Software Dataplane Verification

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Katerina Argyraki

EPFL

Software dataplanes

intrusion detection

application acceleration

IP forwarding

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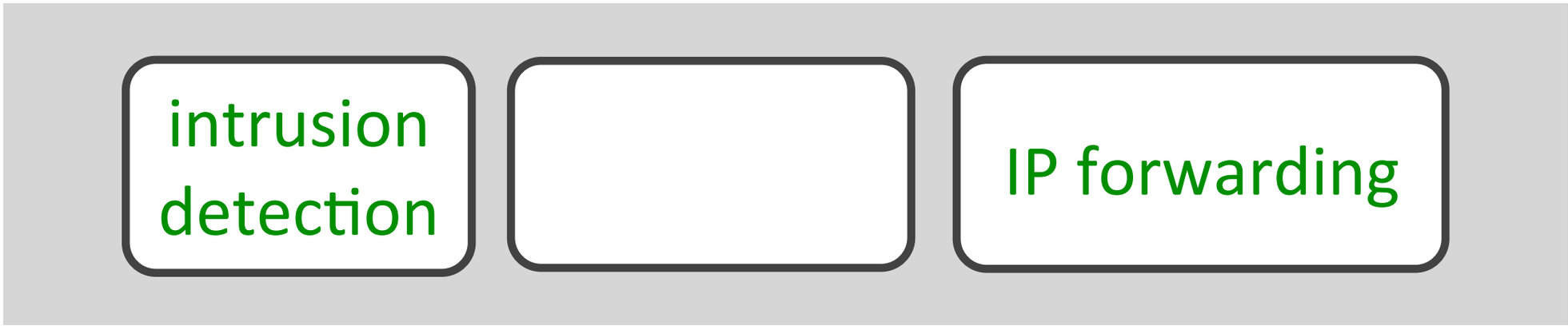

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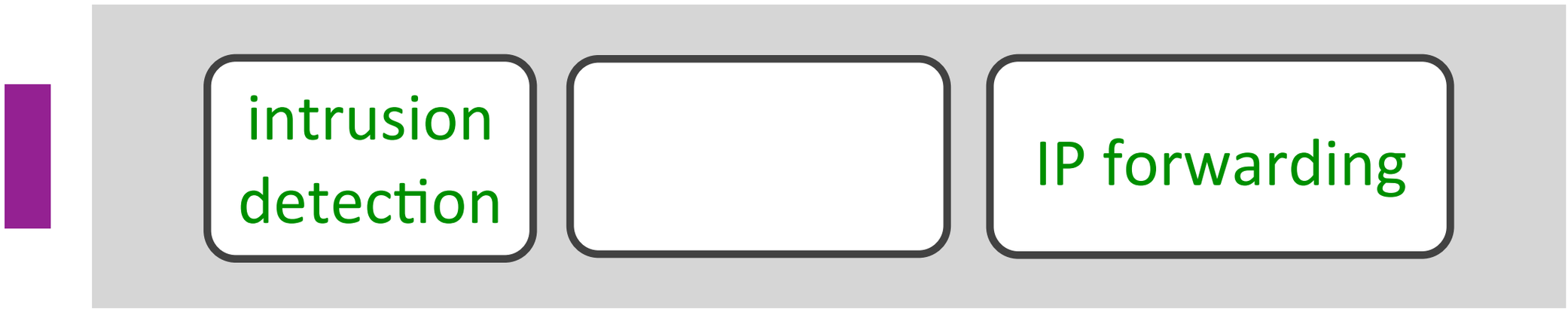

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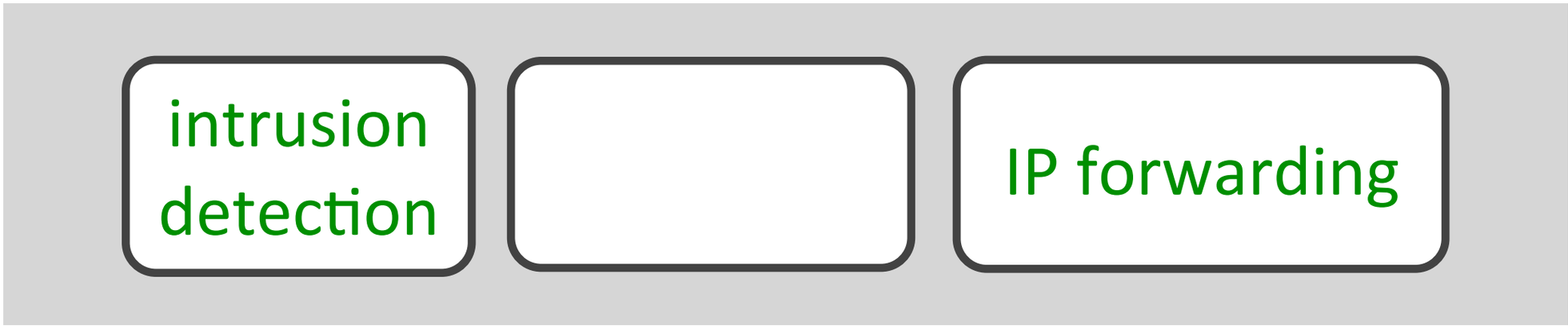

Software dataplanes

- Flexibility
  - *new intrusion detection, traffic filtering, sampling, application acceleration, ...*

- Unpredictability
  - *special packet causes router to crash*
  - *or doubles per-packet latency*

Dataplane verification

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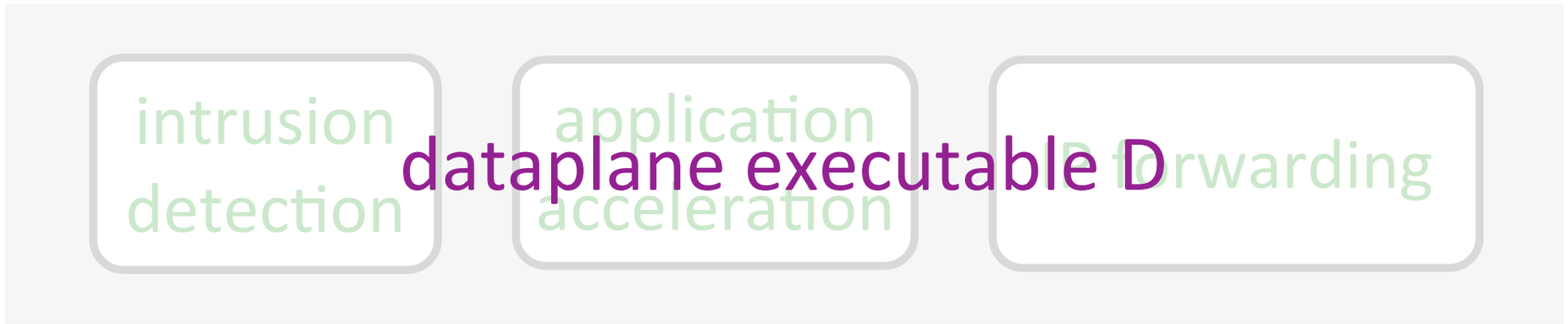
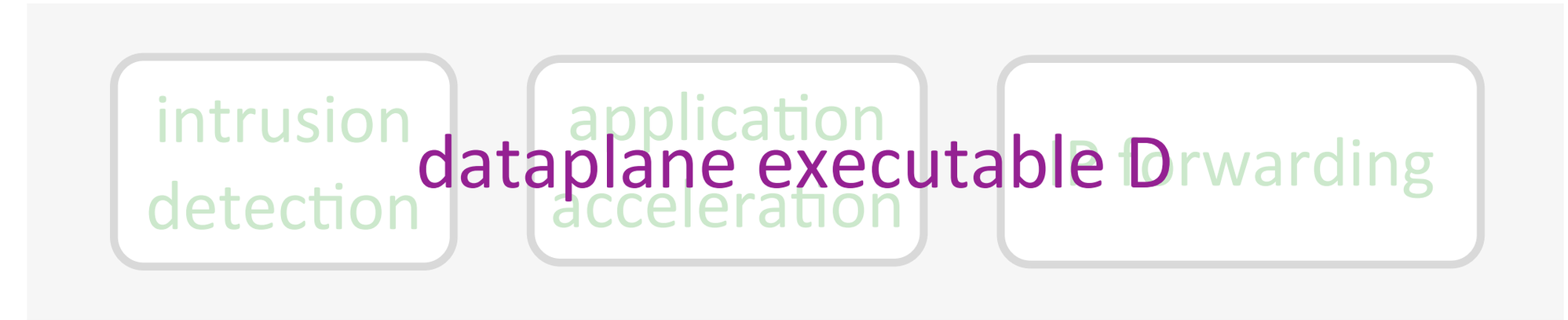


verification tool

Dataplane verification



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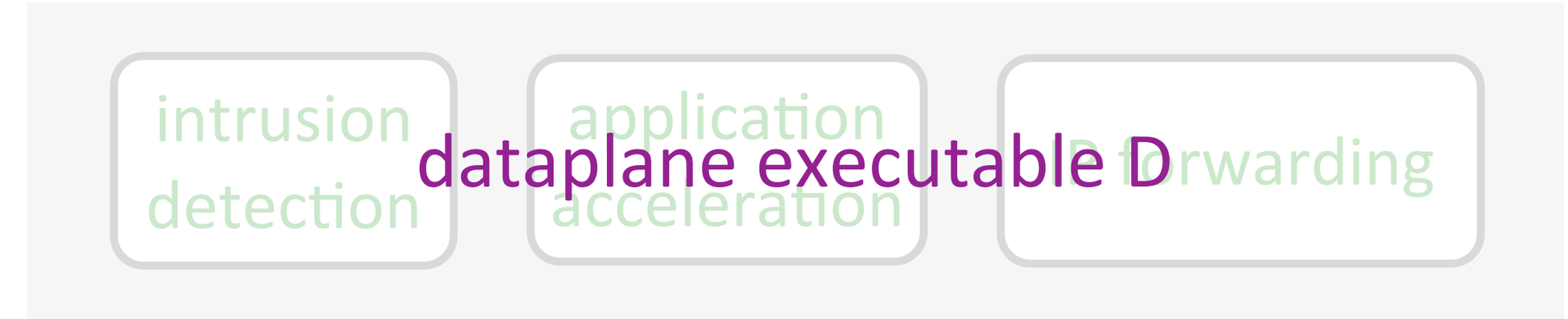

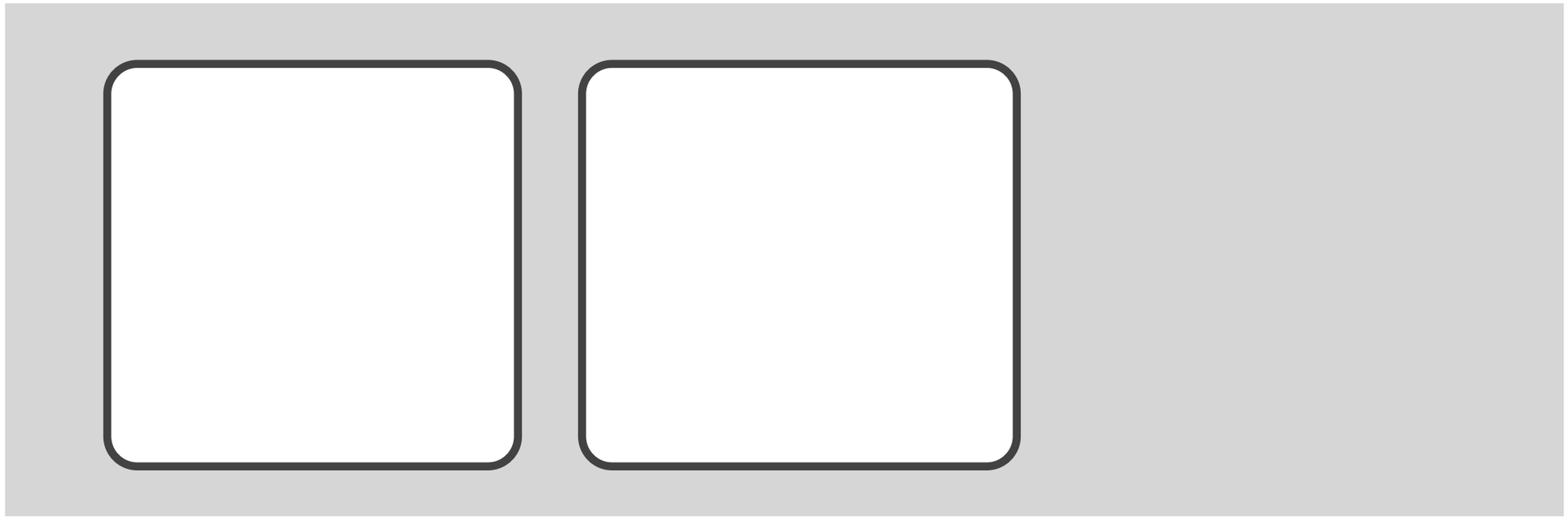

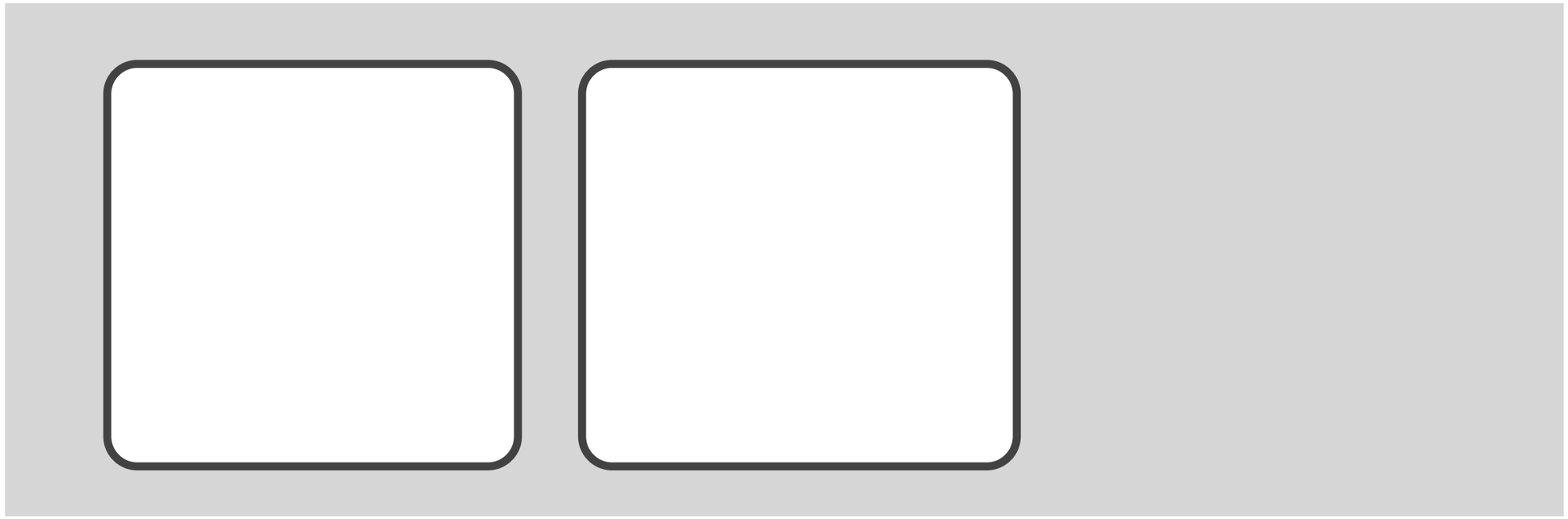

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Klee, OSDI 2008

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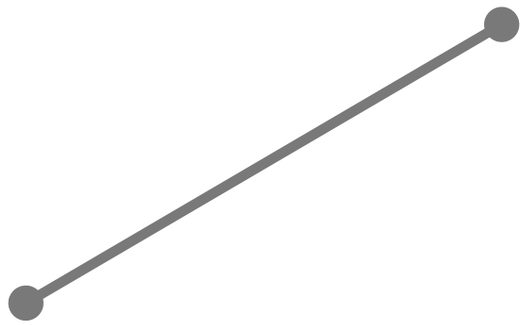

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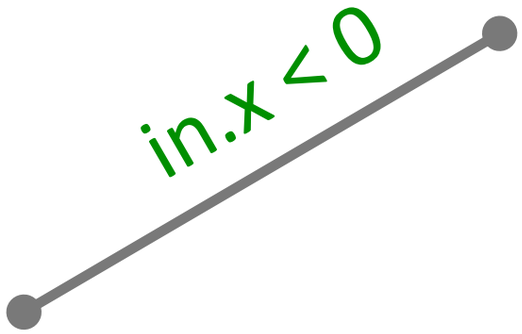

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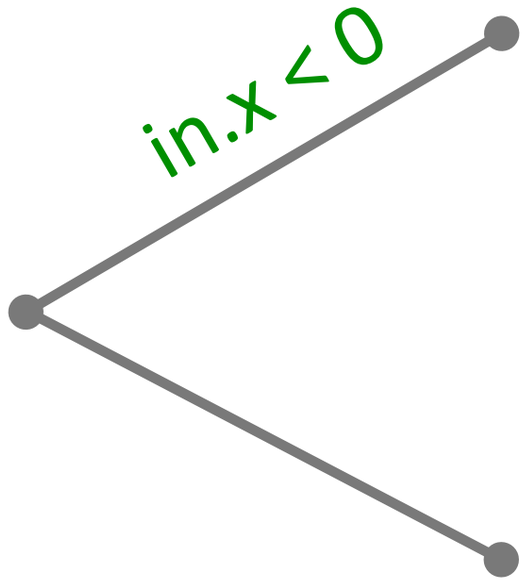

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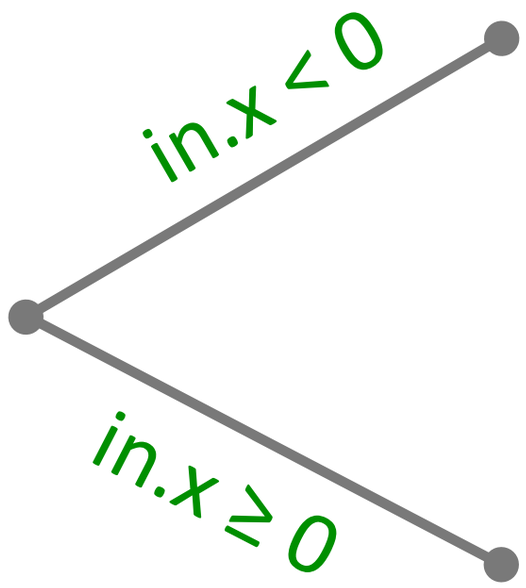

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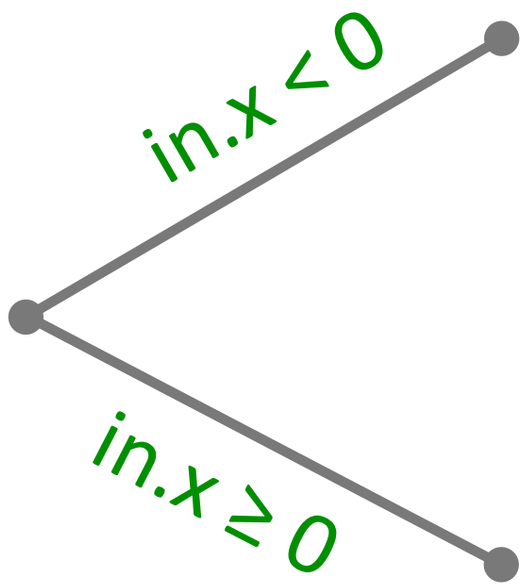

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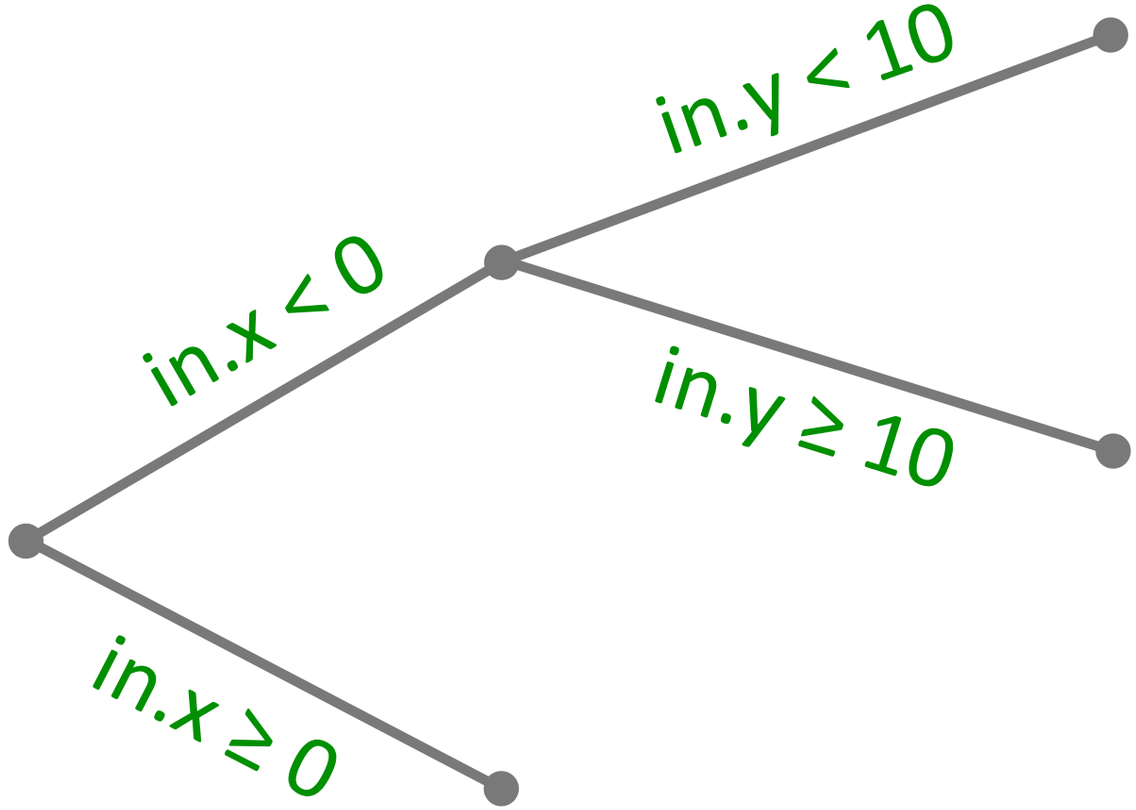

