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Director of Engineering at DataStax, Inc.
Project Management Committee, Apache TinkerPop

Abstract

Open Problems in the Universal Graph Theory

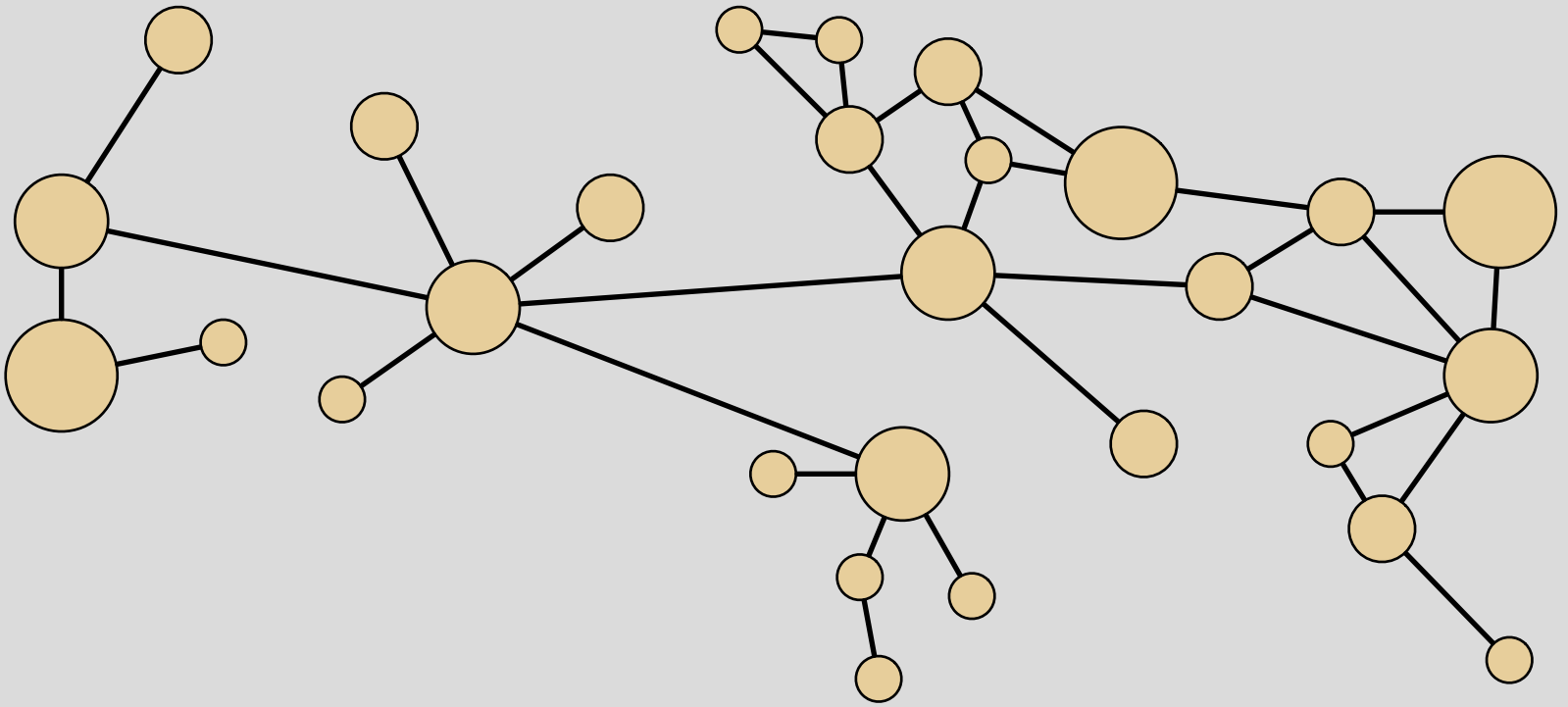
The universal graph is a theoretical construct capturing the idea that every aspect of reality can be modeled as a graph composed of vertices and edges and, as such, reality is a graph. From the physical world of atoms, people, and galaxies to the mental planes of thoughts, words, and knowledge, there exists a universal graph hosting all such structures. While this idea is enticing, there are still strides to be made in coming to terms with a reality that is not composed of atoms bound by spacetime, but instead, a graph composed of vertices united by edges.

Rodriguez, M.A., "Open Problems in the Universal Graph Theory," GraphDay `17, 2(2), pages 1-5, San Francisco, CA, June 2017.

