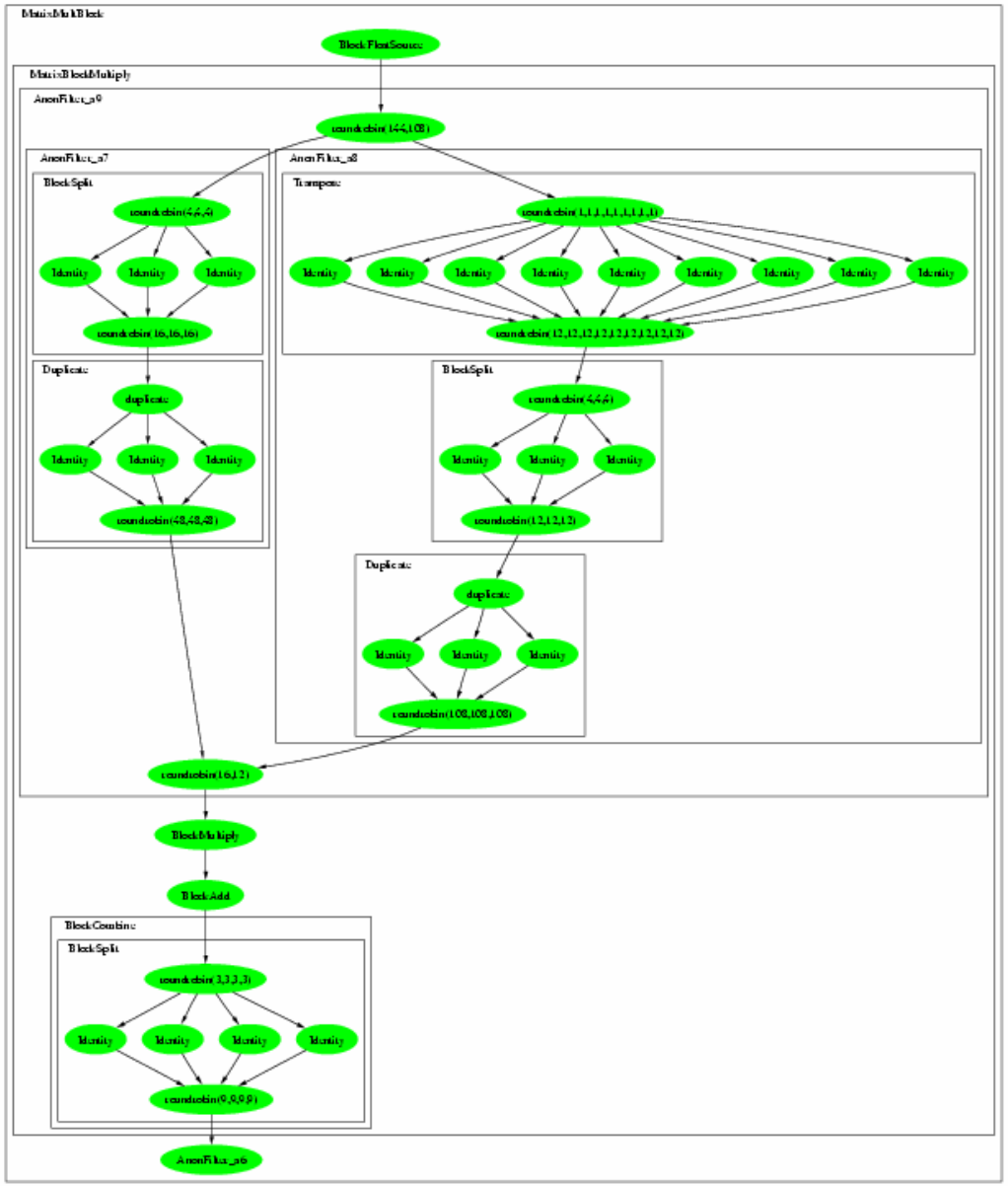
FFT



Courtesy of William Thies.
Used with permission.

Block Matrix Multiply



Courtesy of William Thies.