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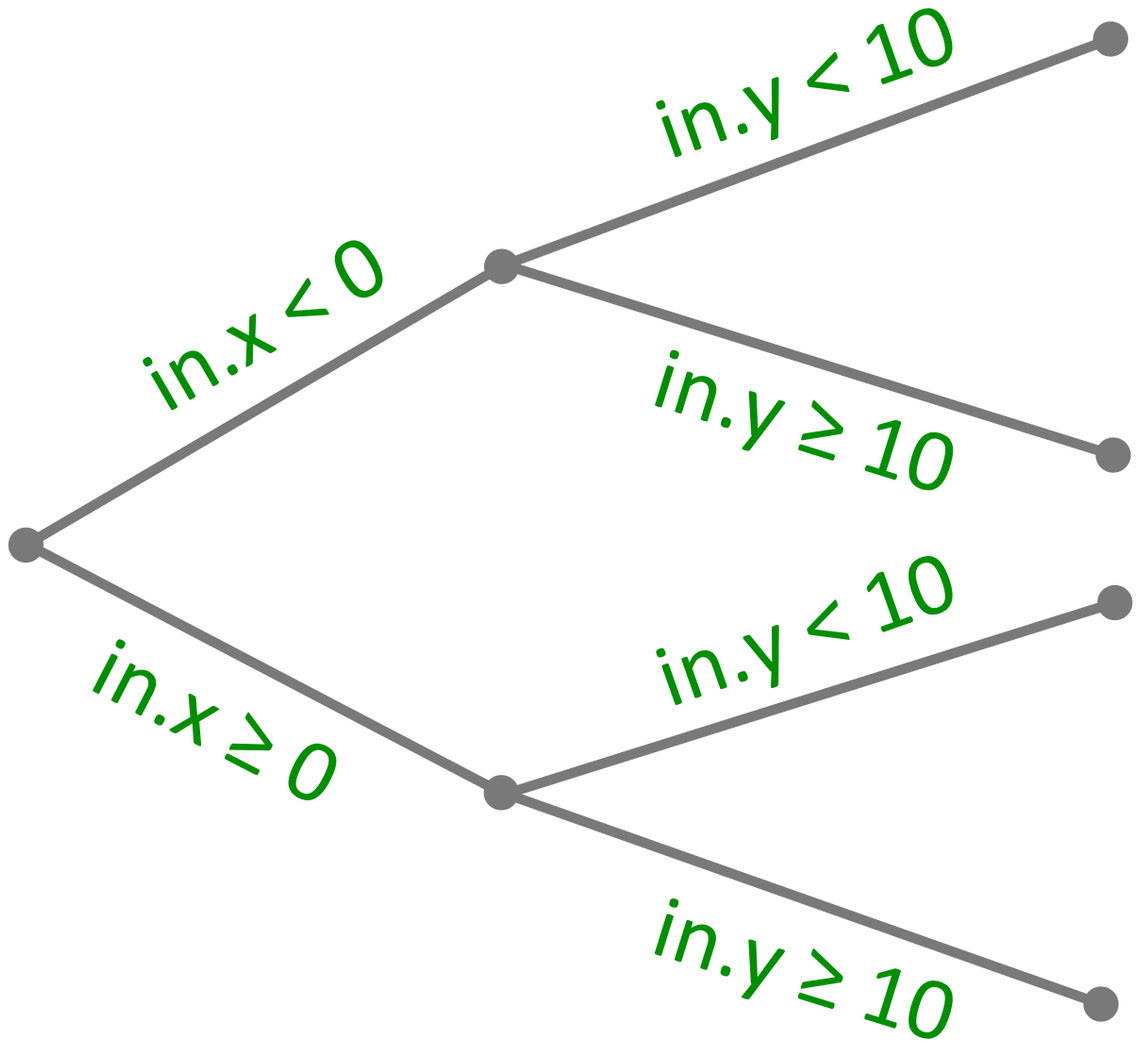

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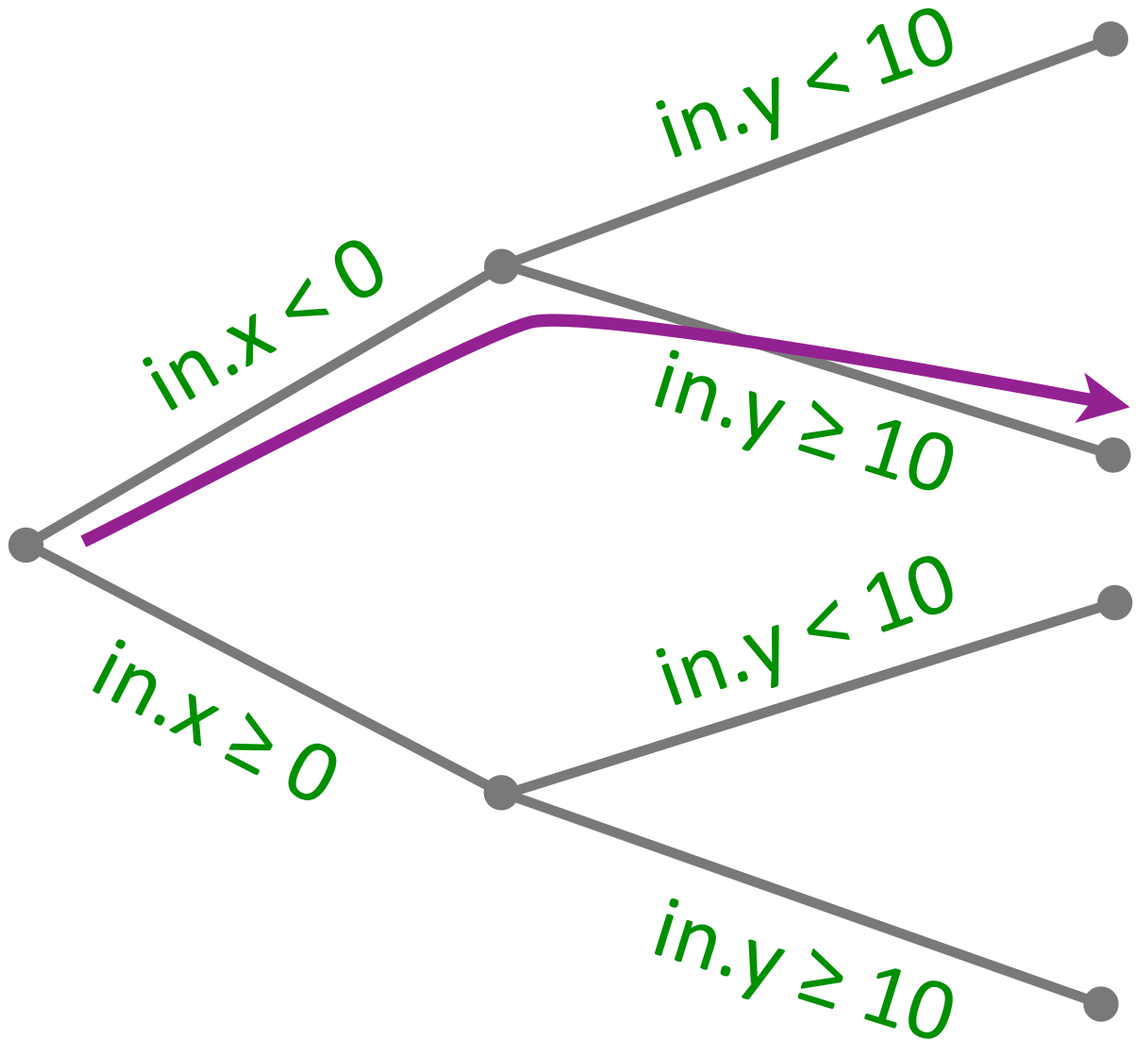

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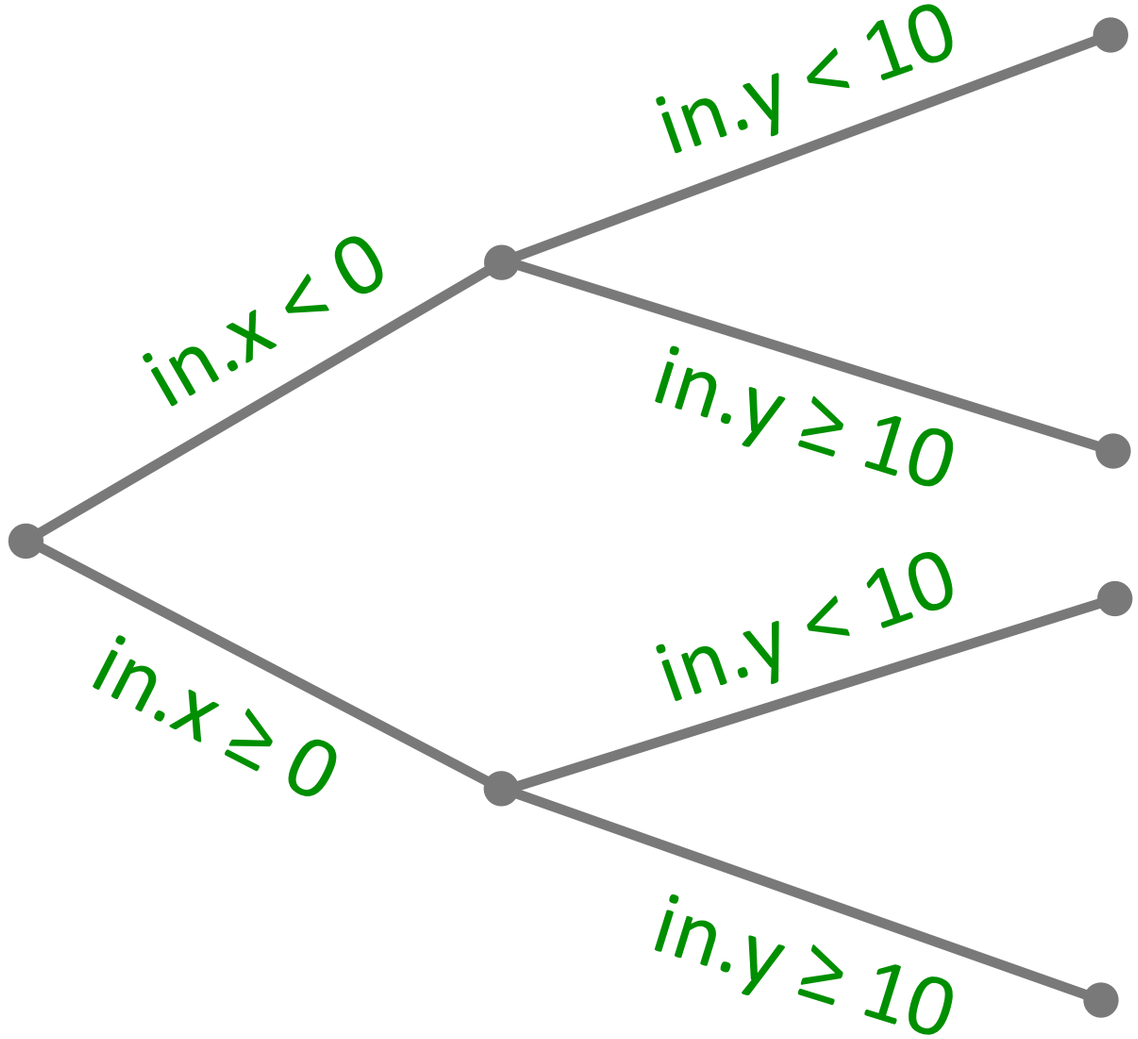

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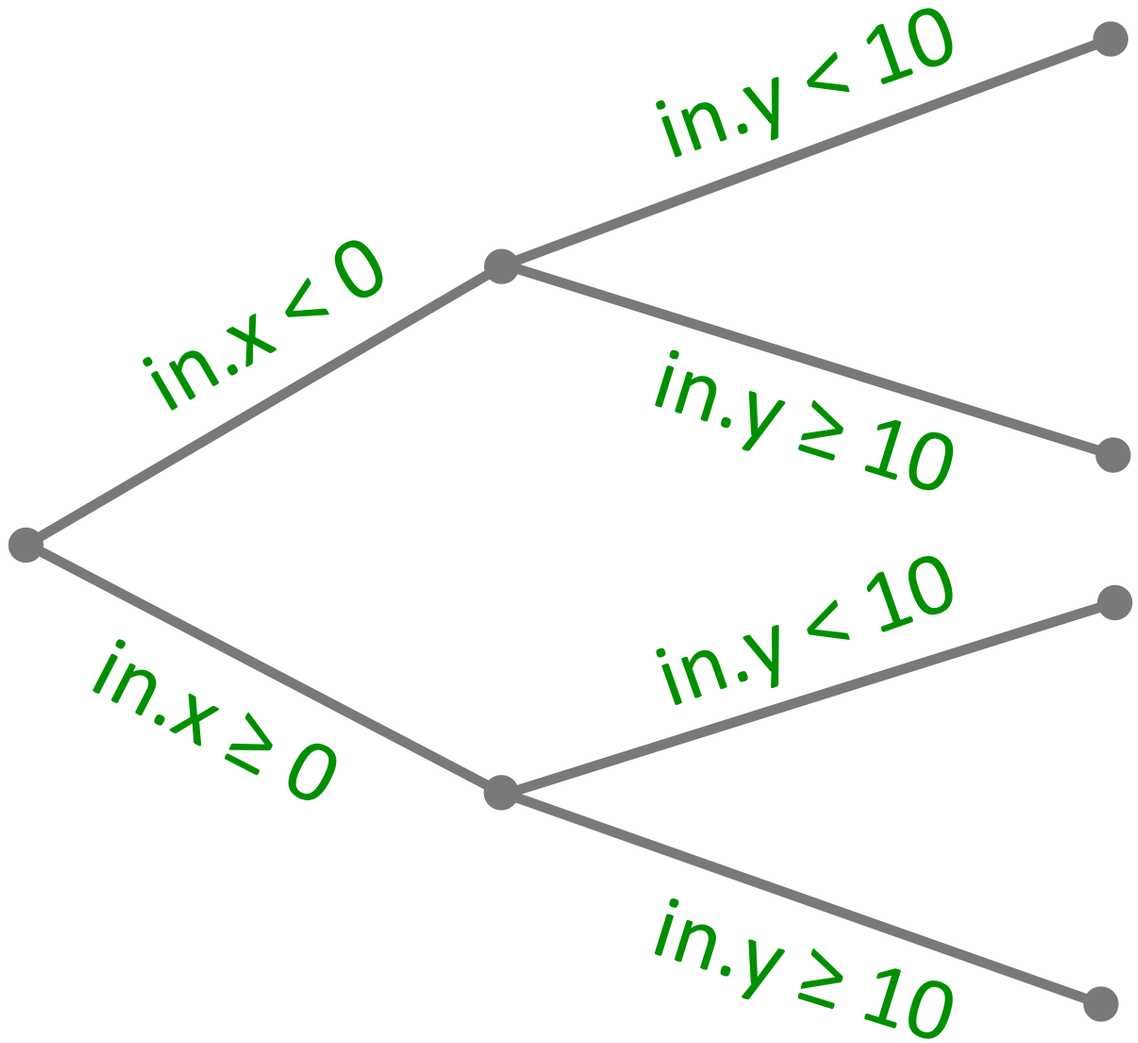

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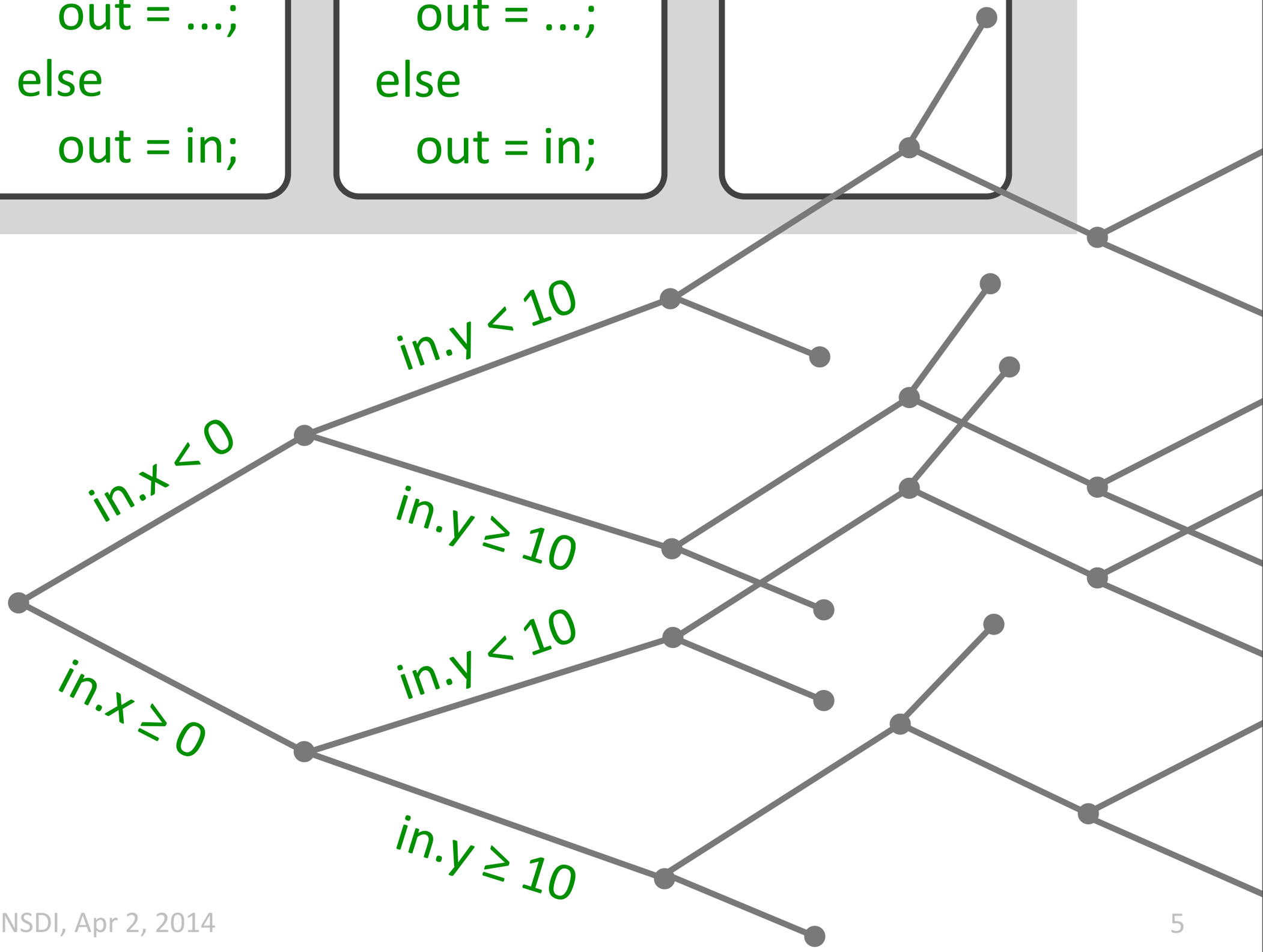

Compositional Test Generation, POPL 2007

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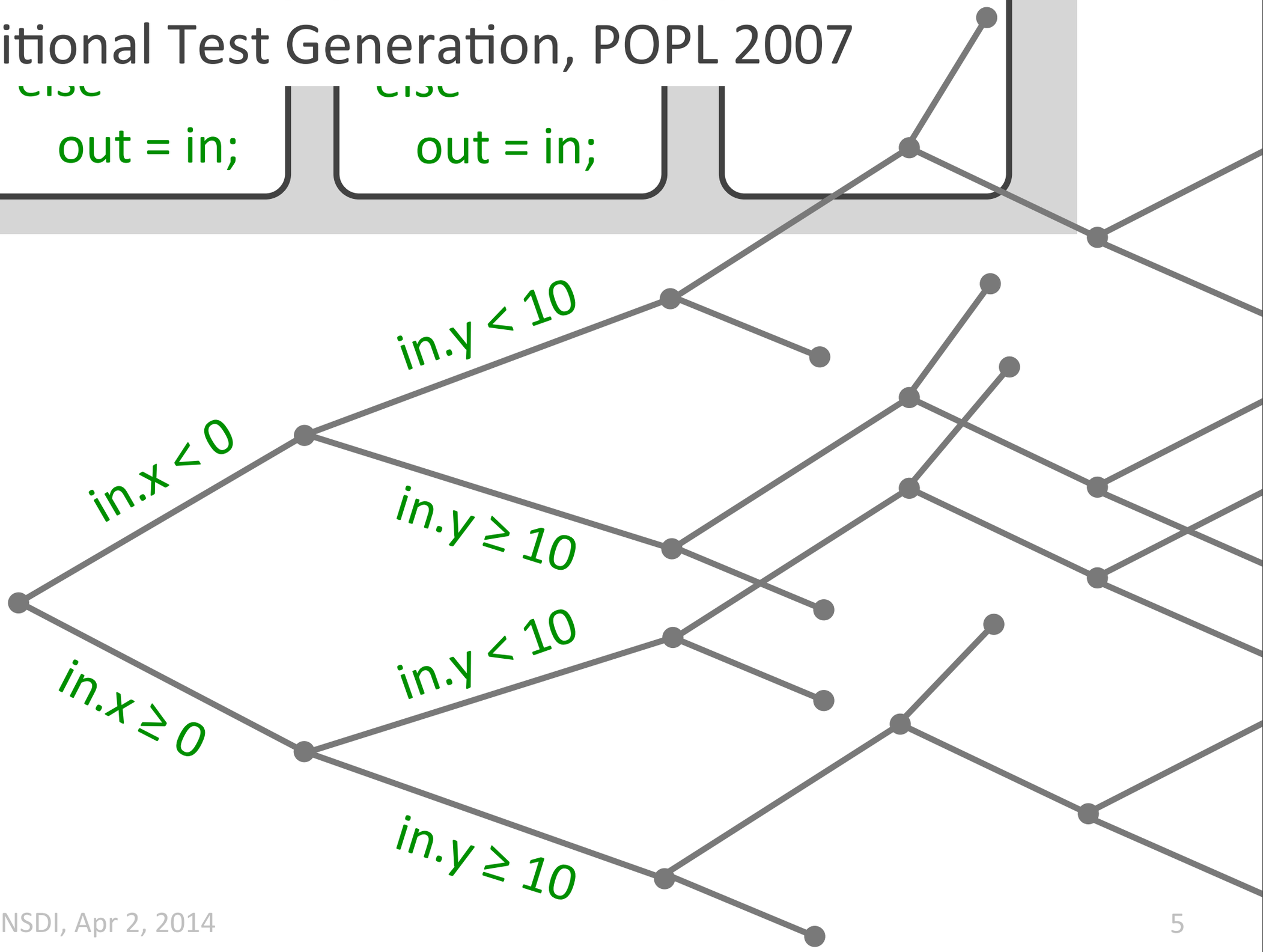

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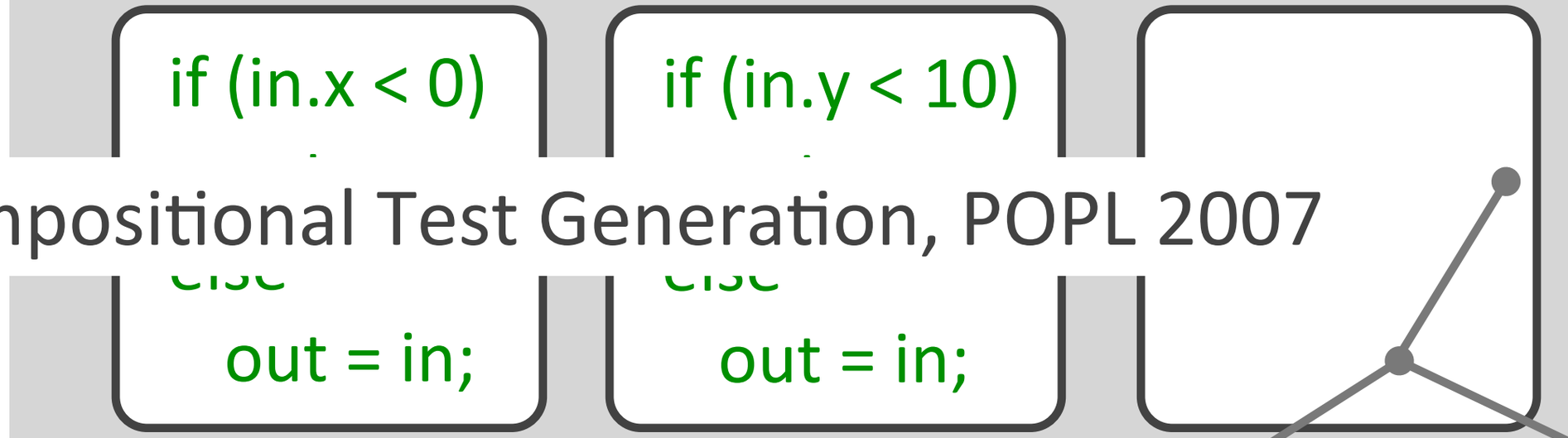

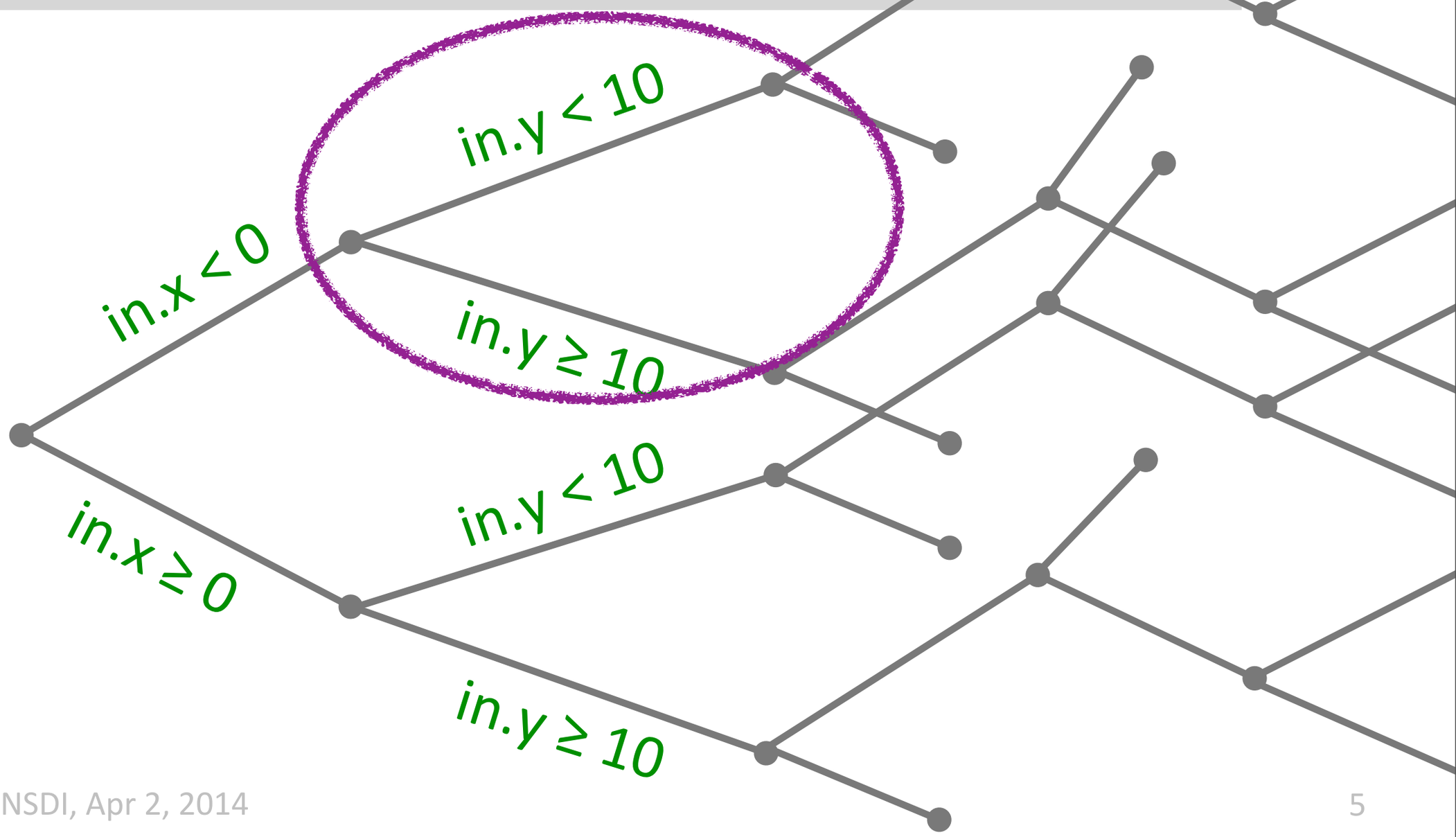

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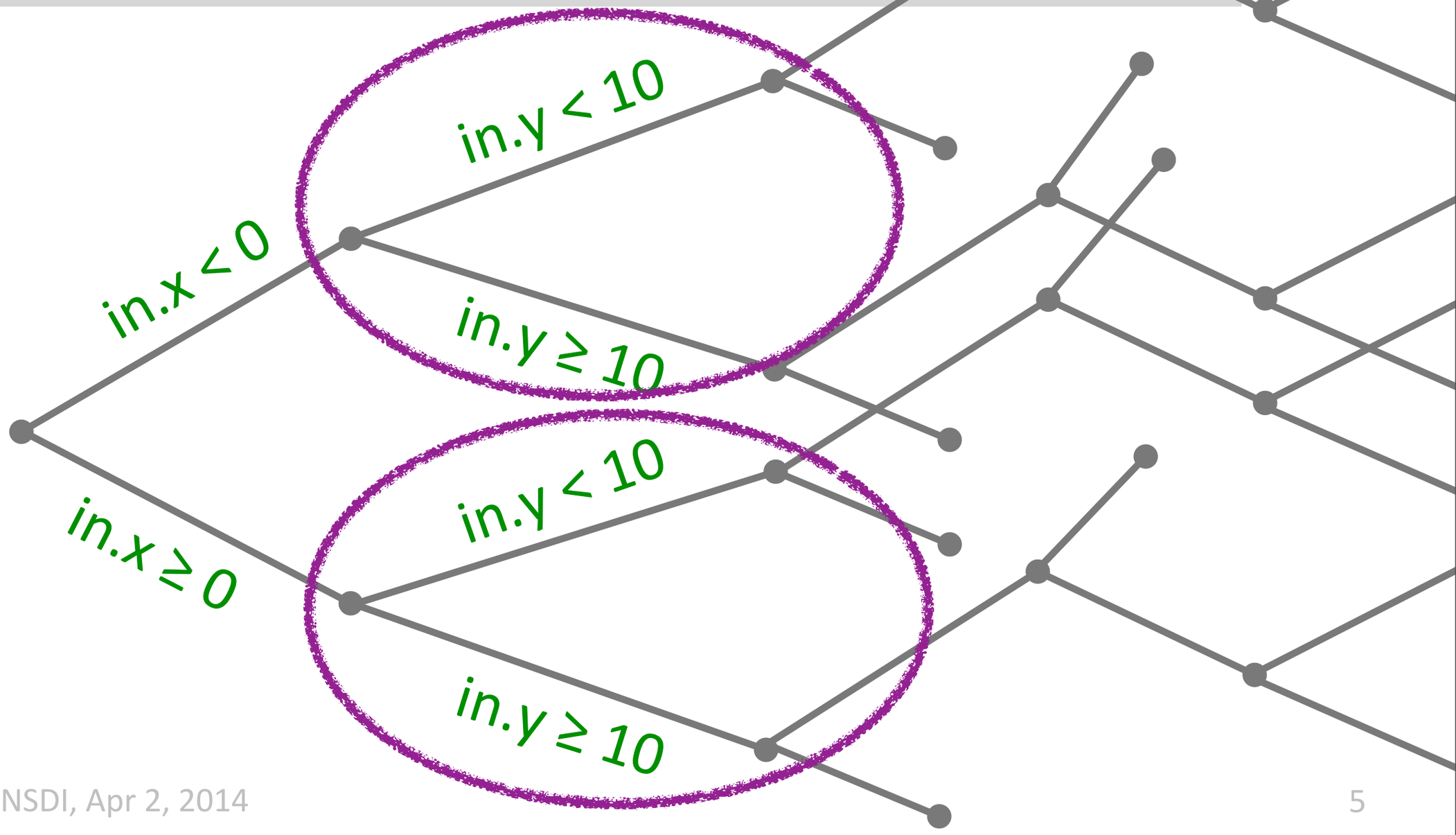

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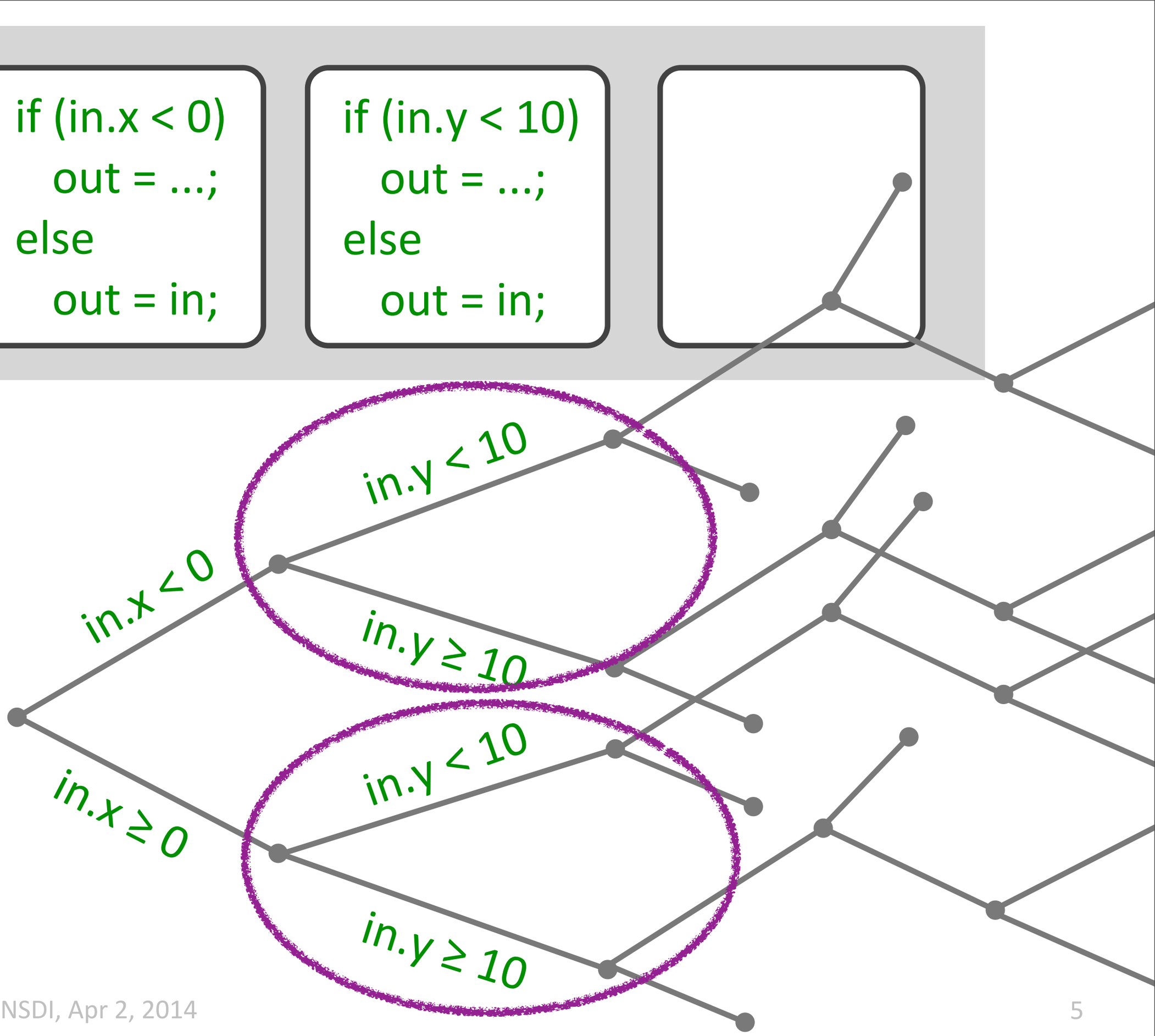

Dataplane-specific verification

- Define the domain
  - *propose rules on how to write dataplanes*
  - *make it easy to apply composition*

- Leverage the domain specificity
  - *use it to sidestep path explosion*
  - *open the door to dataplane verification*

Outline

- Pipeline
- Loops
- Data structures
- Results

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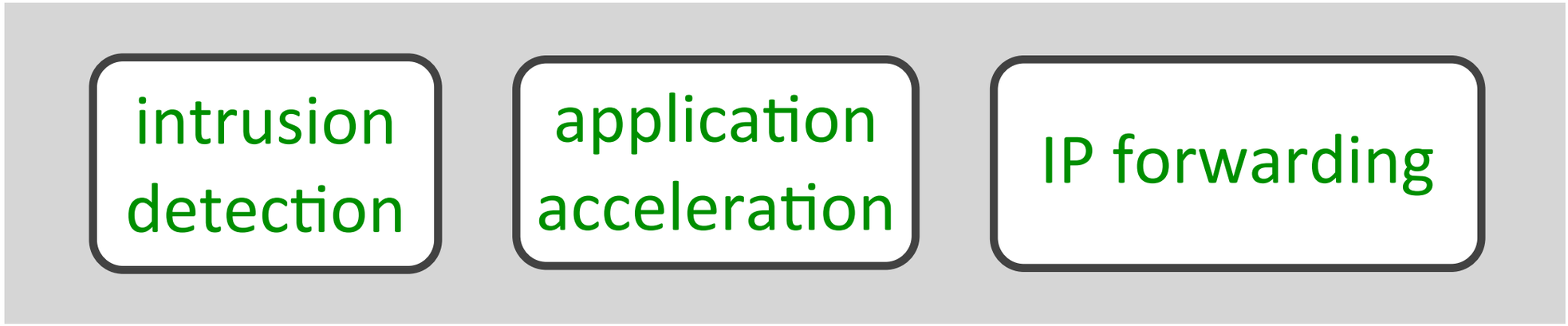
intrusion detection
application acceleration
IP forwarding

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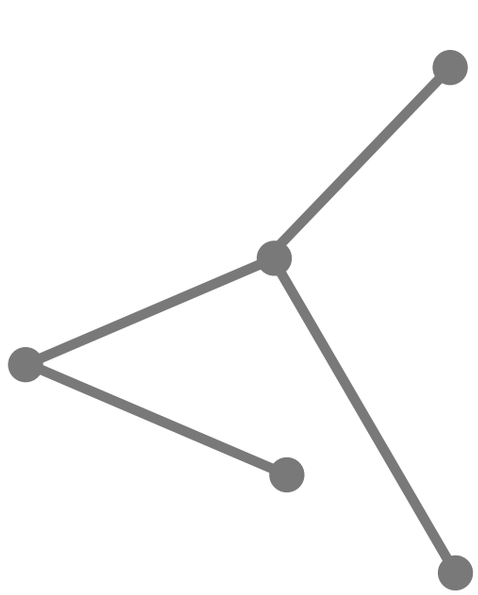

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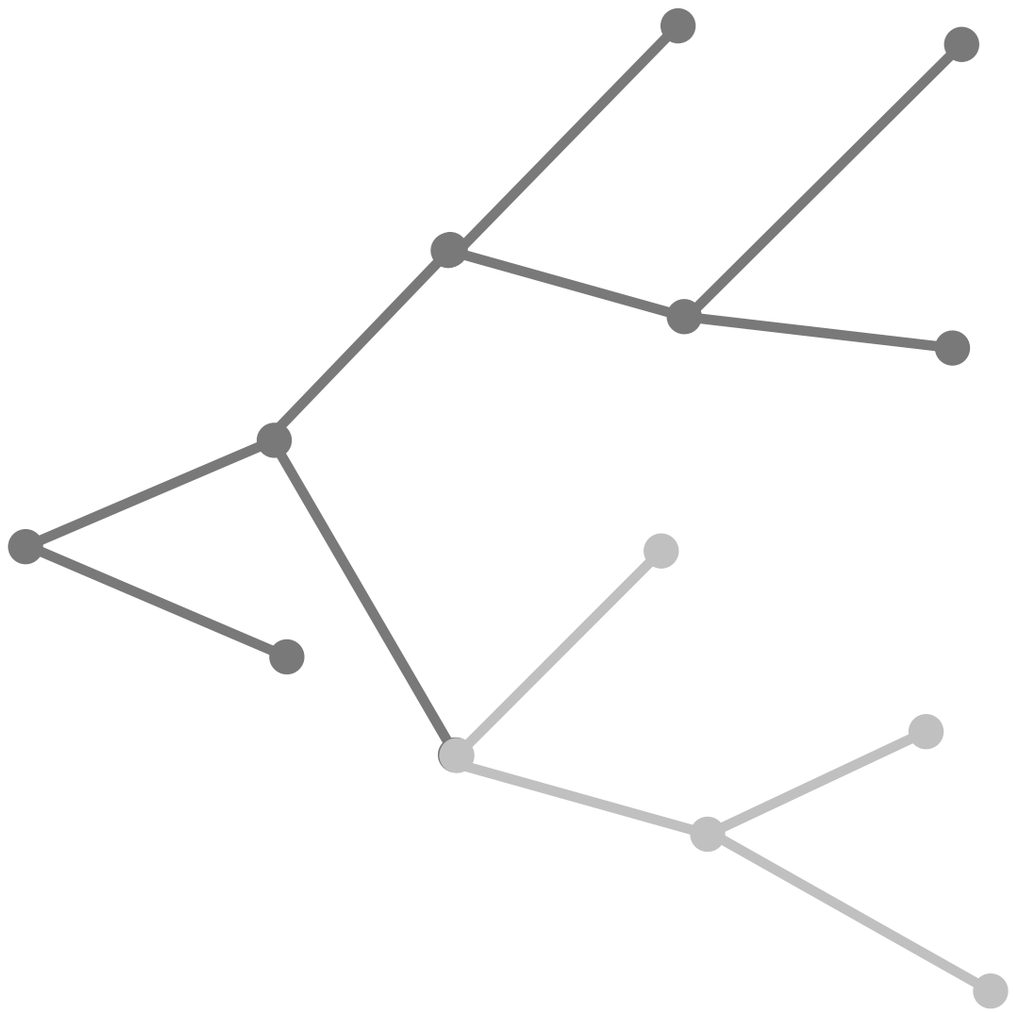

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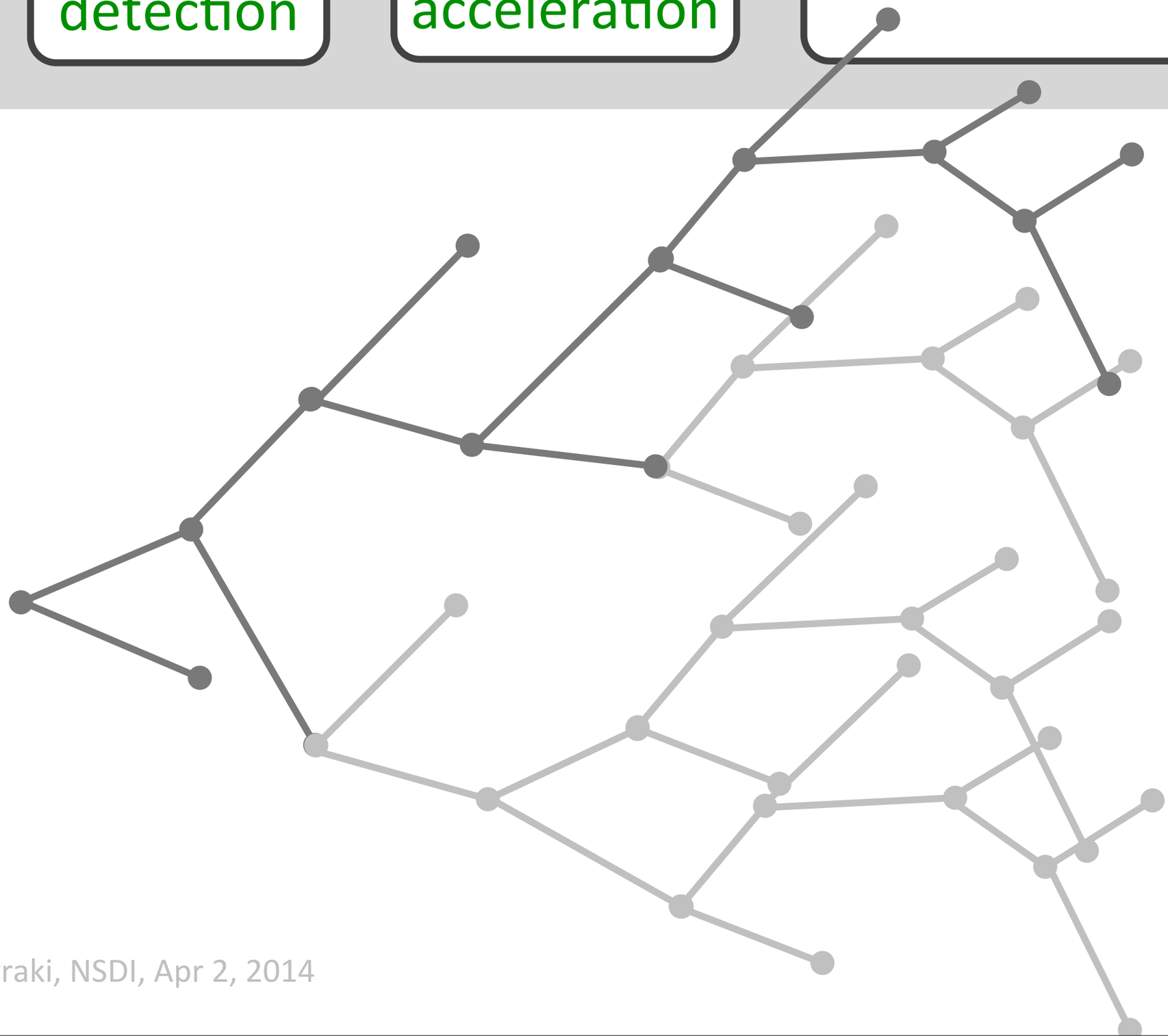