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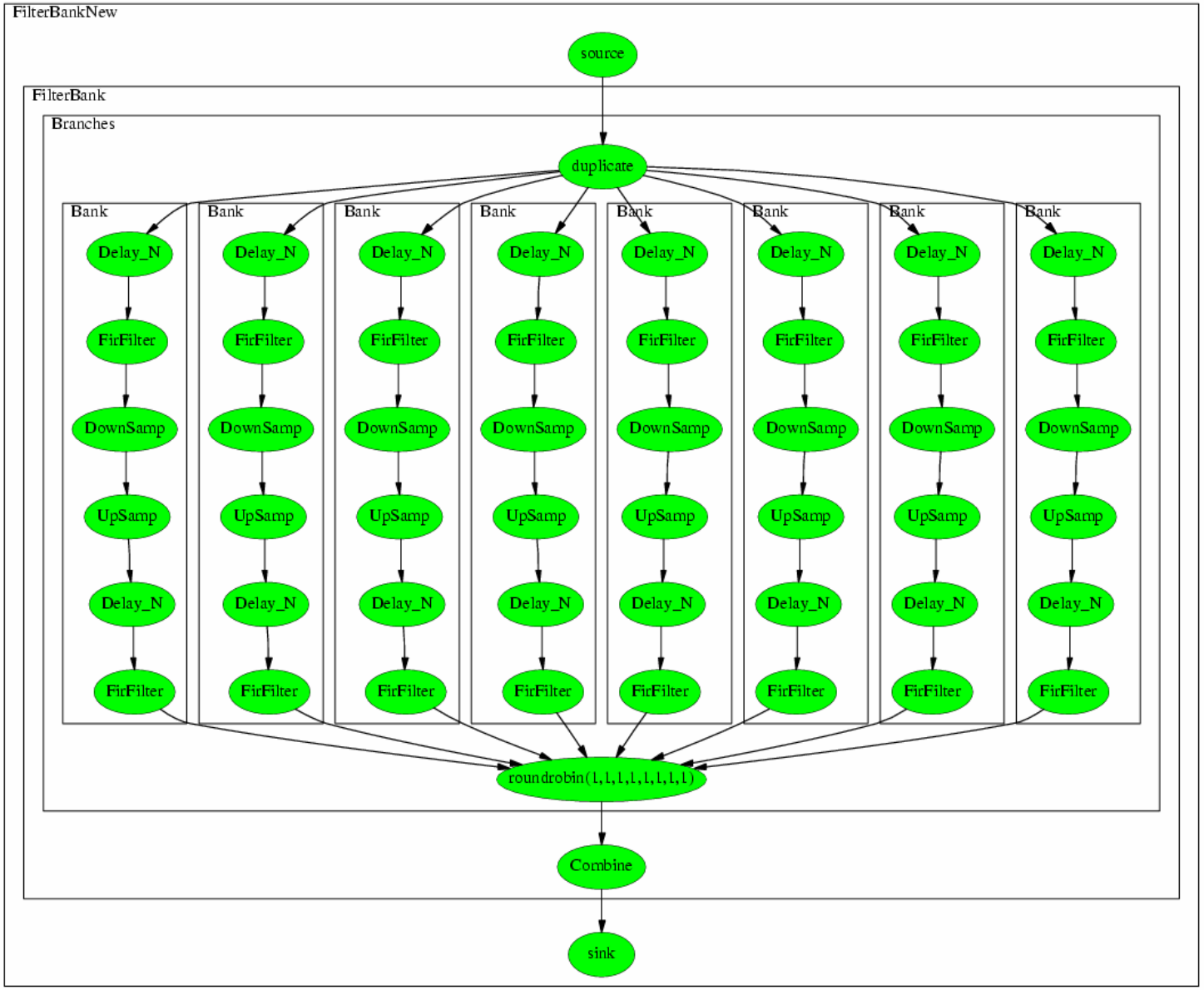
Filterbank



Courtesy of William Thies.
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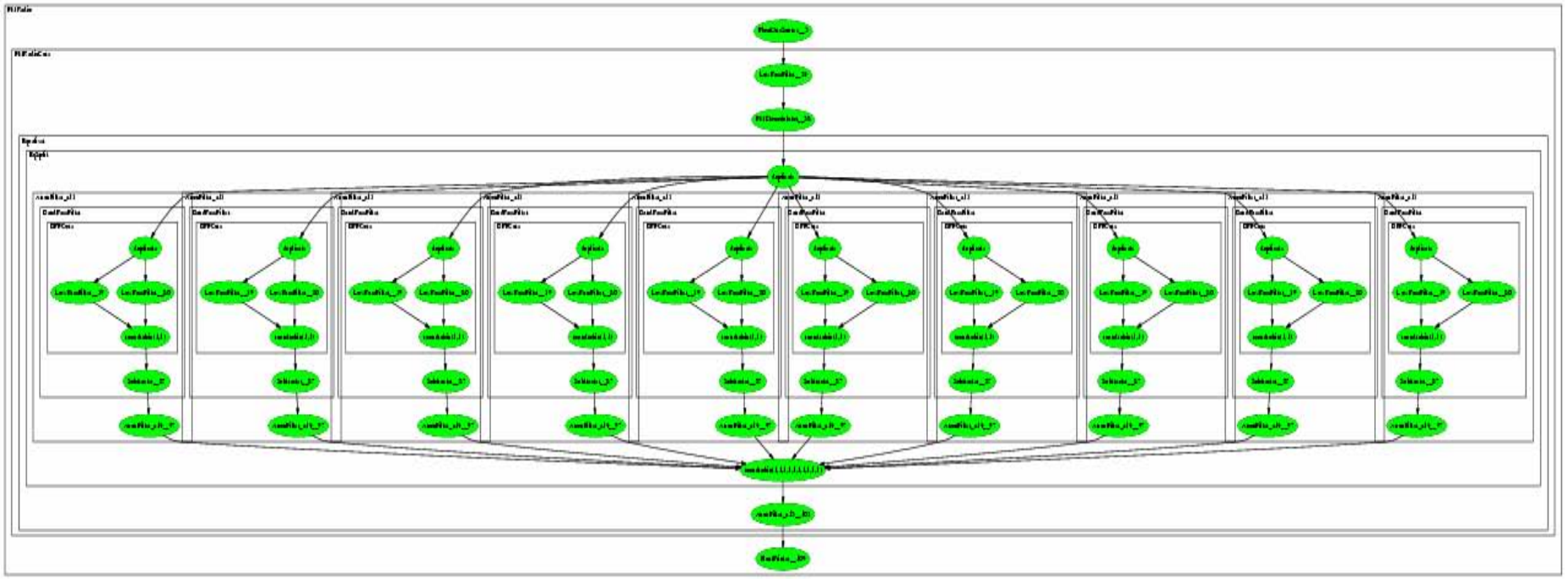
FM Radio with Equalizer



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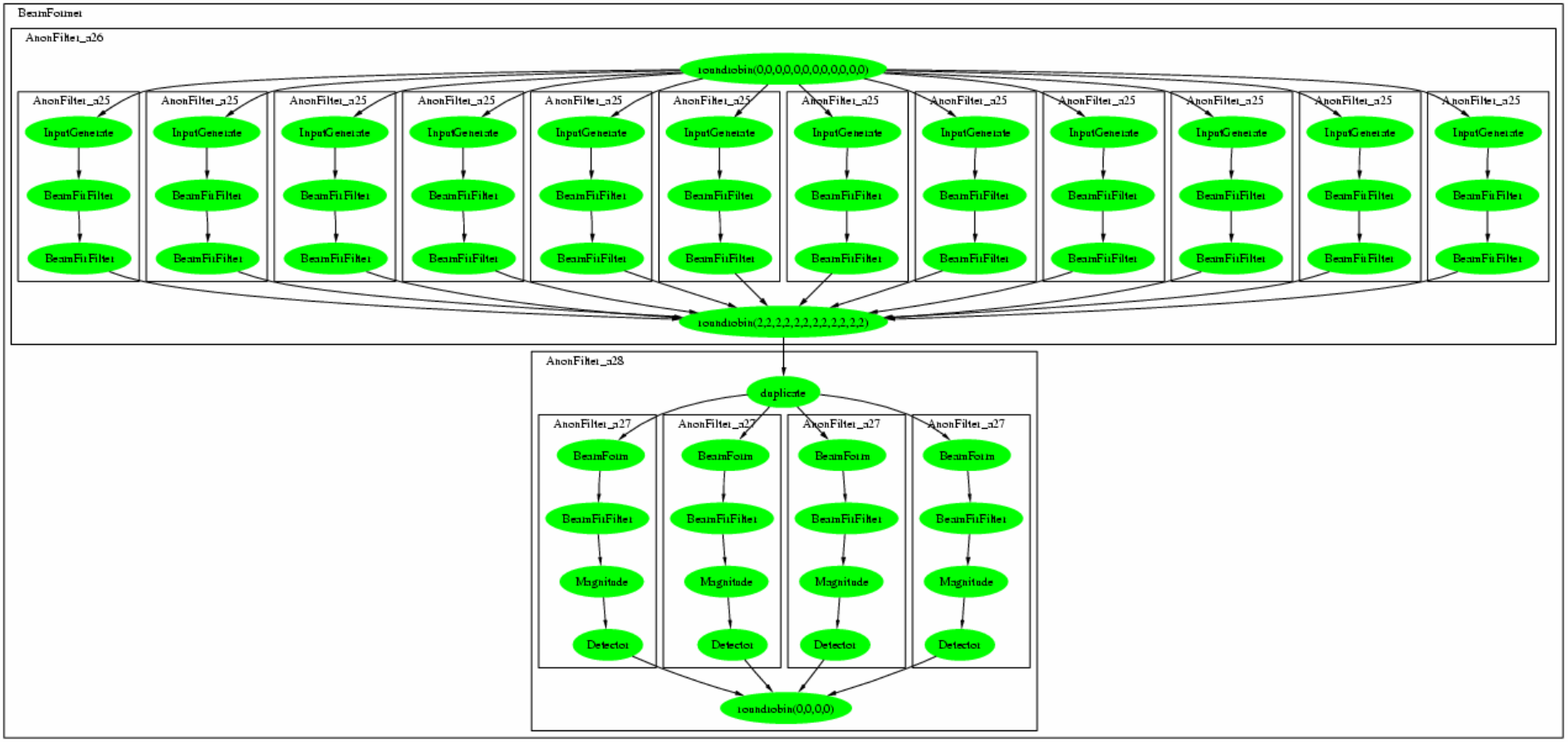