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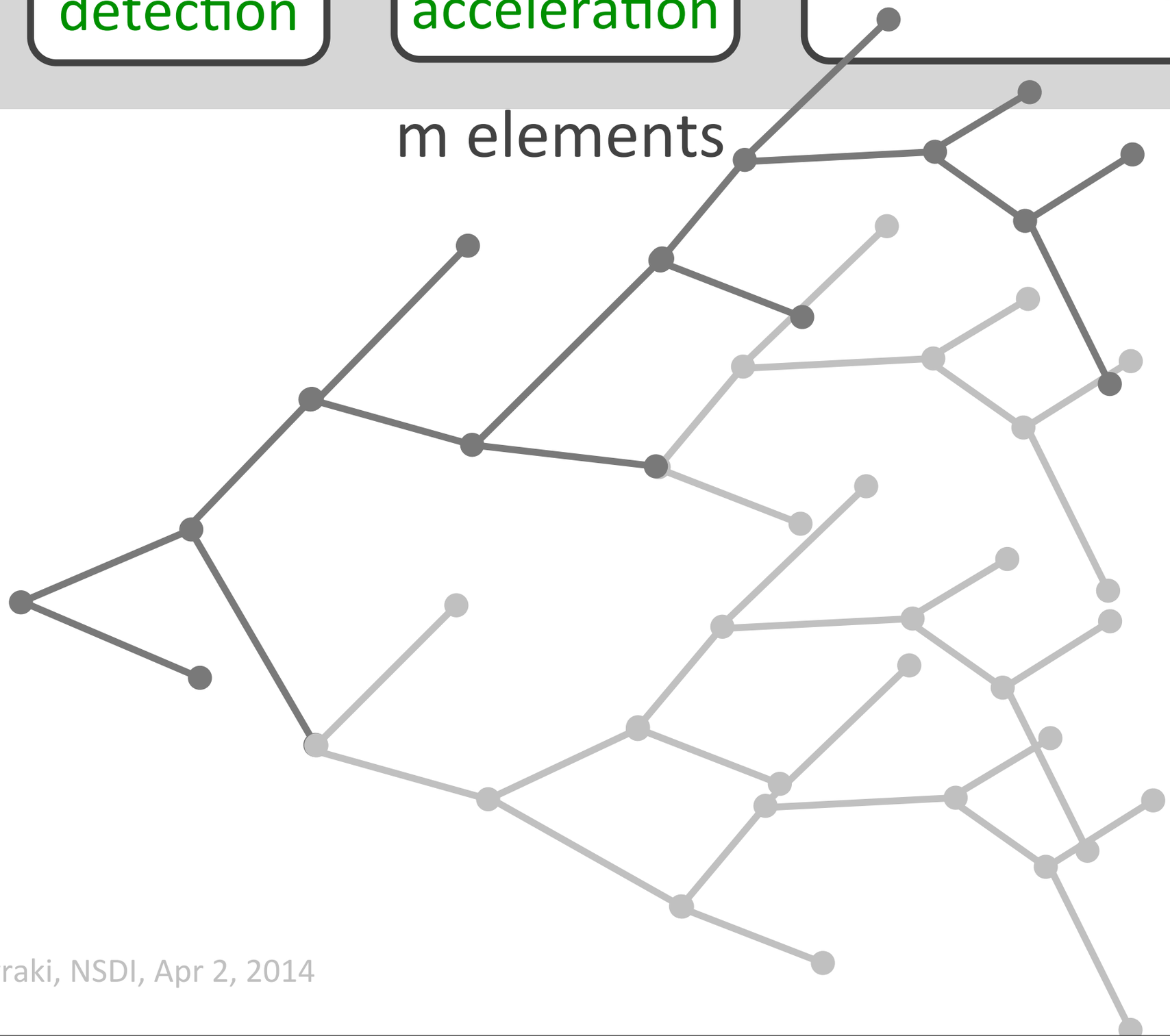
IP forwarding

m elements



intrusion detection

application acceleration

IP forwarding

m elements

n branches per element

intrusion detection

application acceleration

IP forwarding

m elements

n branches per element

verification time ~ $2^{n\,m}$

intrusion detection

application acceleration

IP forwarding

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n branches per element

intrusion detection

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m elements

do not share mutable state

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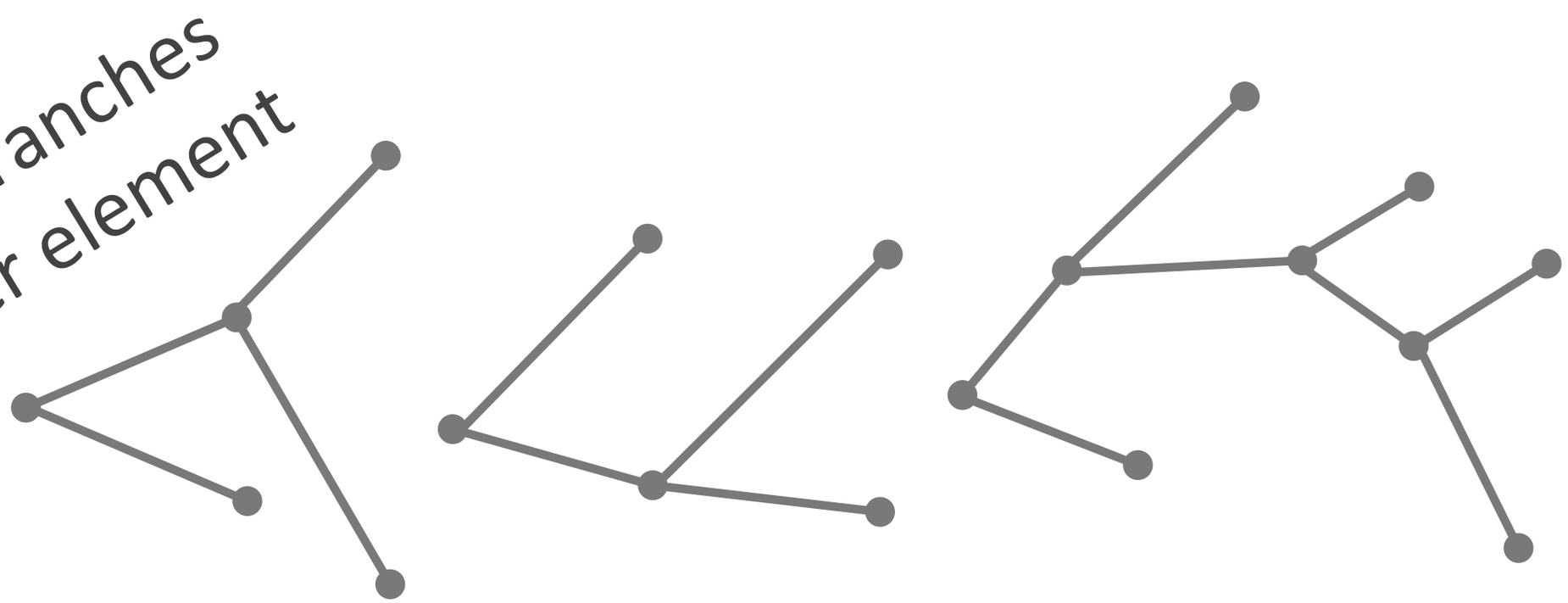

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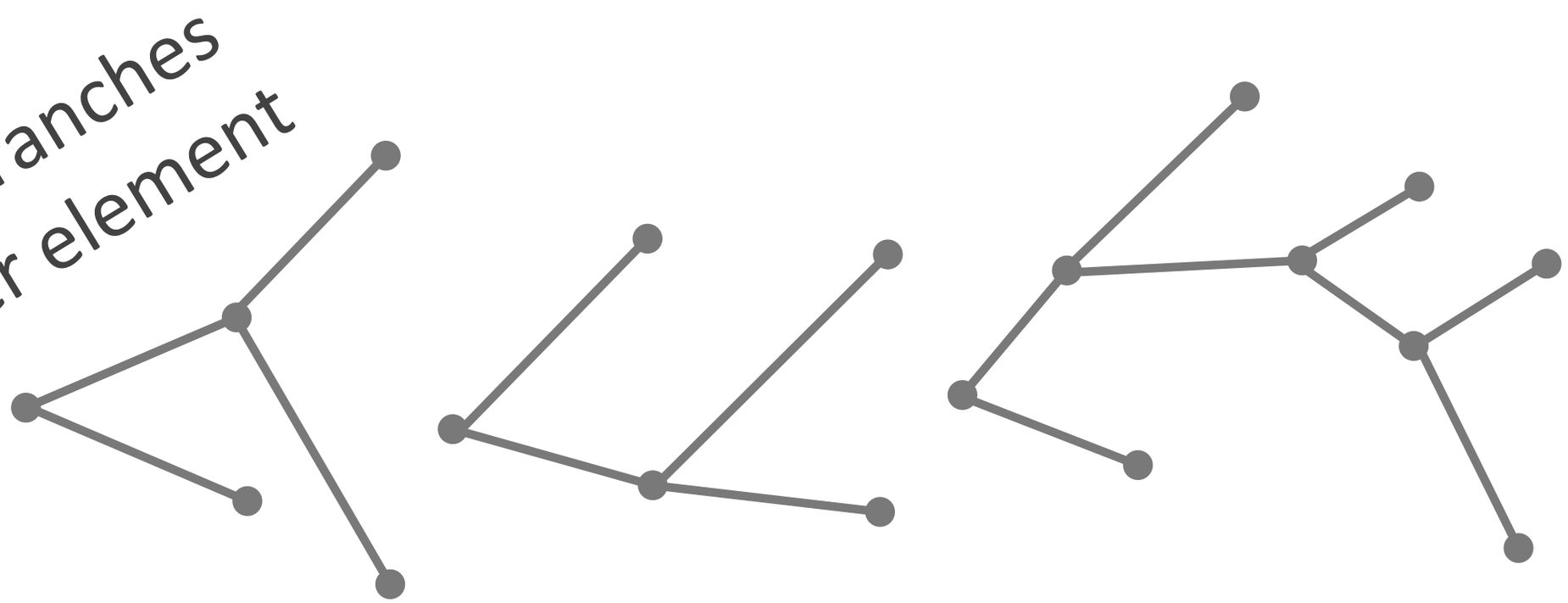

verification time ~ m 2^n

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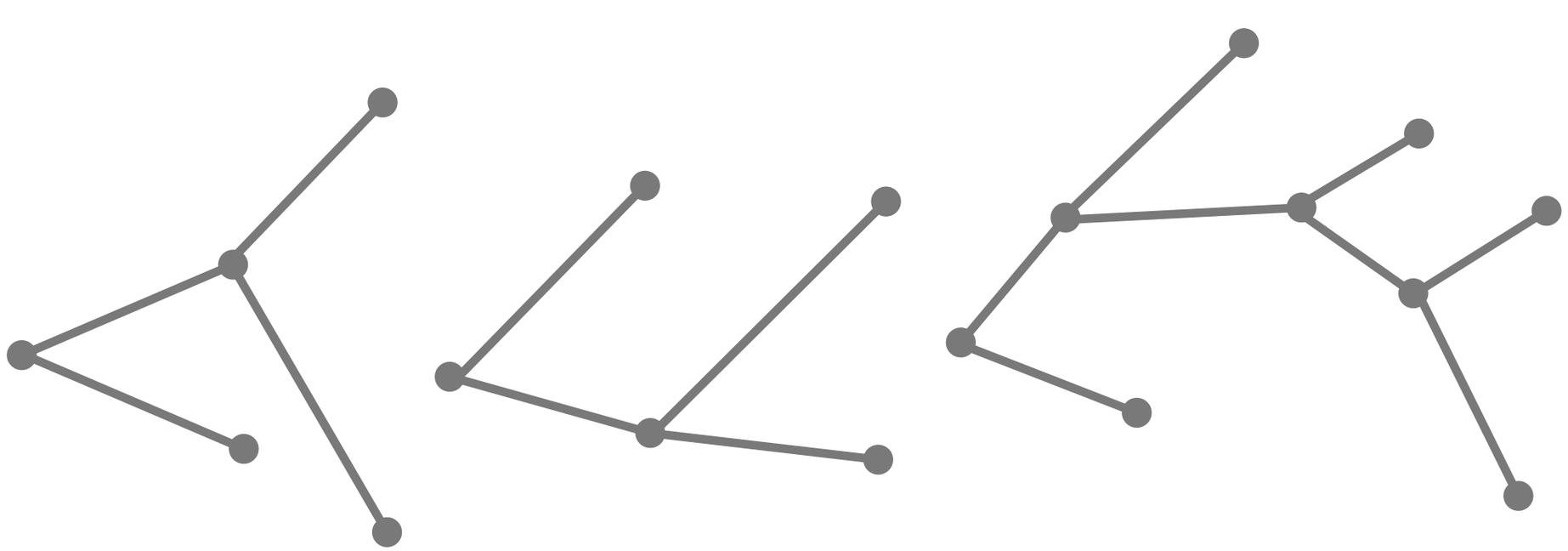

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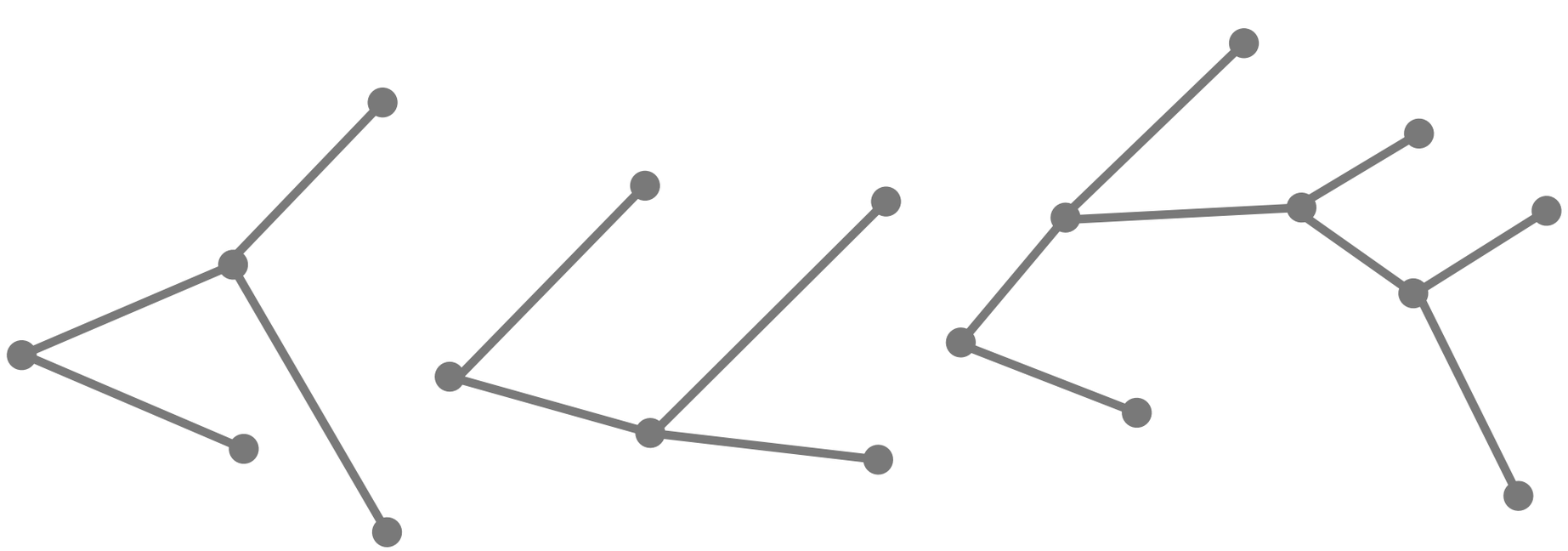

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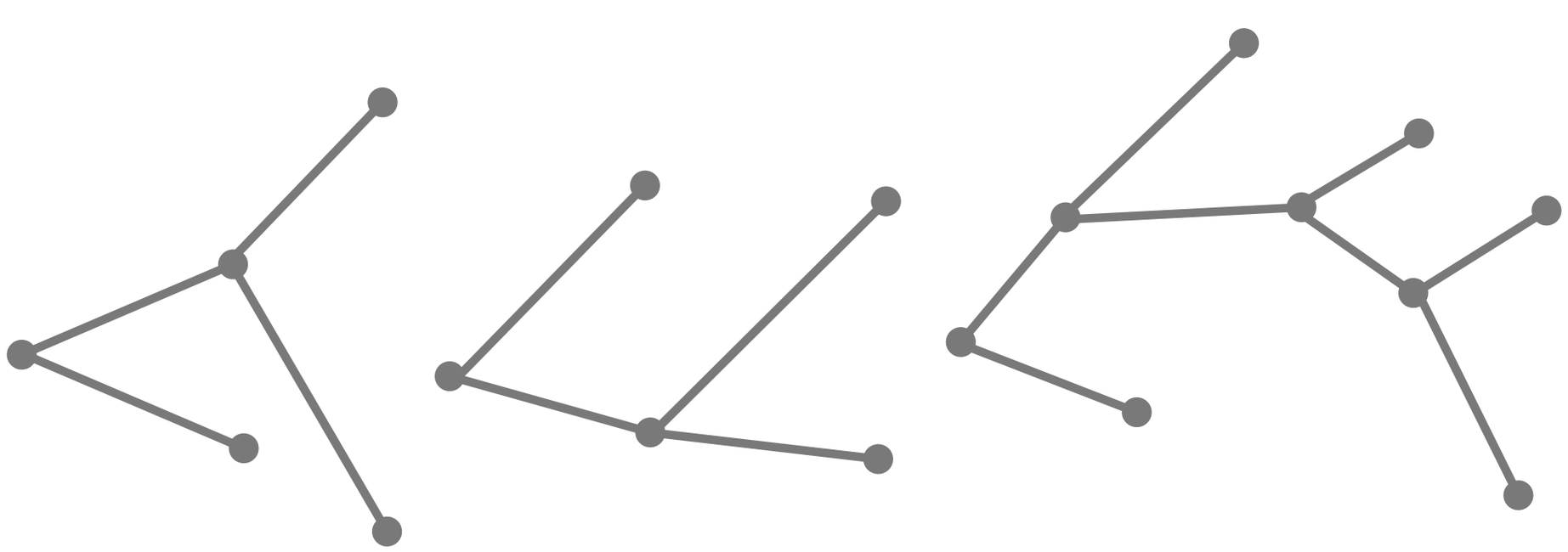
do not share mutable state



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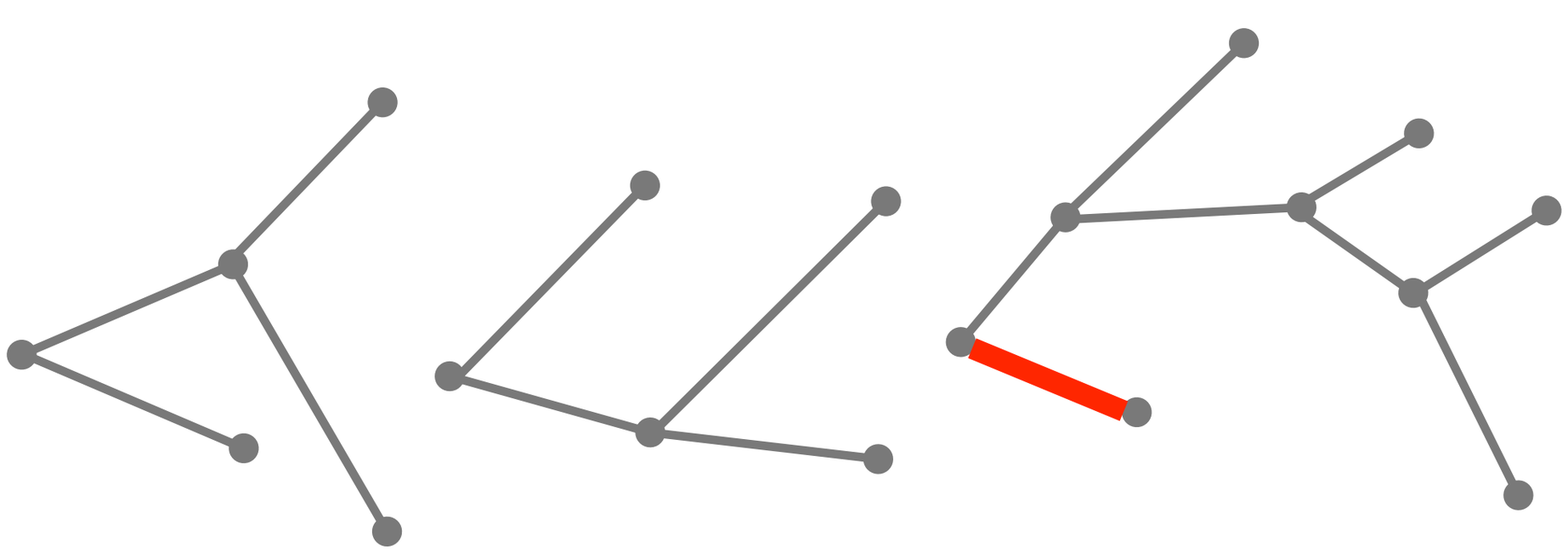

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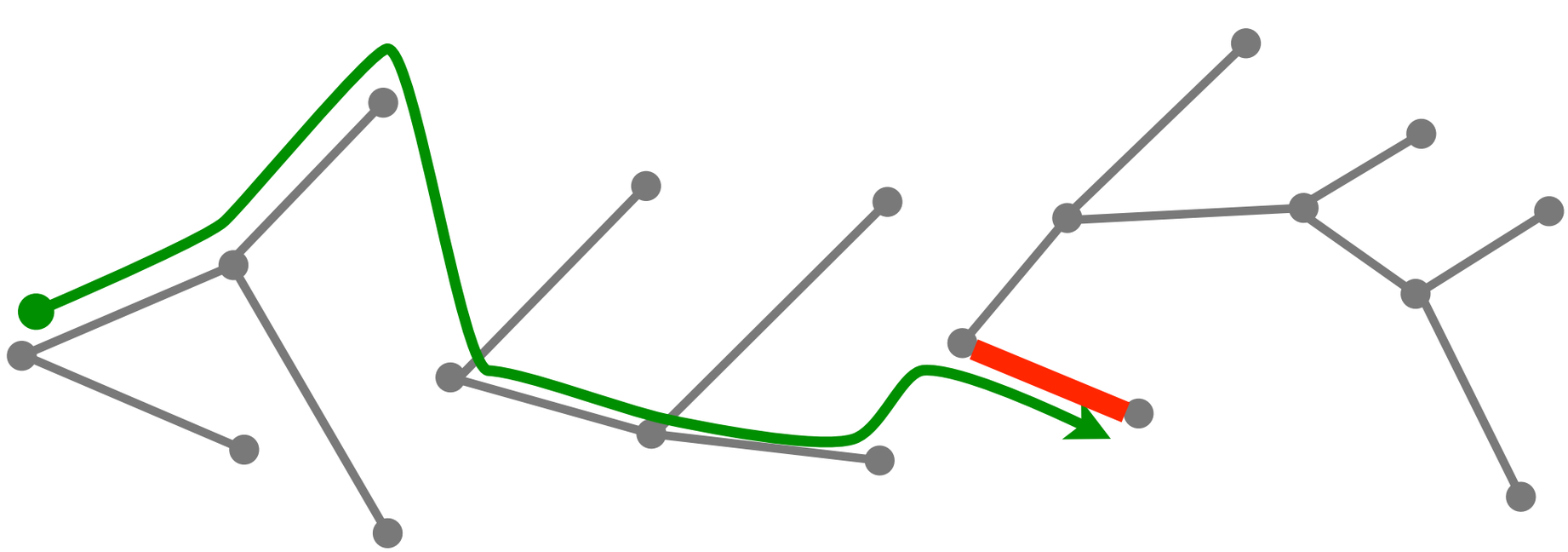

Pipeline decomposition

- Rule: pipeline structure
  - *distinct packet-processing elements*
  - *do not share mutable state*

- Effect: compose at the element level
  - *can reduce #paths from* $\sim 2^{n\,m}$
  - *to* $\sim m\,2^{n}$

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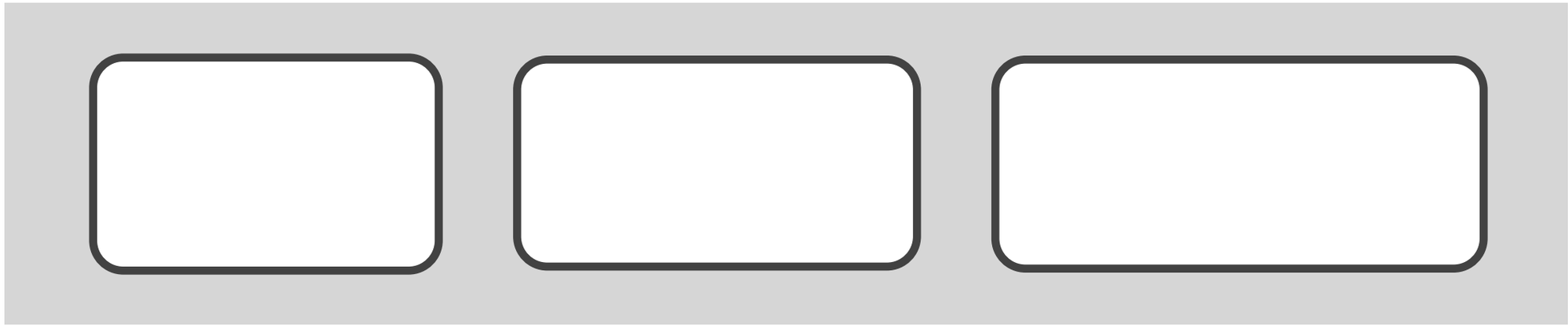
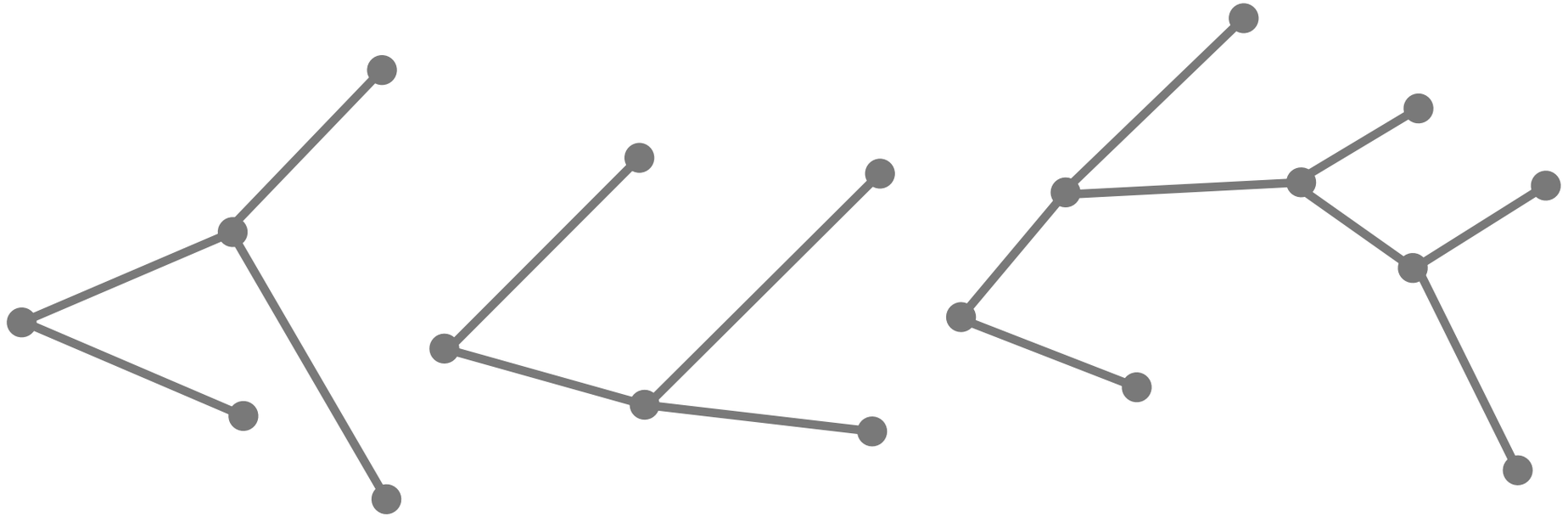
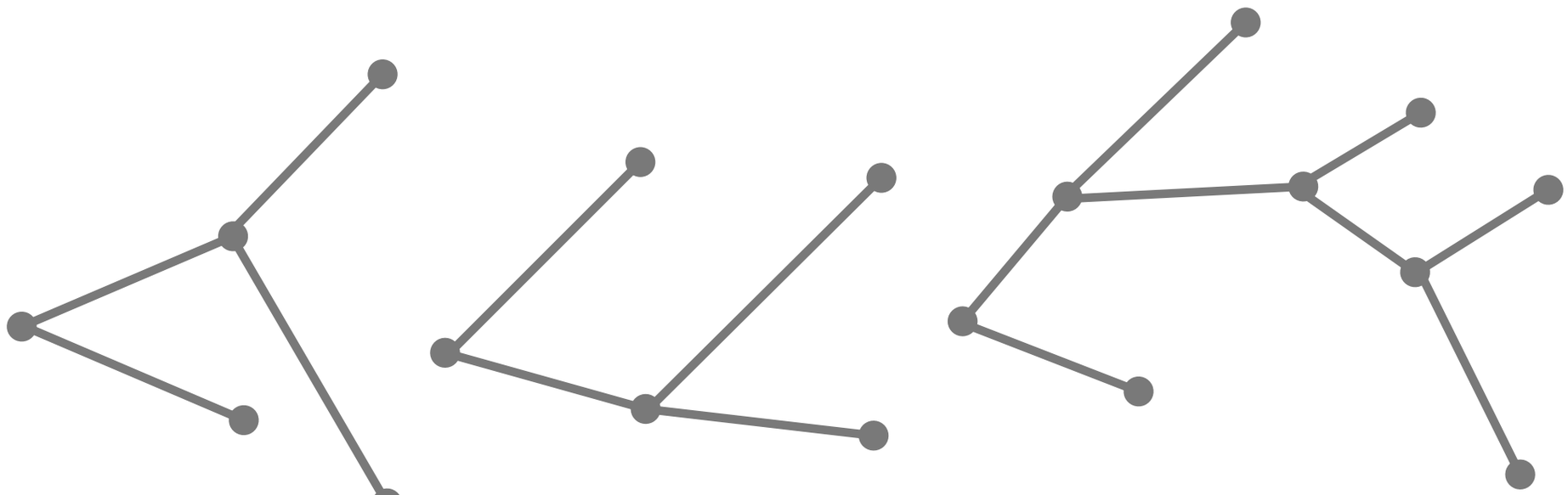





IP options



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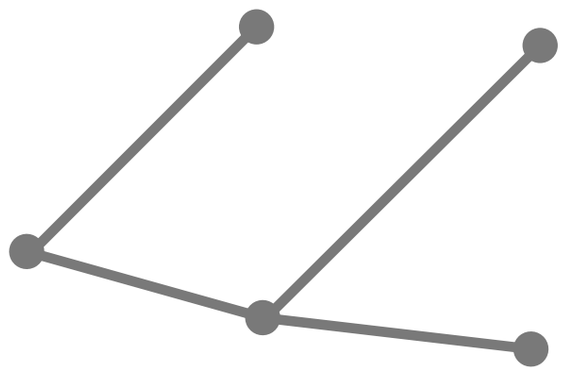

option #1 option #2 ... option #m

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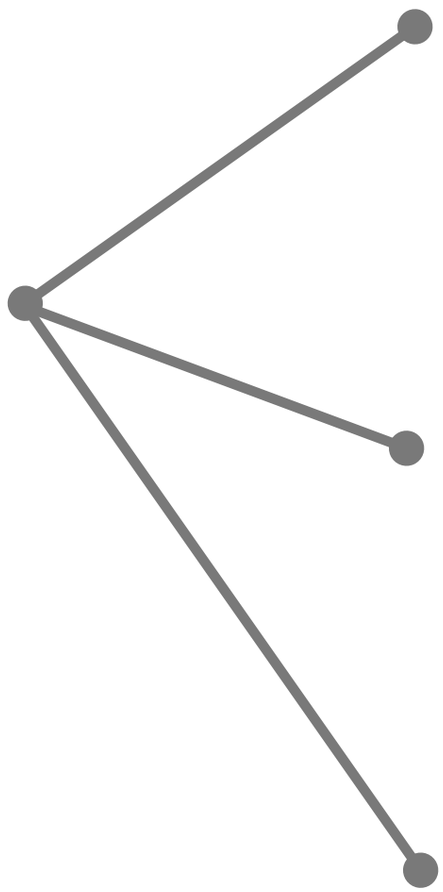

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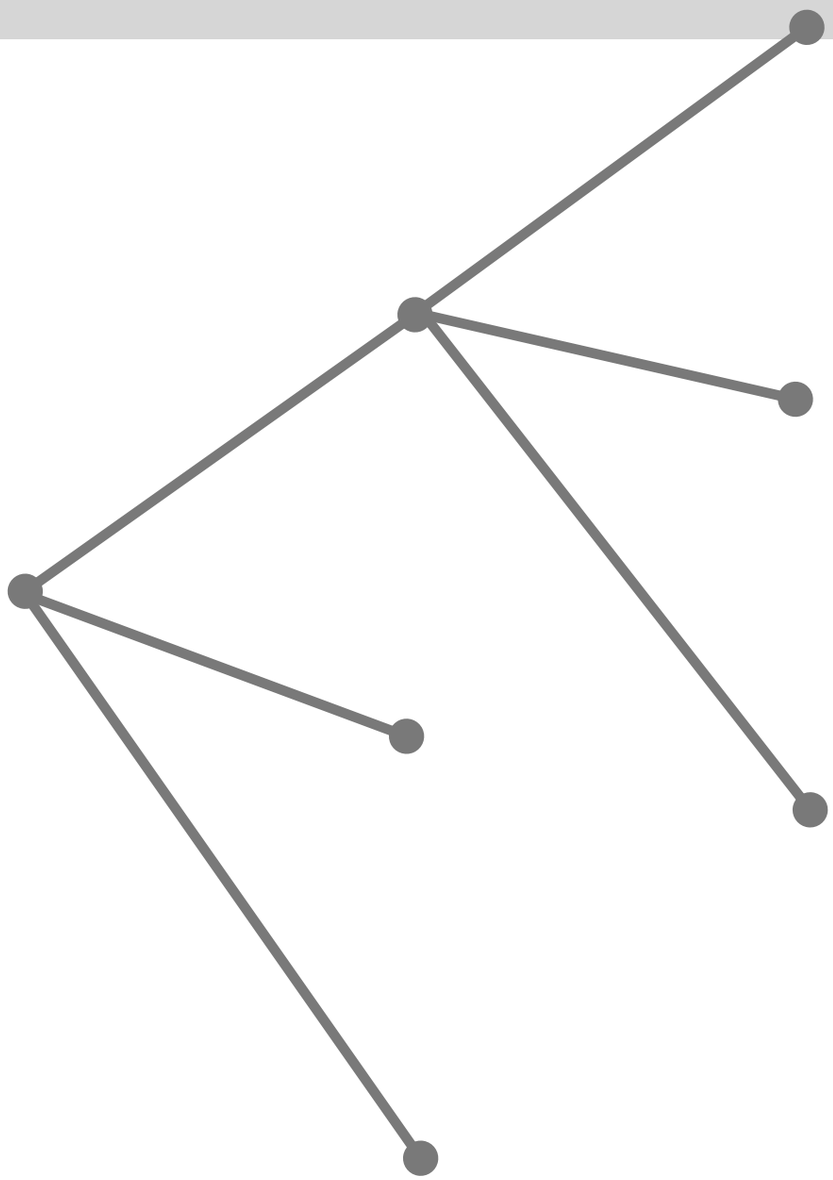

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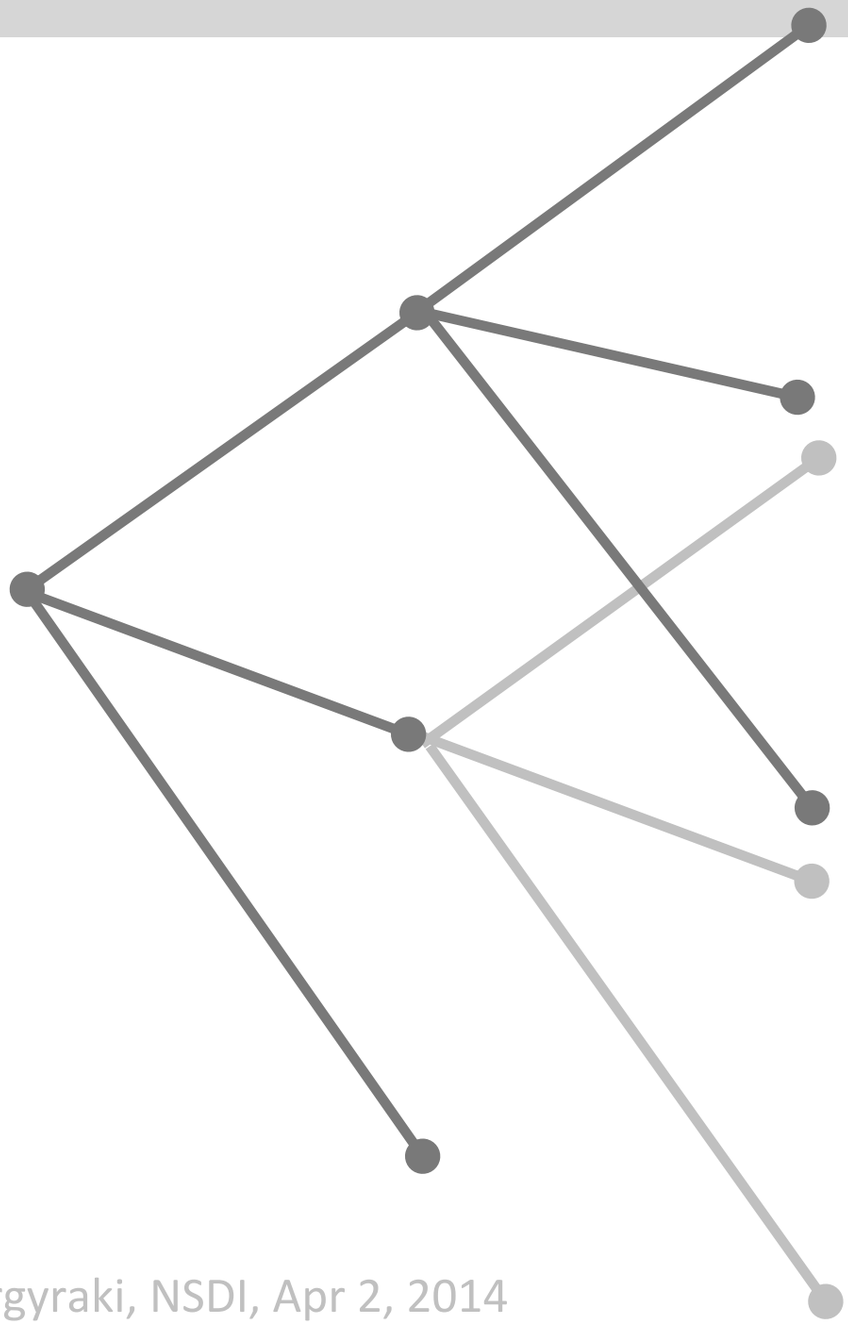

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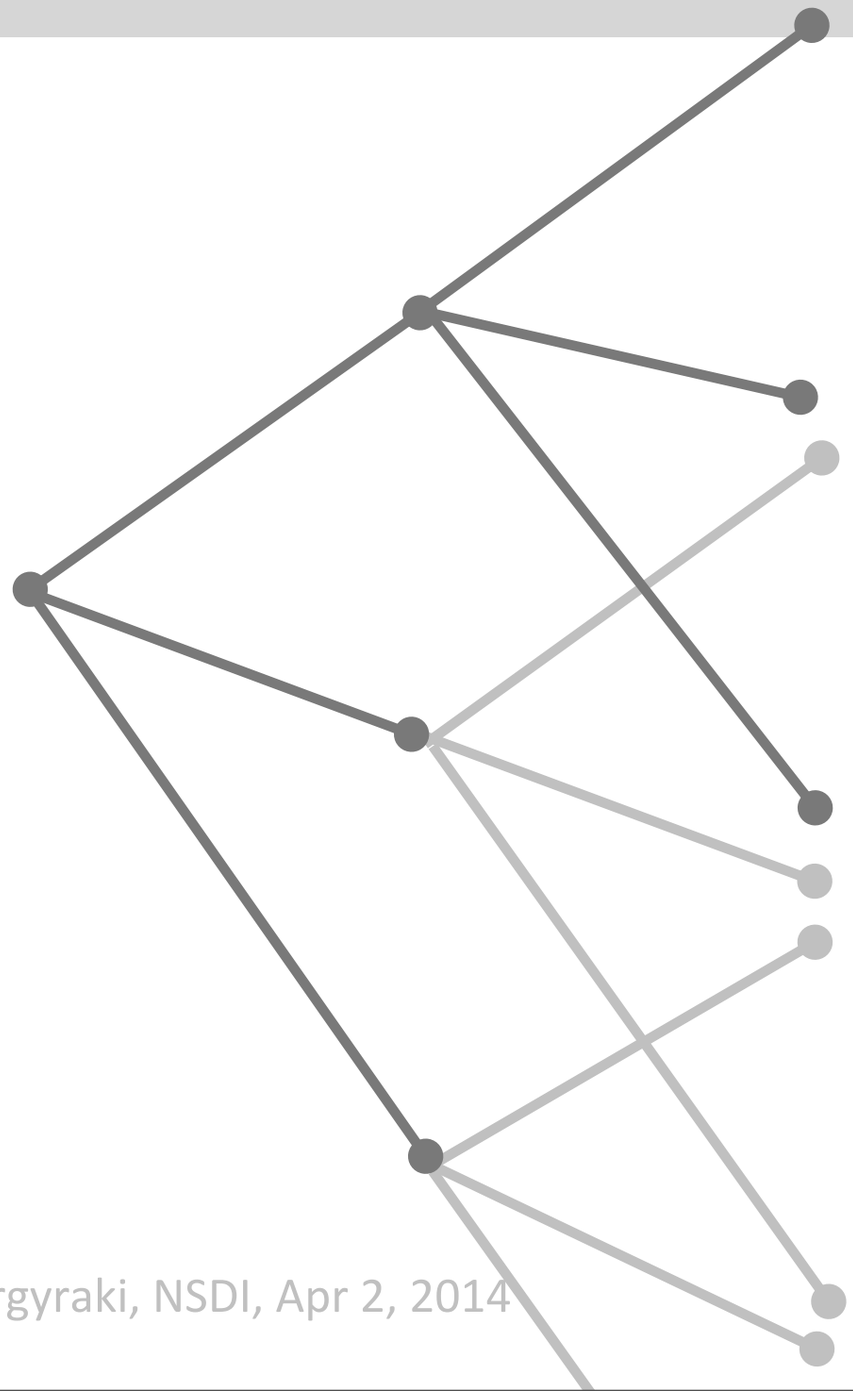