Radar-Array Front End



Courtesy of William Thies.
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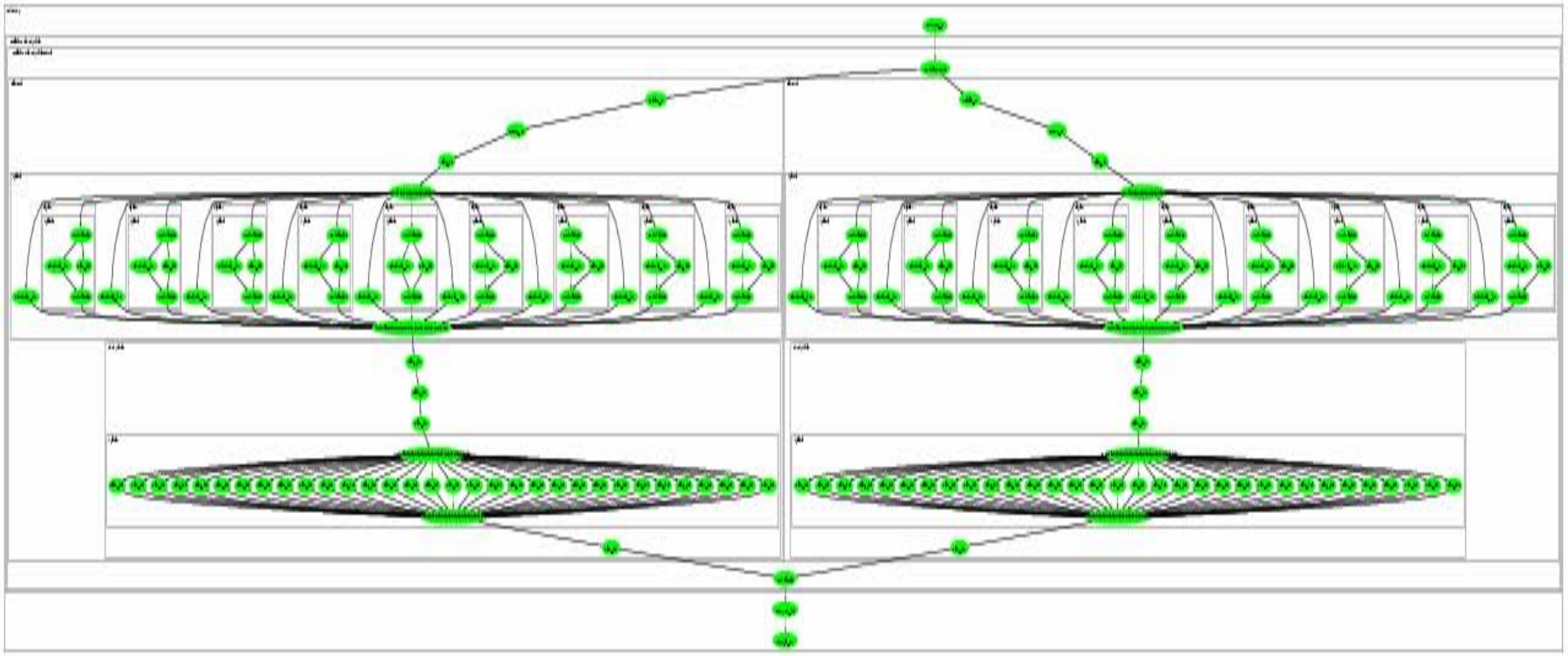
MP3 Decoder



Courtesy of William Thies.