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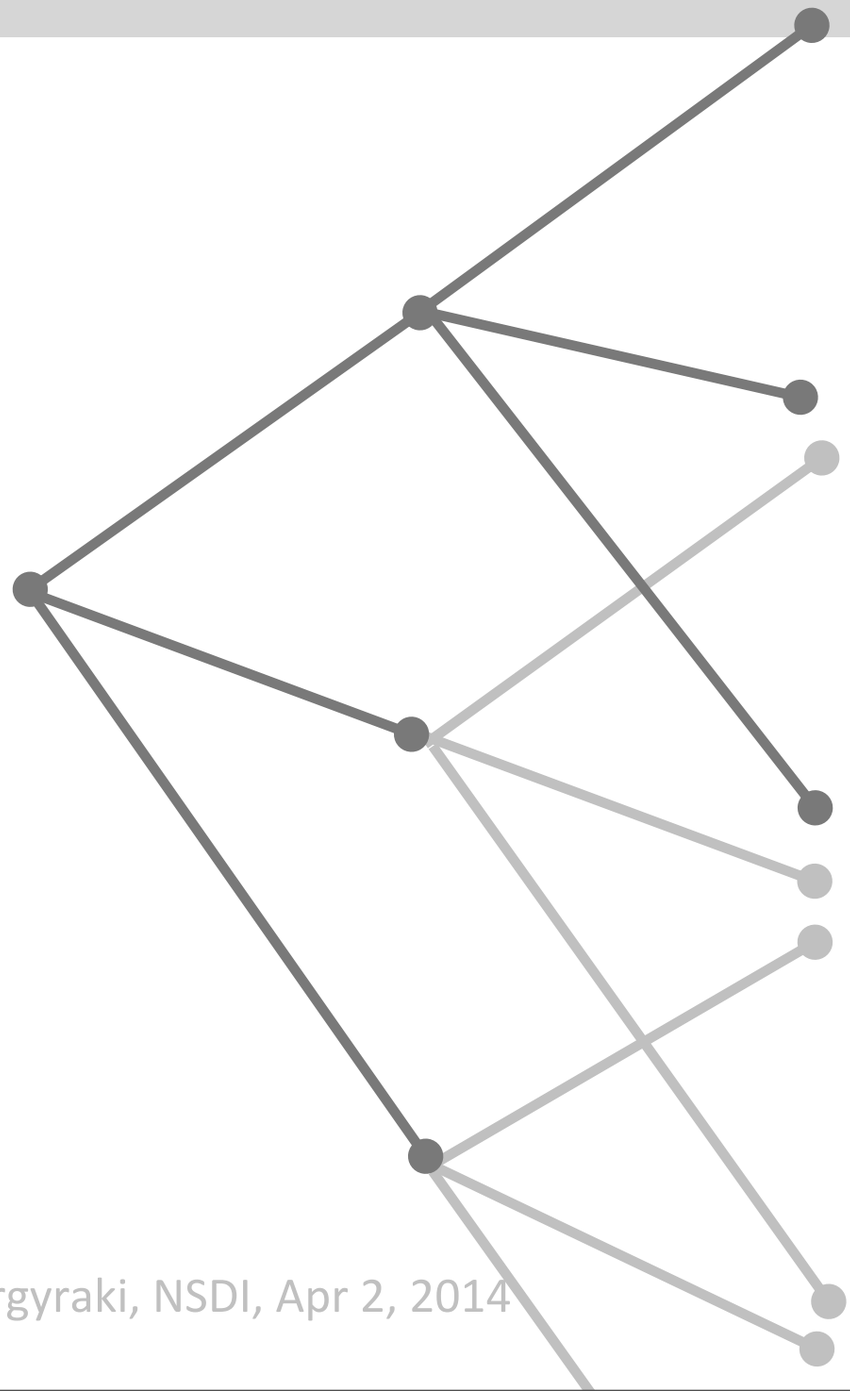
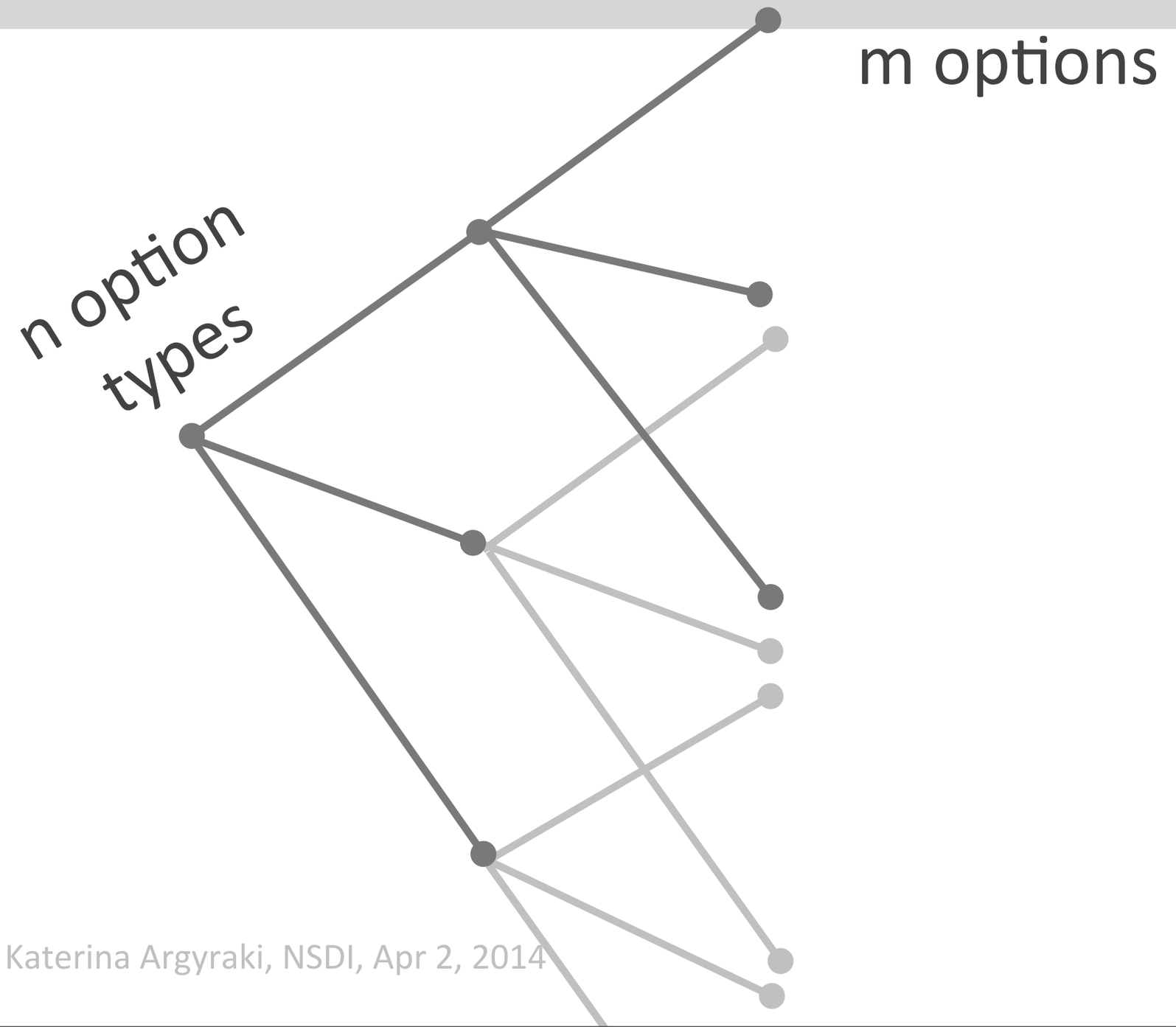


m options

option #1 option #2 ... option #m



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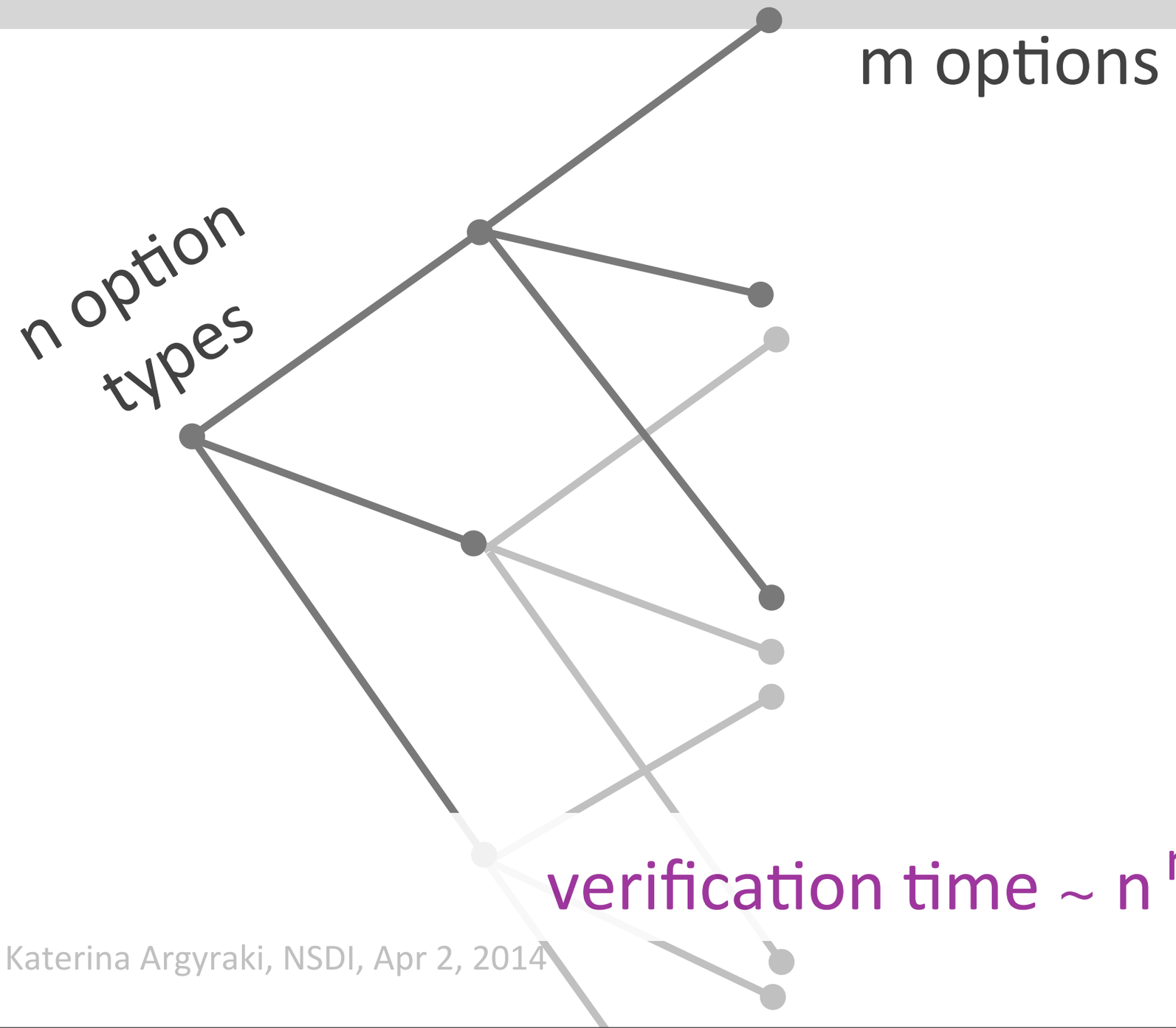