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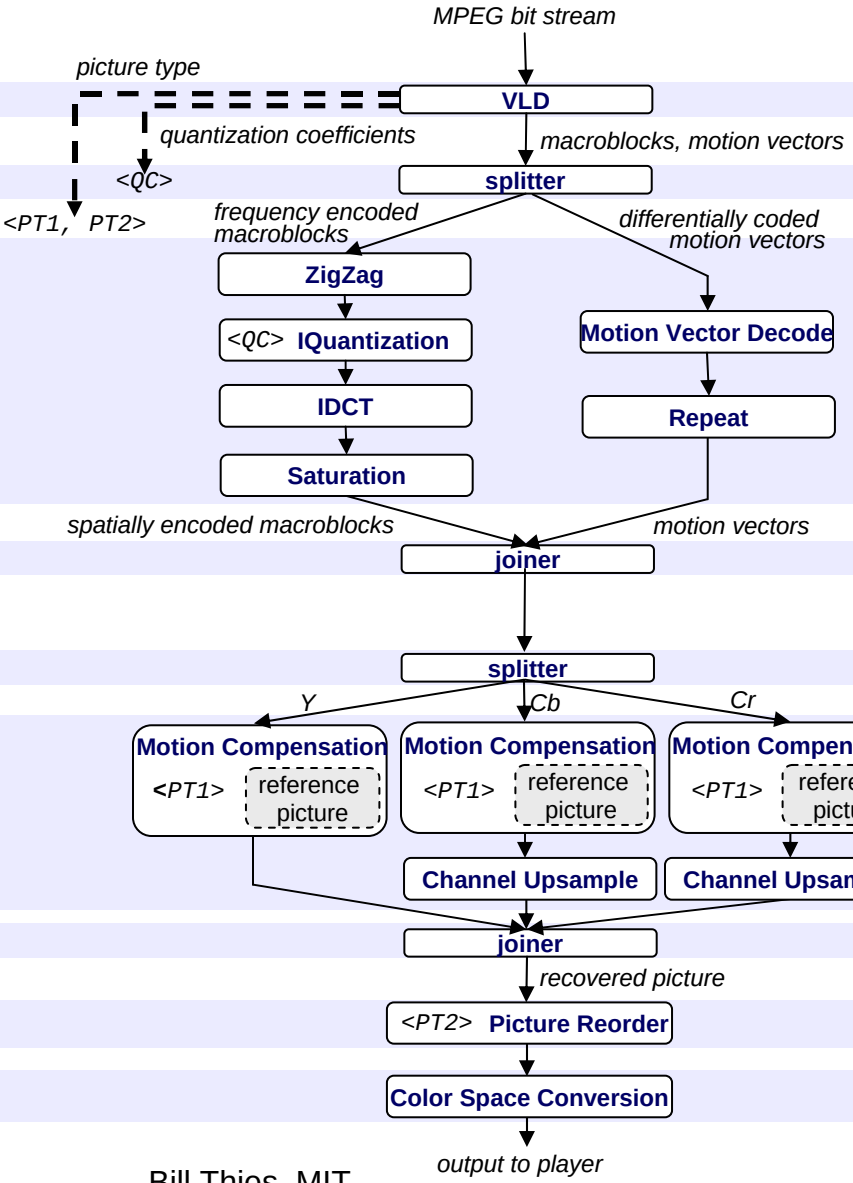
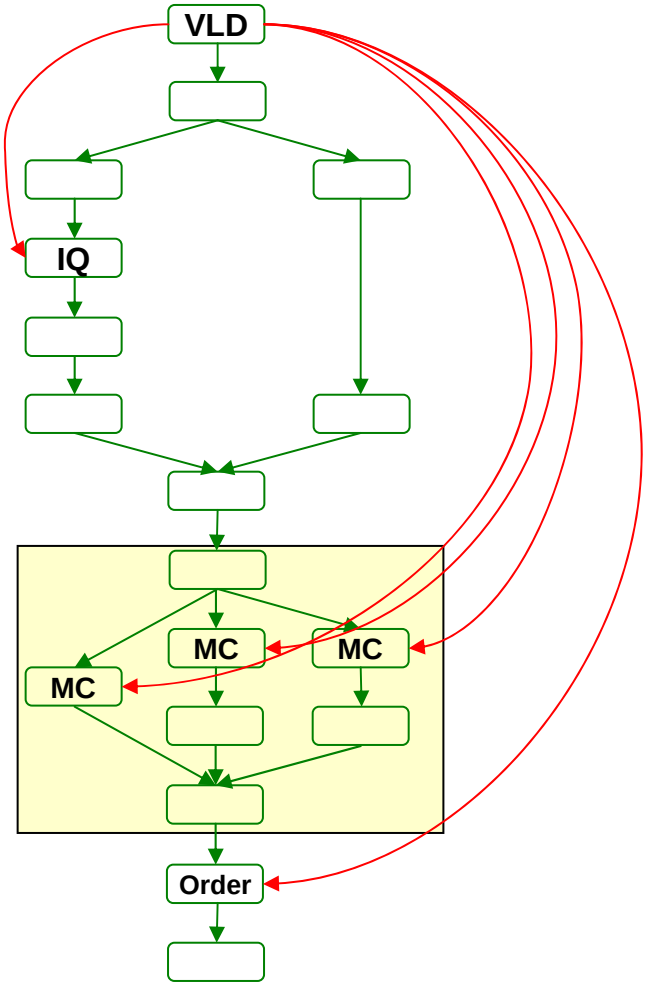