verification time ~ n^m

option #1 | option #2 | ... | option #m

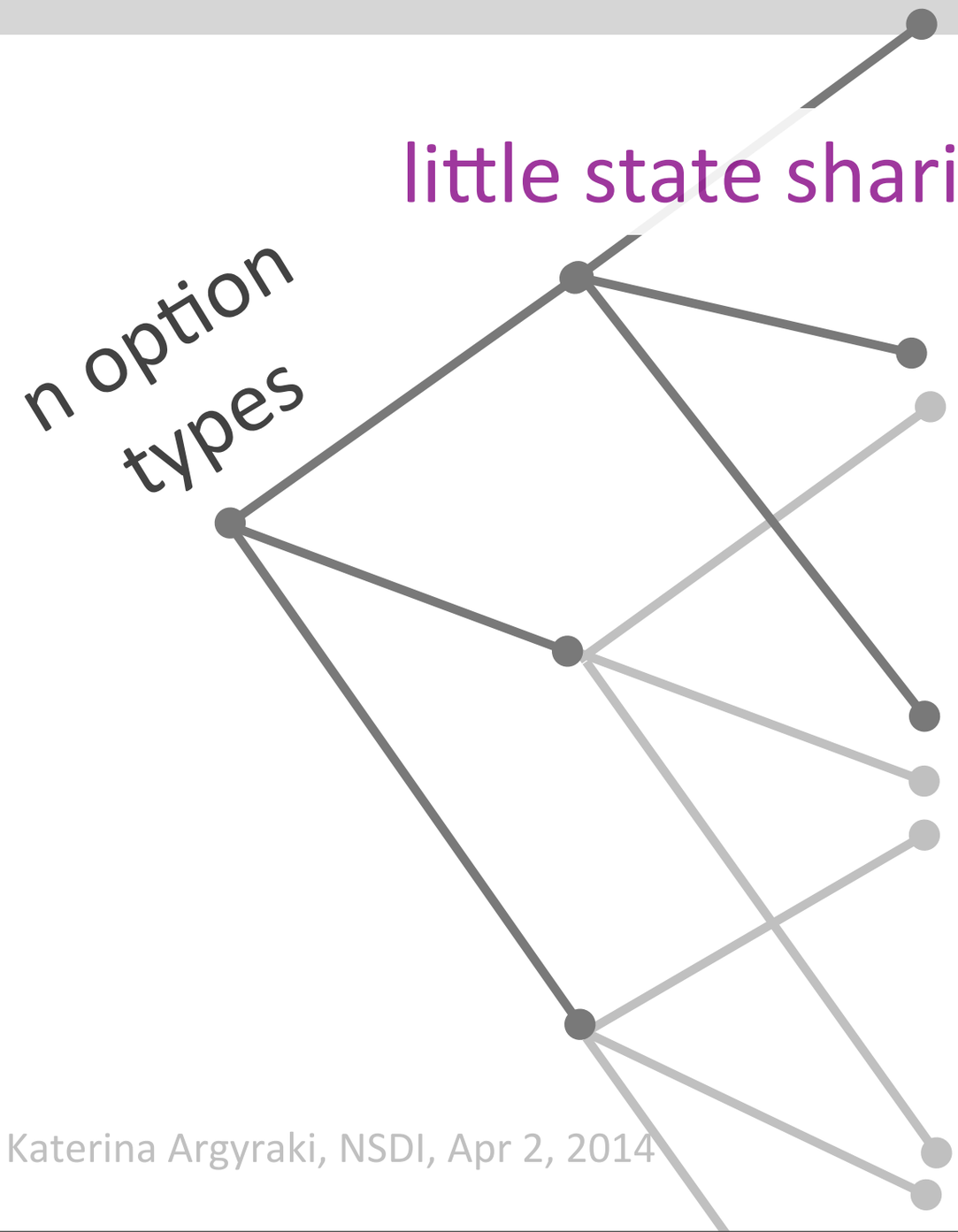
m options

n option types

option #1 | option #2 | ... | option #m

m options

little state sharing across iterations

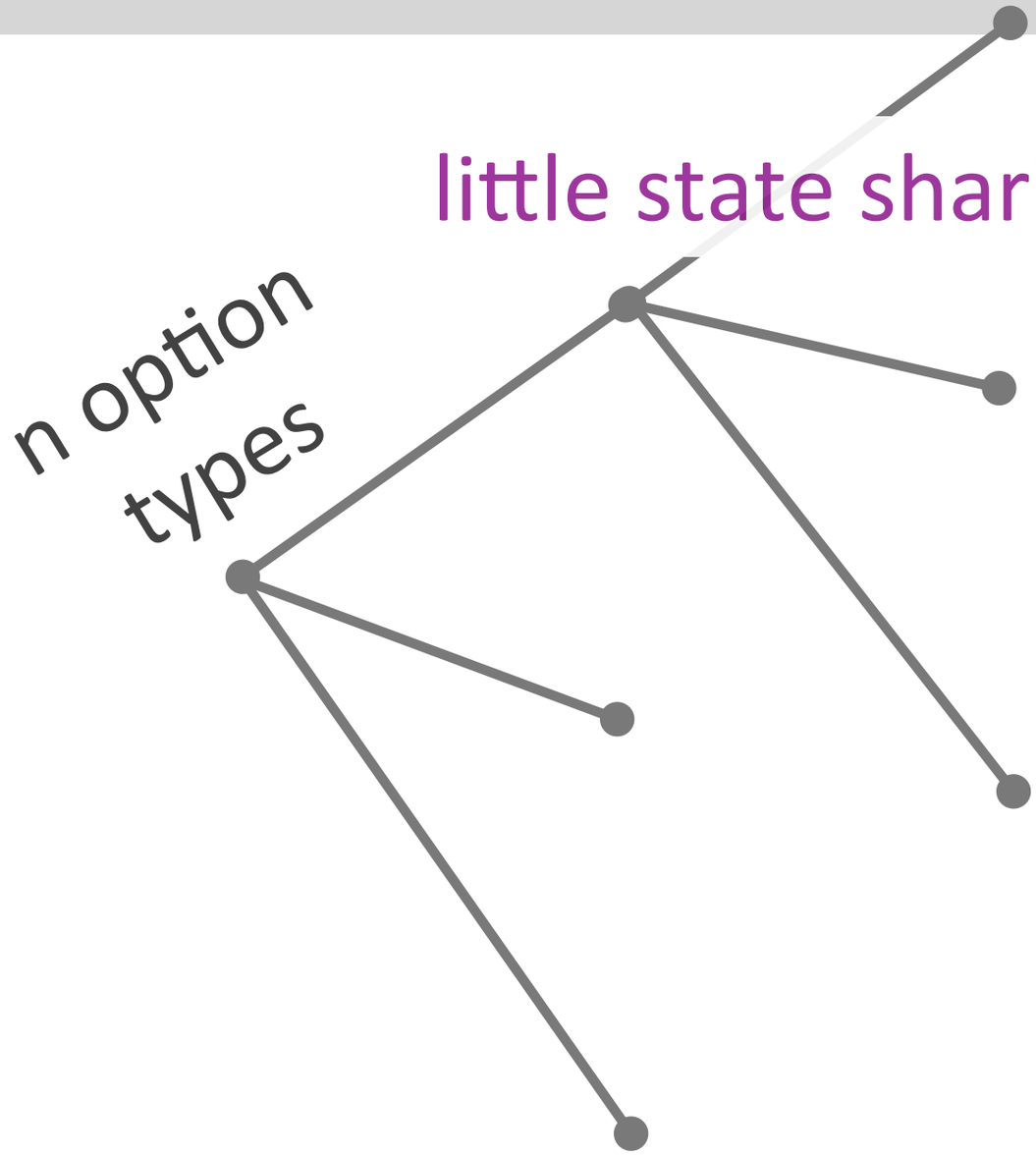


option #1 | option #2 | ... | option #m

m options

little state sharing across iterations

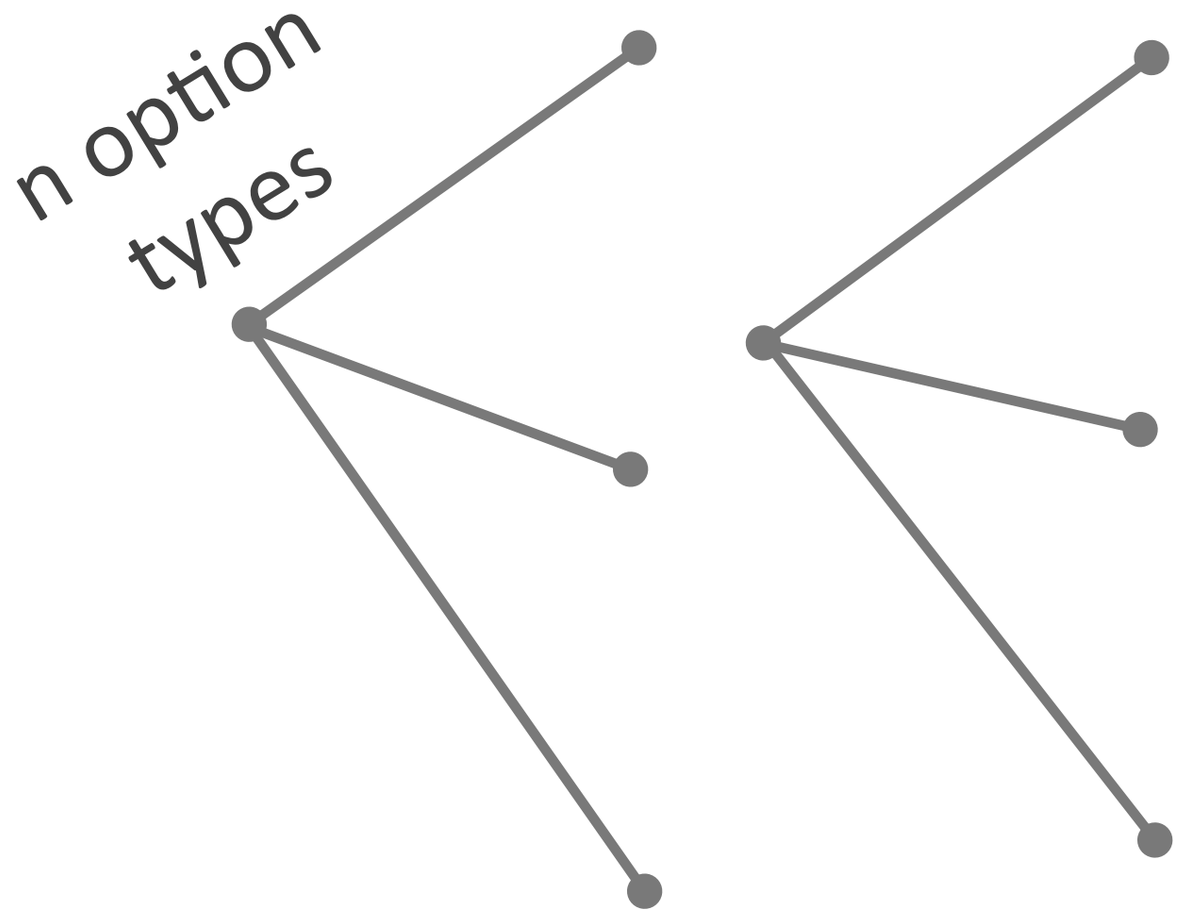
n option types



option #1 | option #2 | ... | option #m

m options

little state sharing across iterations



option #1 | option #2 | ... | option #m

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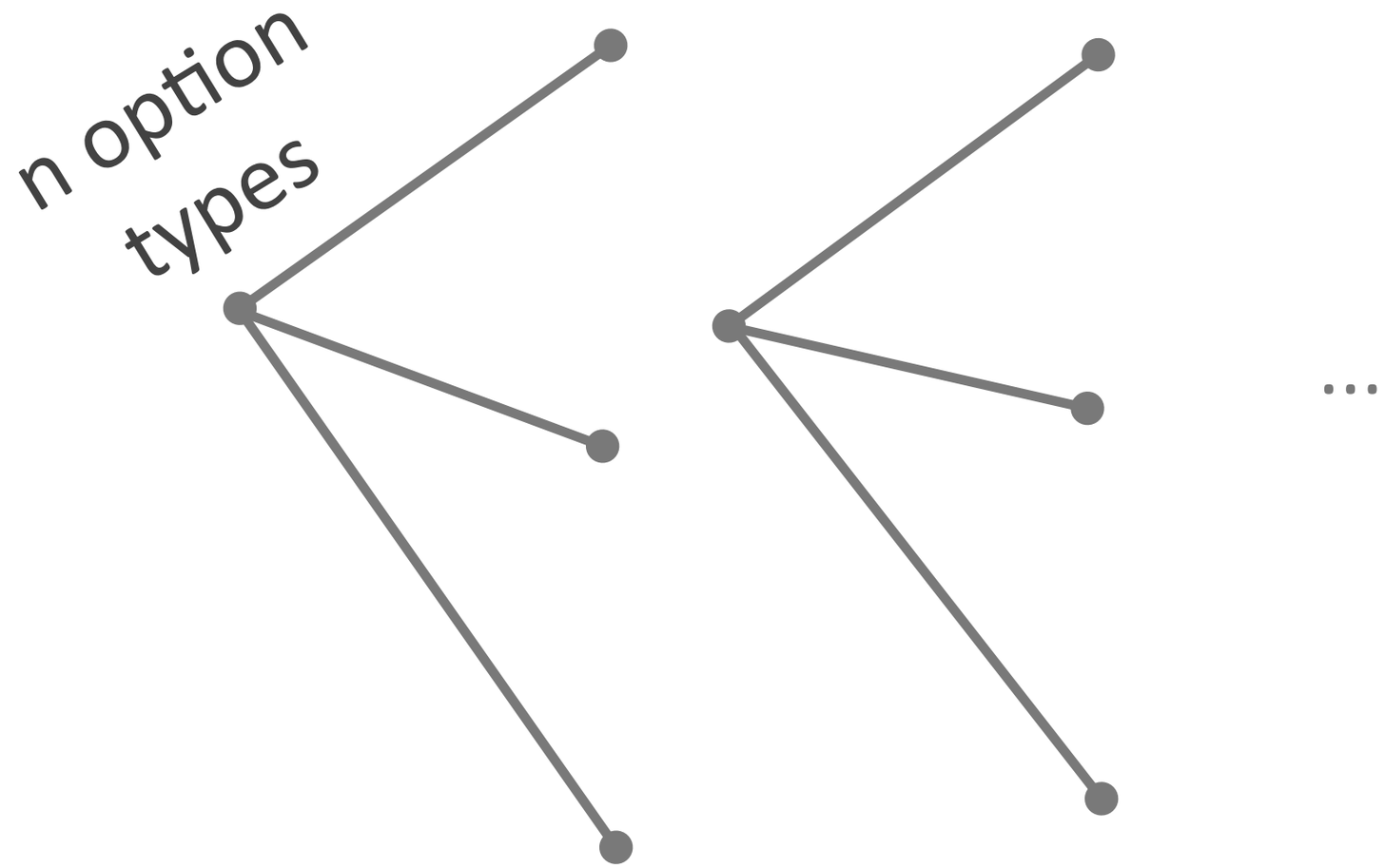
little state sharing across iterations



option #1 | option #2 | ... | option #m

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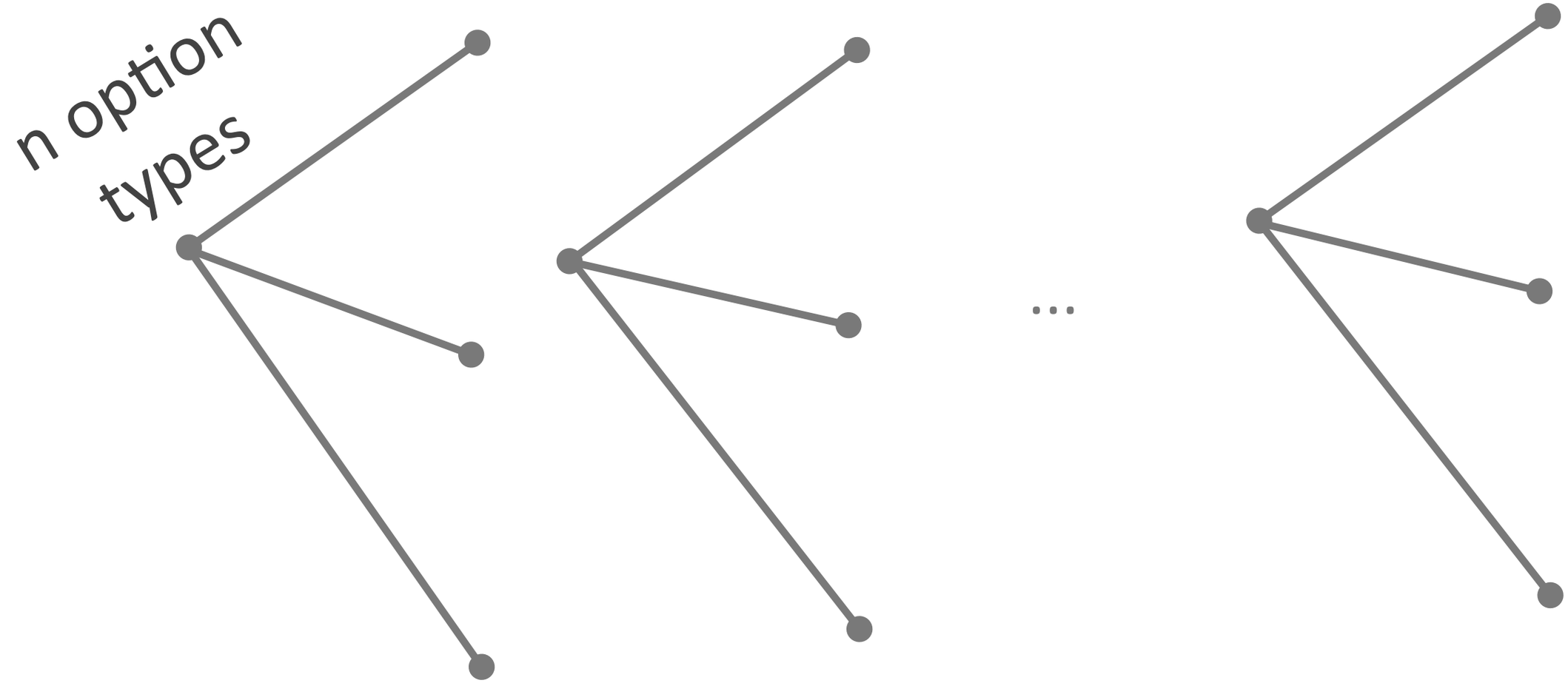

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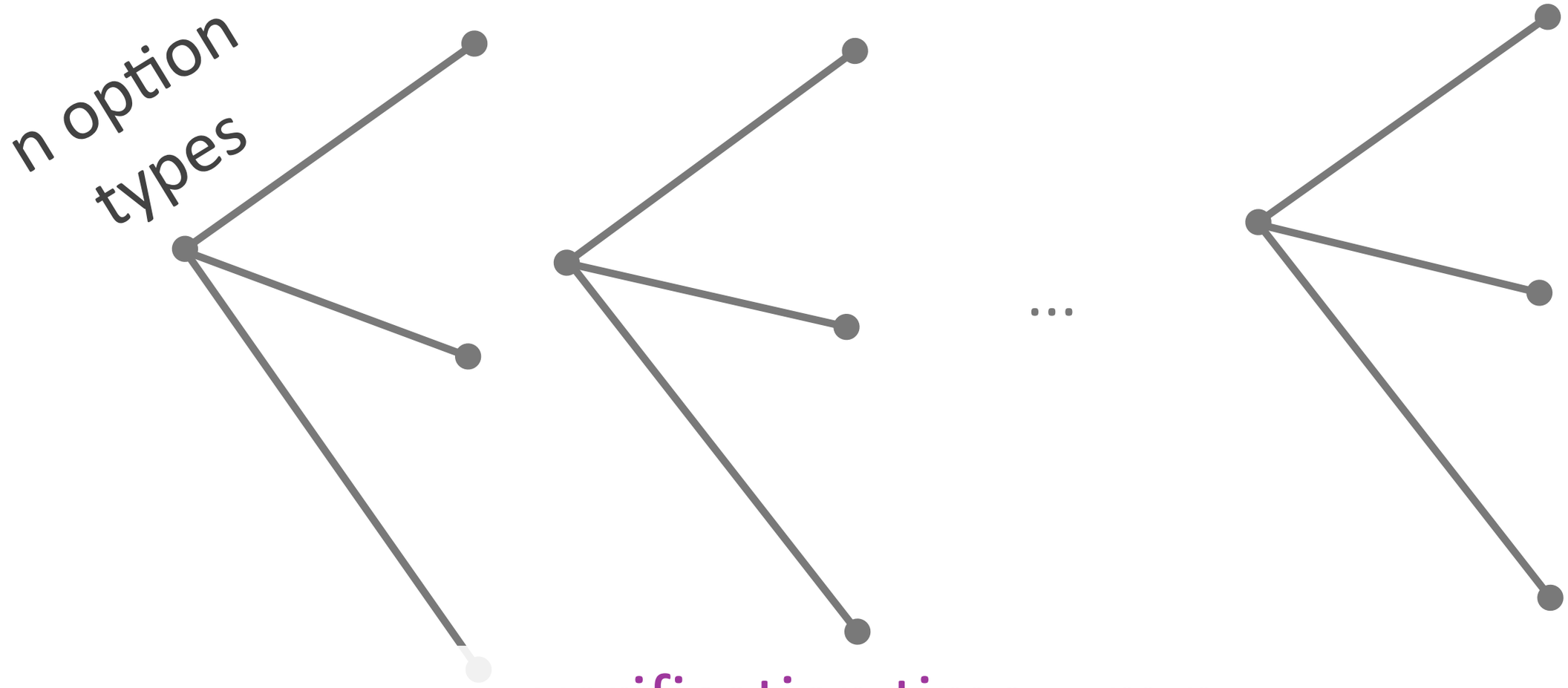


verification time ~ m n

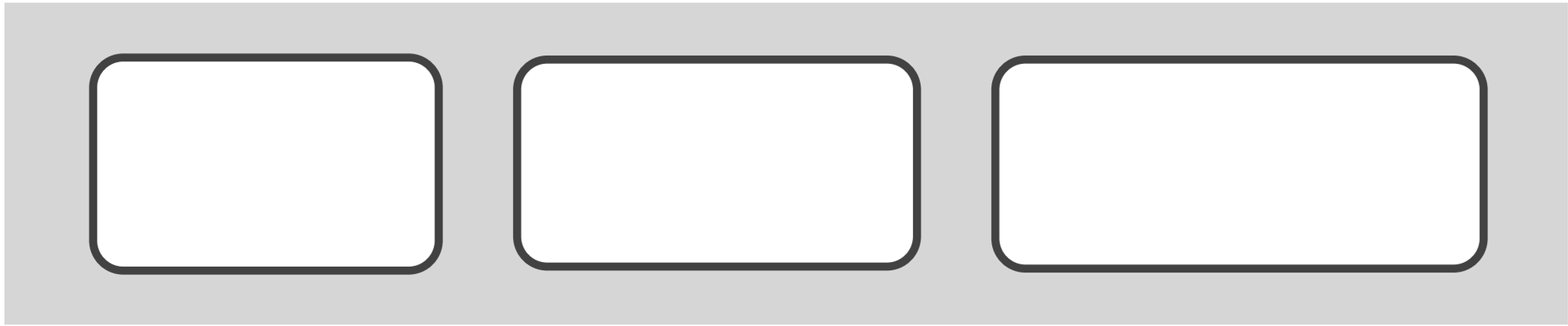
Loop decomposition

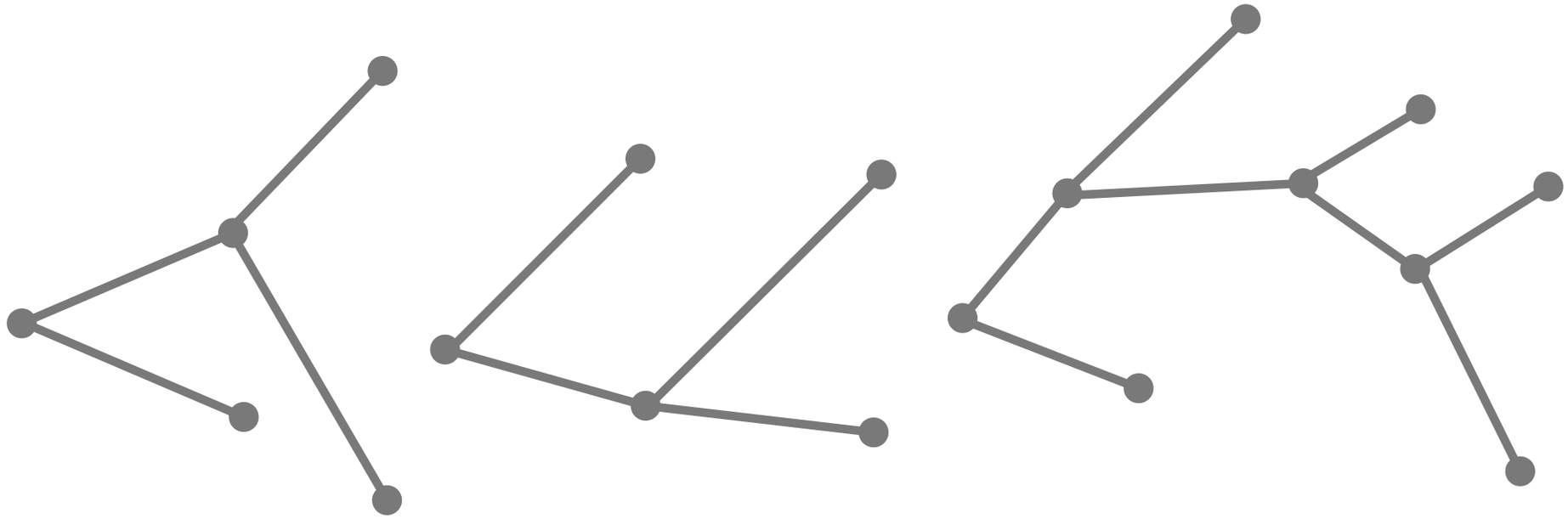
- Rule: "mini-pipeline" structure
  - *little state shared across iterations*
  - *made explicit by the programmer*

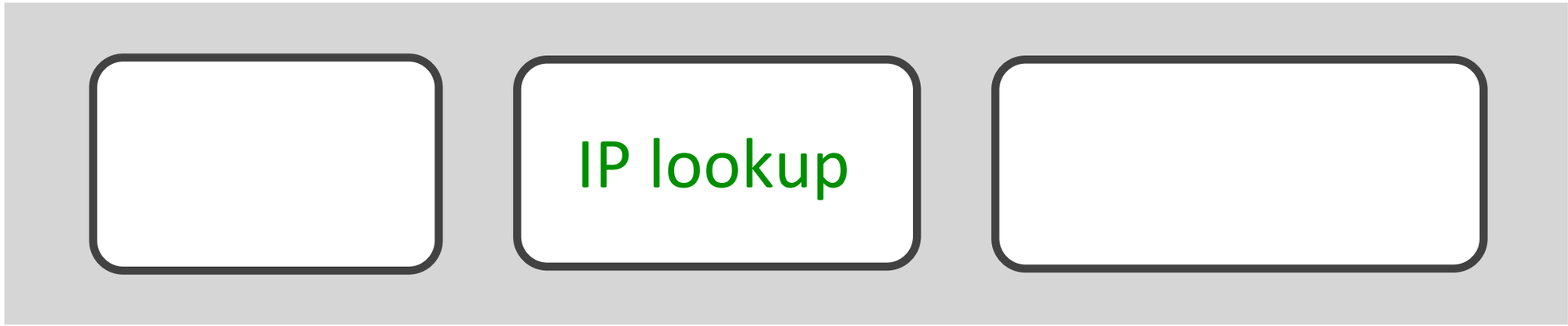
- Effect: compose at the iteration level
  - *can reduce #paths from* $\sim n^m$
  - *to* $\sim m\,n$

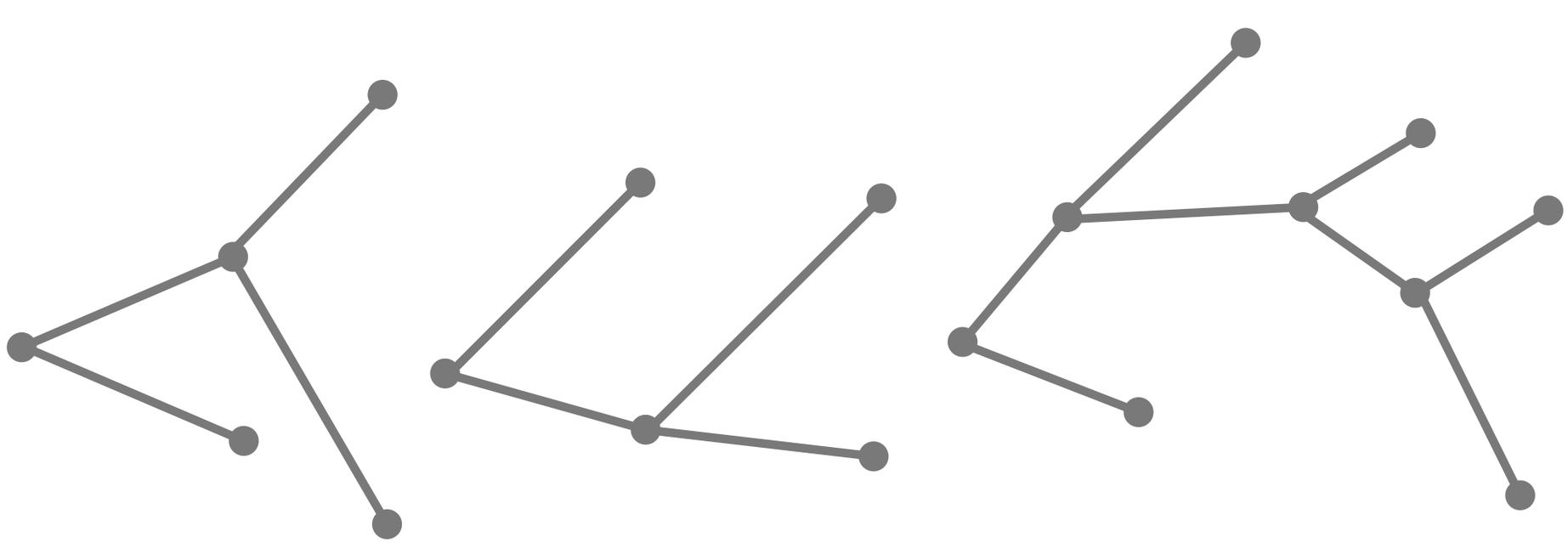
Outline

- Pipeline
- Loops
- Data structures
- Results

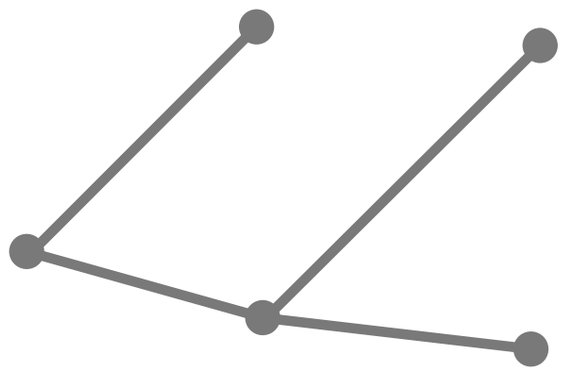





IP lookup



IP lookup



... output_port = table[dst_prefix] ...