Case Study:
MPEG-2 Decoder in StreamIt

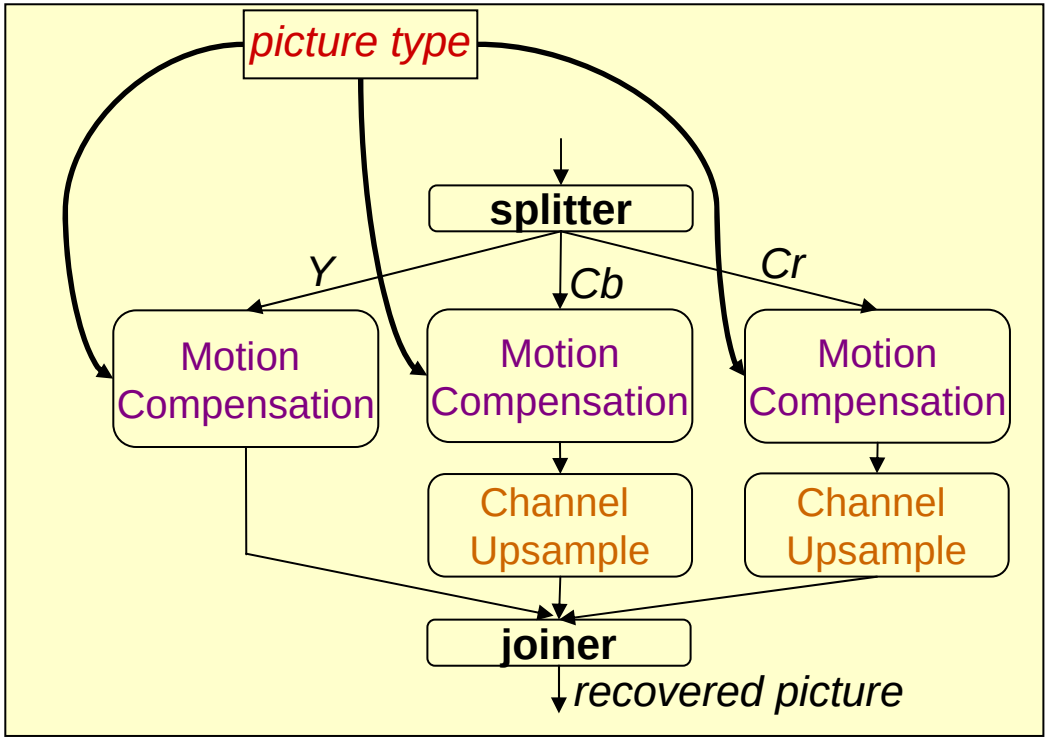
MPEG-2 Decoder in StreamIt



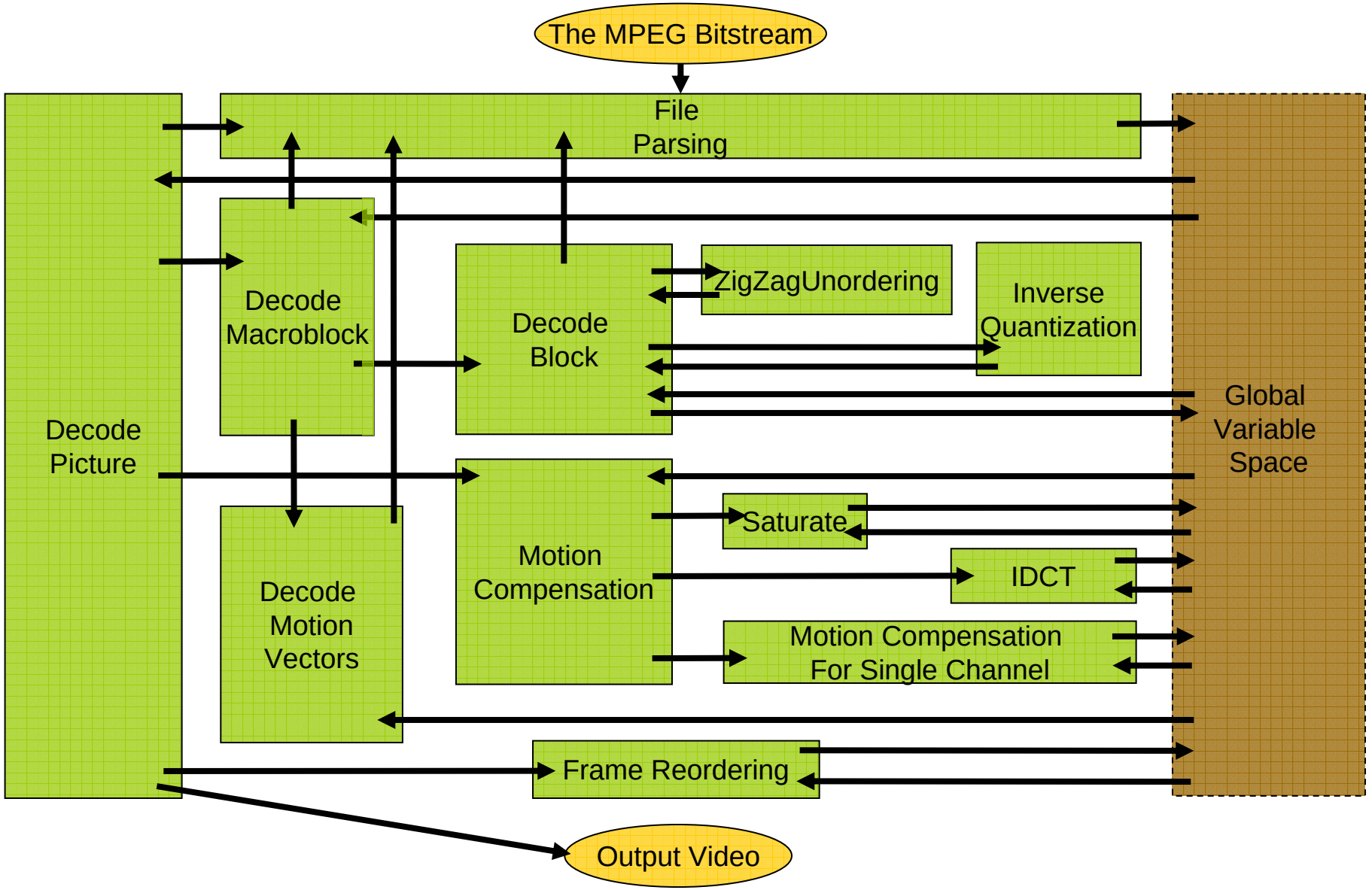

```
add VLD(QC, PT1, PT2);
add splitjoin {
    split roundrobin(N*B, V);

    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