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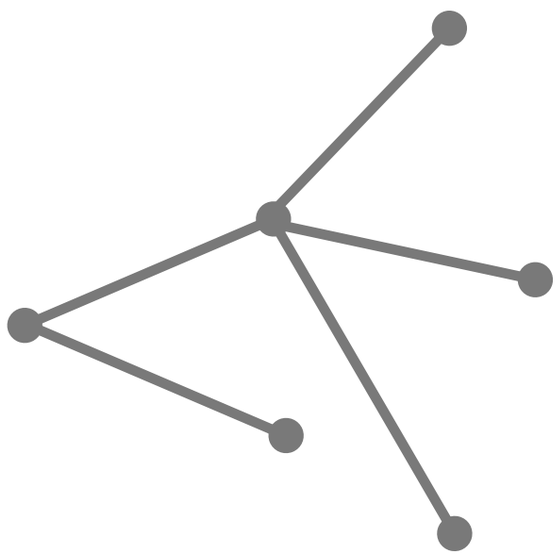

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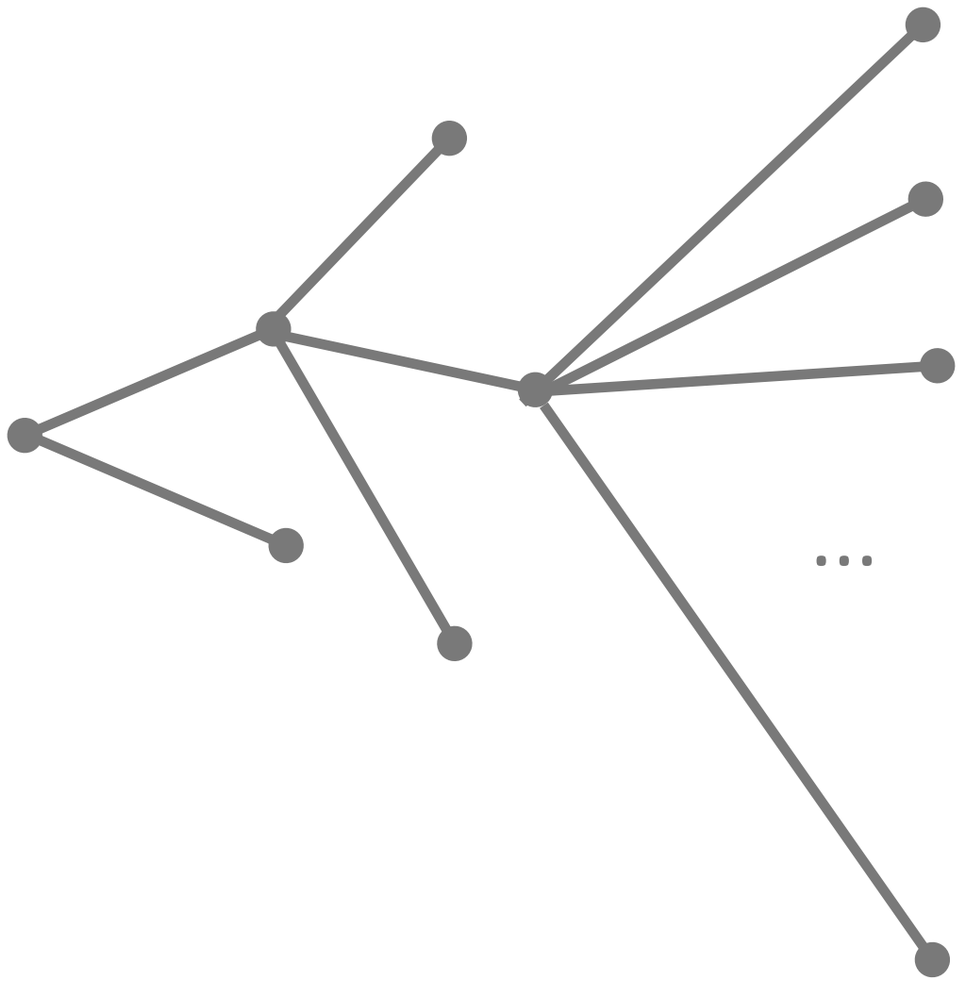

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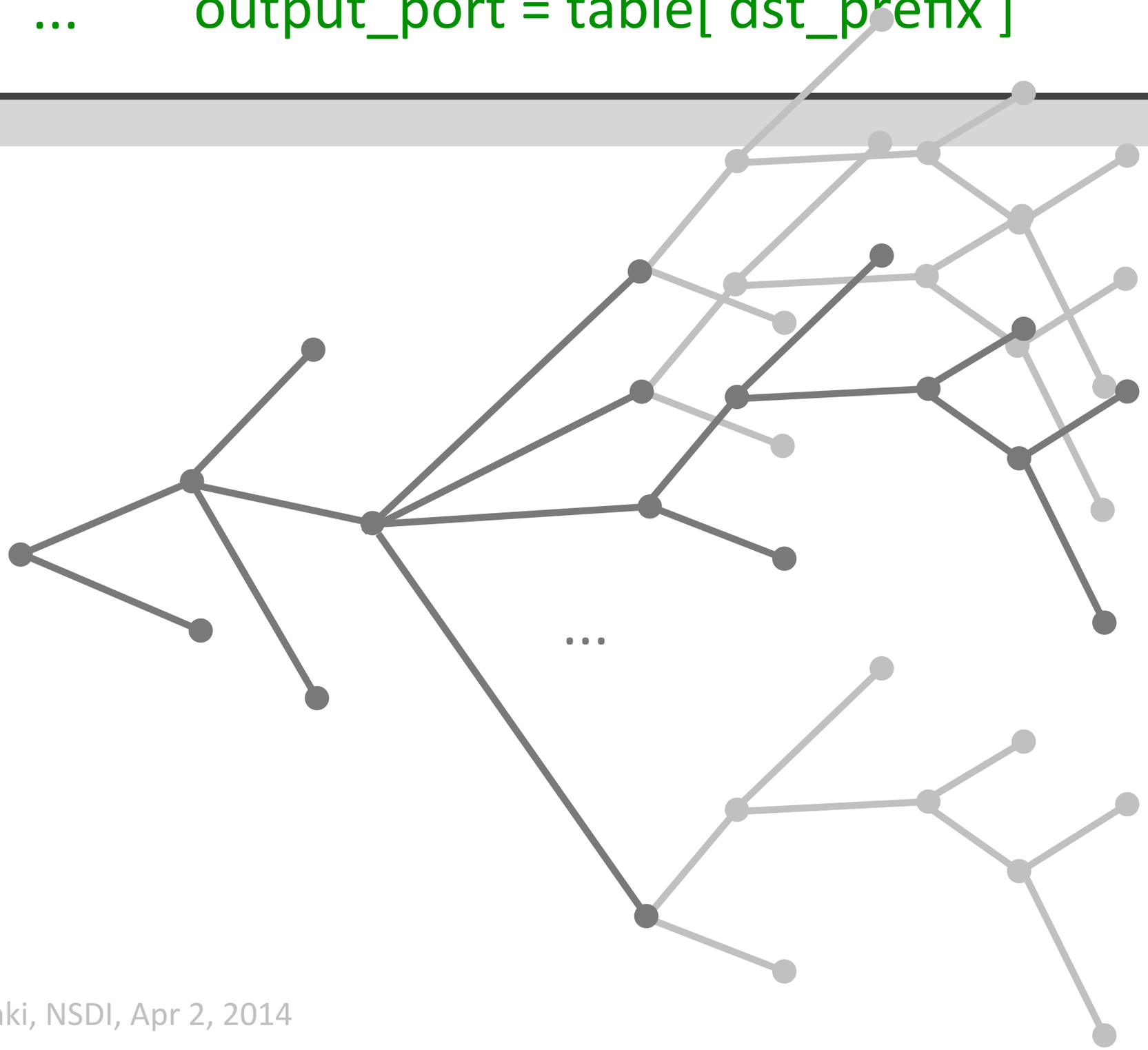

```
... output_port = table.read( dst prefix ) ...
```

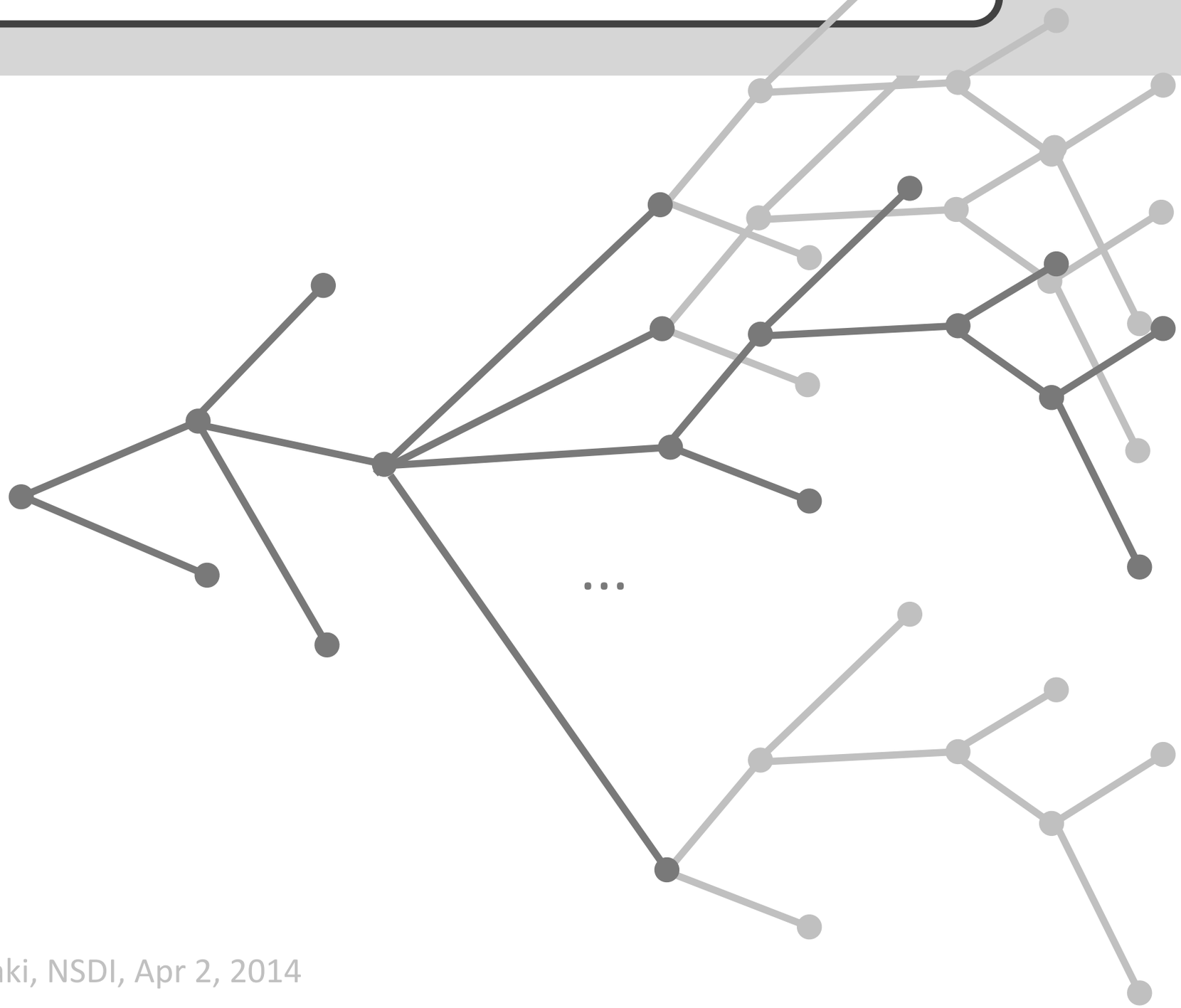

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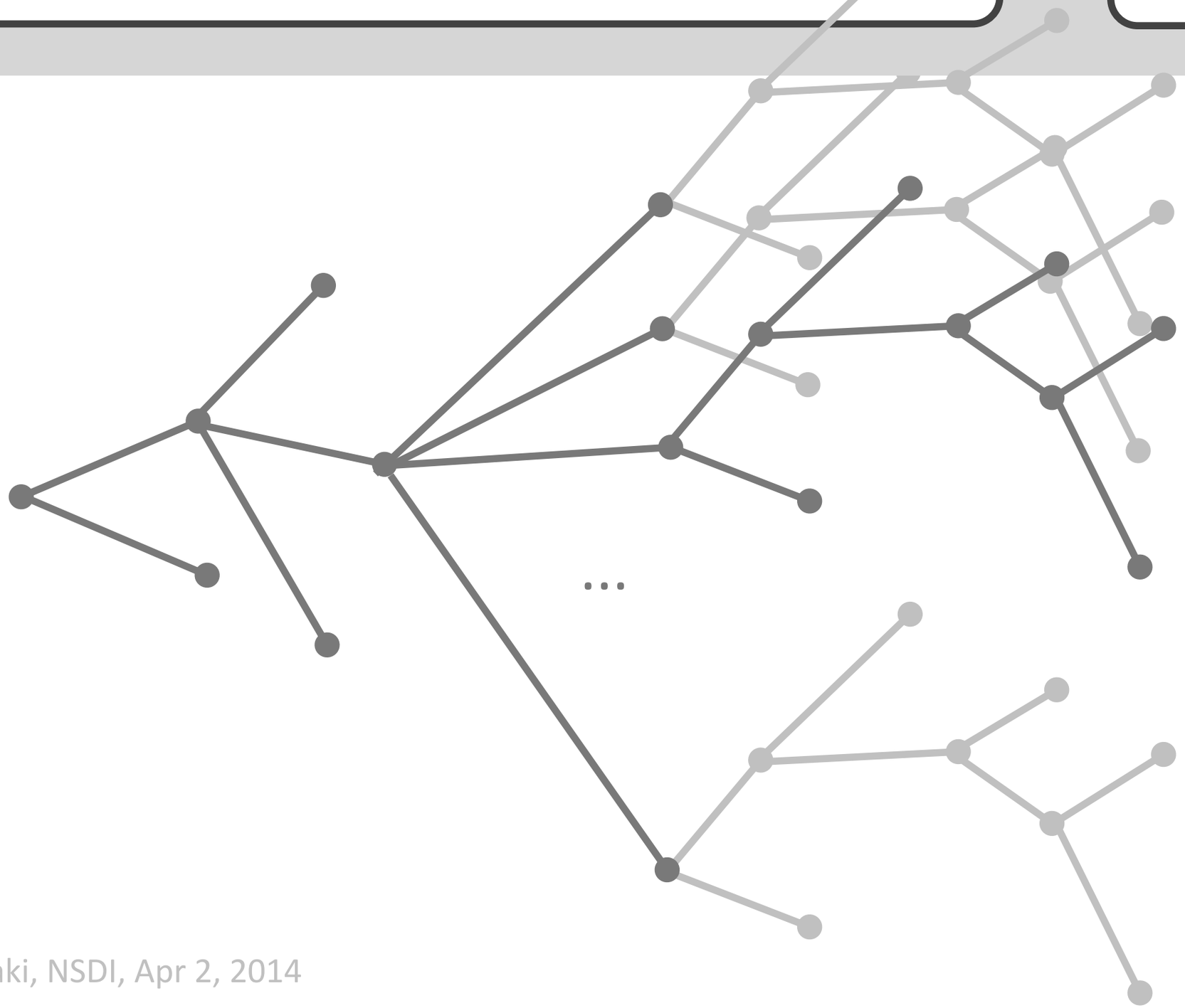
table impl



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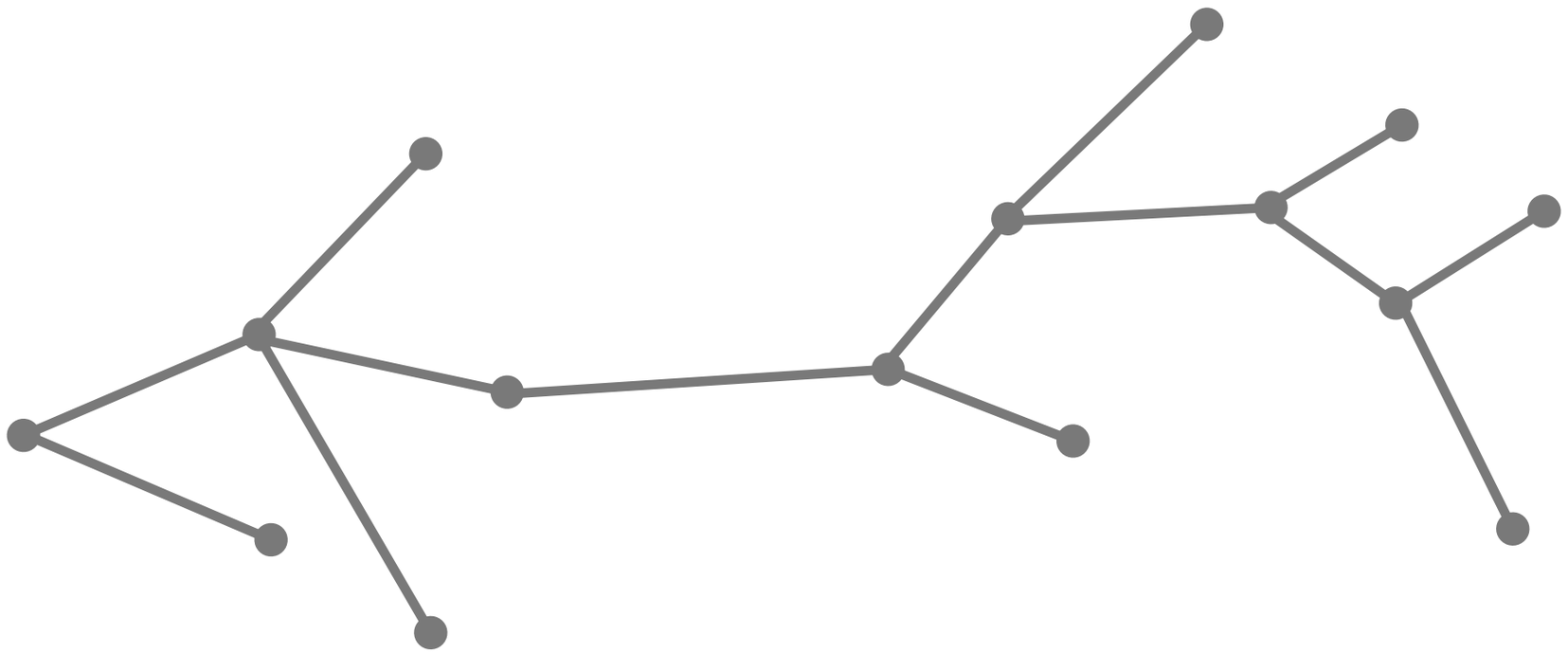

Data-access decomposition

- Rule: data-structure interface
  - *made explicit by the programmer*

- Effect: abstract data-structure implementation
  - *prevents data-structure size from contributing to path explosion*

Verified data structures

- Use pre-allocated arrays
  - *no dynamic memory (de)allocation*
  - *hash table, longest prefix match*

- Trade-off memory for “verifiability”
  - *at least as fast (array lookups)*
  - *but larger memory footprint (pre-allocation)*

Outline

- Pipeline
- Loops
- Data structures
- Results

Results

- Verified stateless & simple stateful pipelines
  - *IP router, NAT box, traffic monitor*
- Proved bounded execution
  - *no more than X instructions per packet*
  - *disparity between worst-case and common path*
- Proved crash-freedom
  - *no packet will cause the pipeline to abort*

```
/* IPFragmenter:: optcopy */

    for ( int i = 0; i < opts_len; ) {
       int opt = oin[i], optlen;
       if (opt == IPOPT_NOP)
          optlen = 1;
       else if (opt == IPOPT_EOL || i == opts_len - 1
       || i + (optlen = oin[i+1]) > opts_len)
          break;
       if (opt & 0x80) {
          //copy the option
          memcpy(...);
       }
       i += optlen;
  }
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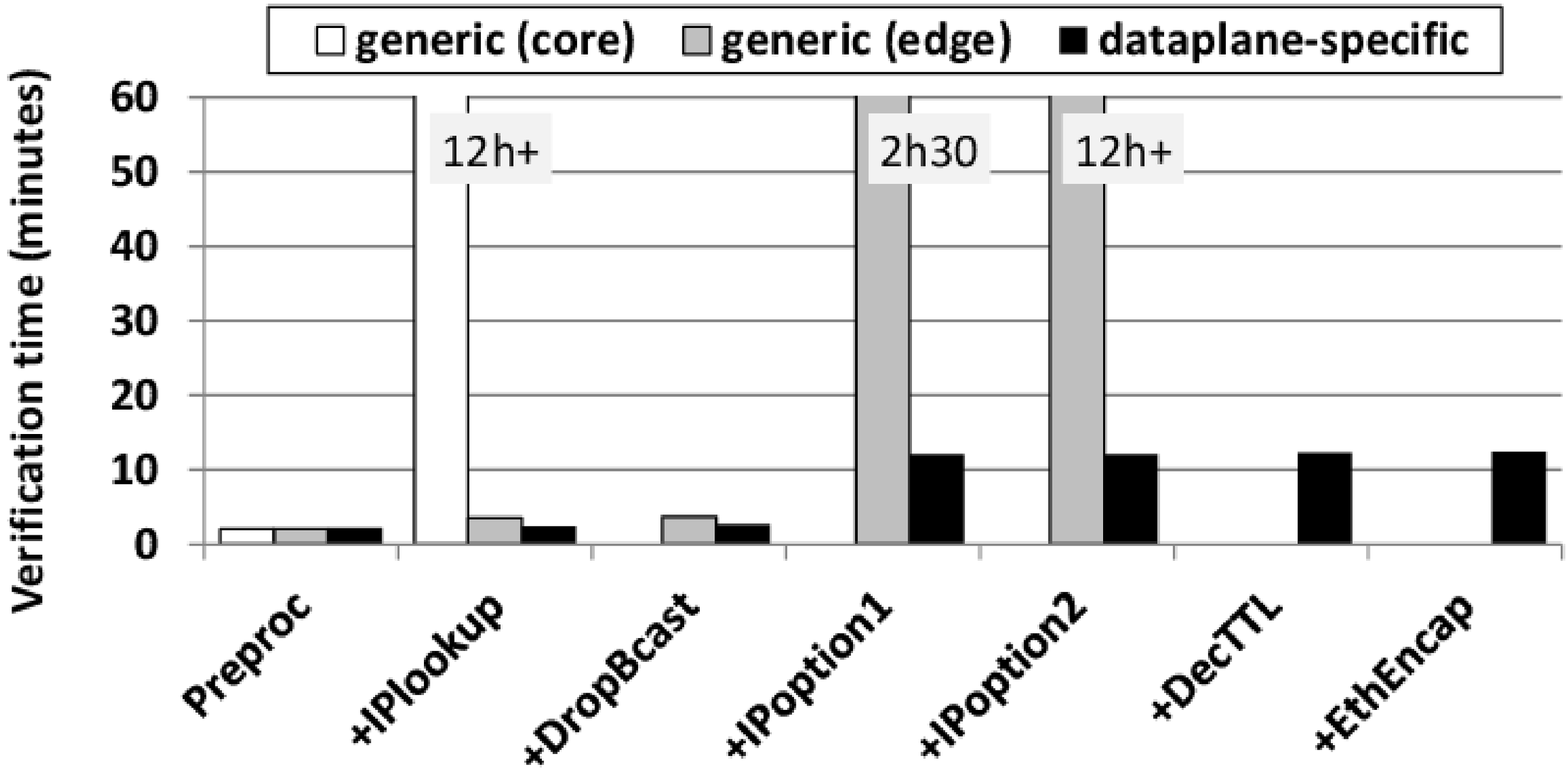
Verification time for Click pipelines



Homage

- Active networks
  - *Tennenhouse & Wetherall, CCR 1996*
- S2E software analyzer
  - *Chipounov et al., ASPLOS 2011*
- Compositional analysis
  - *Godefroid, POPL 2007*
- Click programming framework
  - *Kohler, PhD thesis, 2000*

Conclusion

- Dataplane-specific verification
  - *symbolic execution + composition*
  - *pipeline structure, limited loops, pre-allocated key/value stores*

- Enables dataplane verification in useful time
  - *complete and sound analysis*
  - *of stateless and 2 simple stateful pipelines*