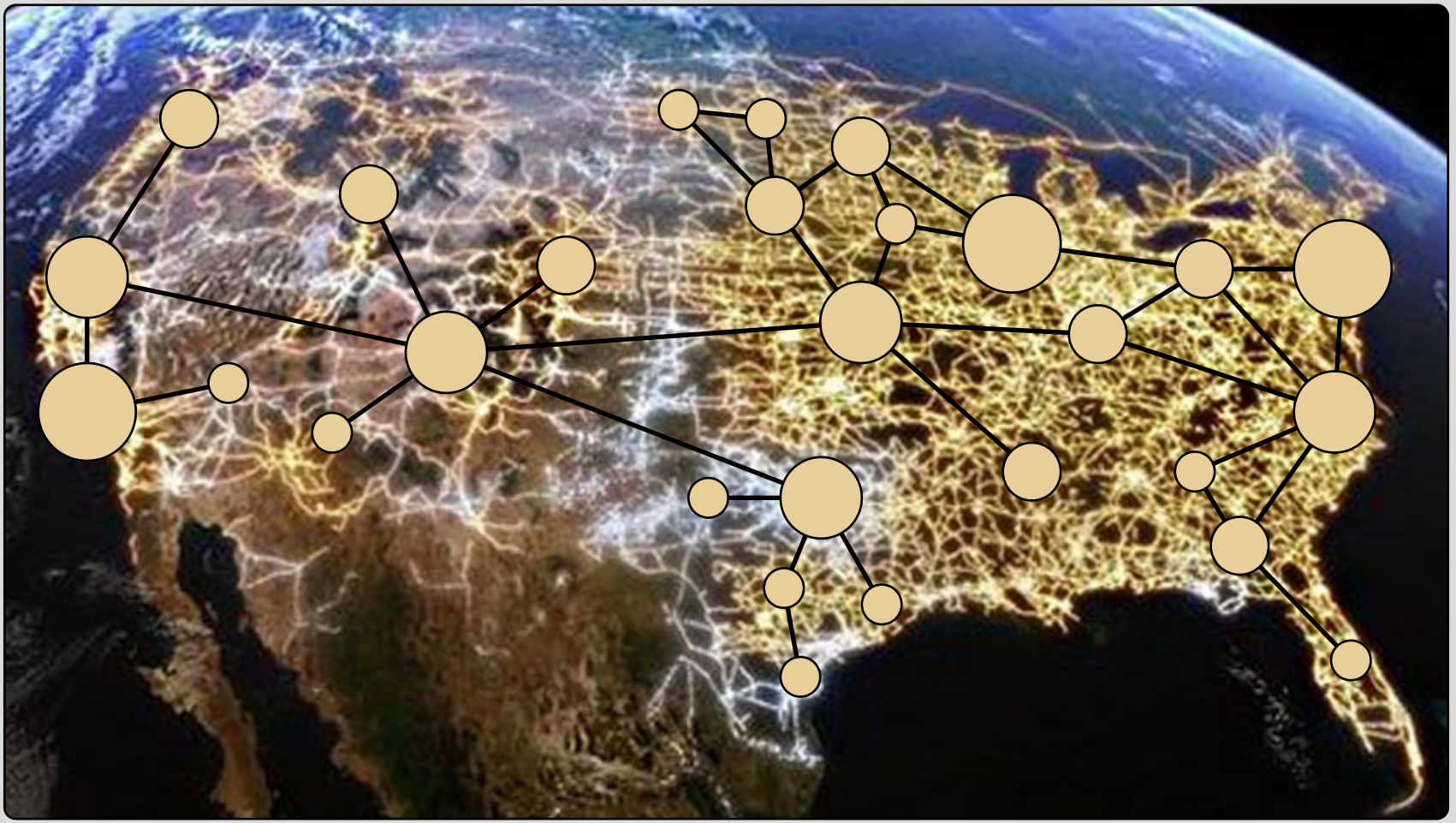
https://doi.org/10.5281/zenodo.583293

Introduction

“Everything is a graph.”



Power Grids



https://en.wikipedia.org/wiki/Electrical_grid

Power Grids

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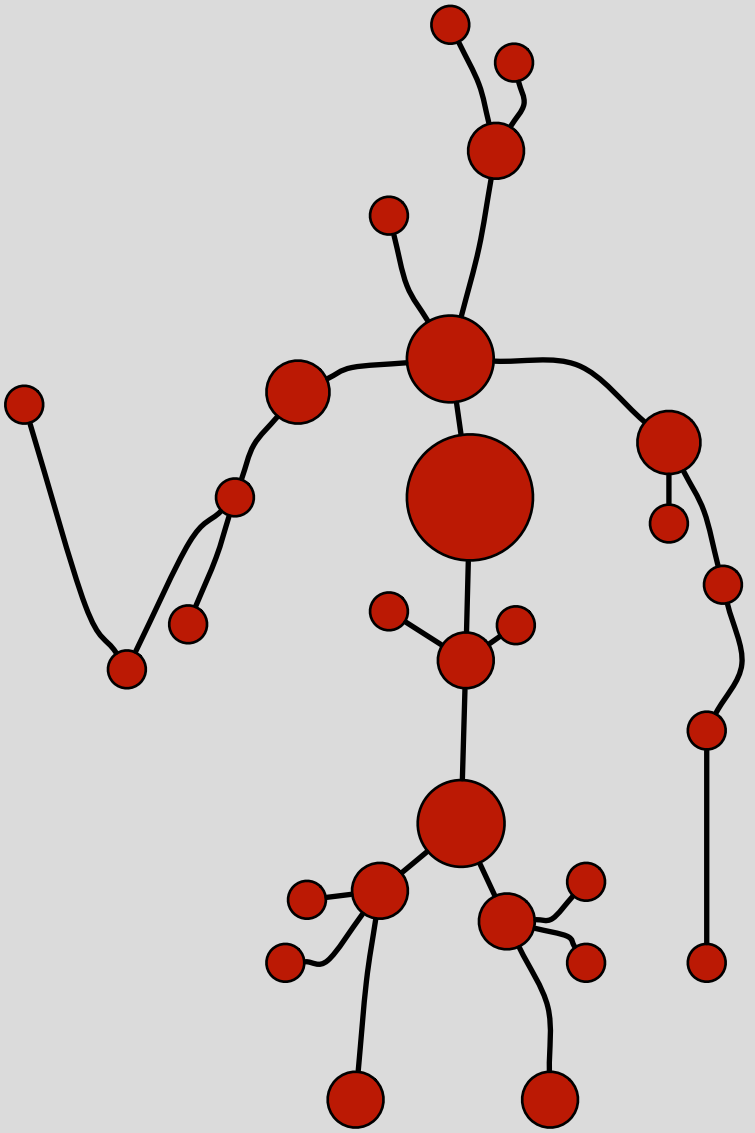
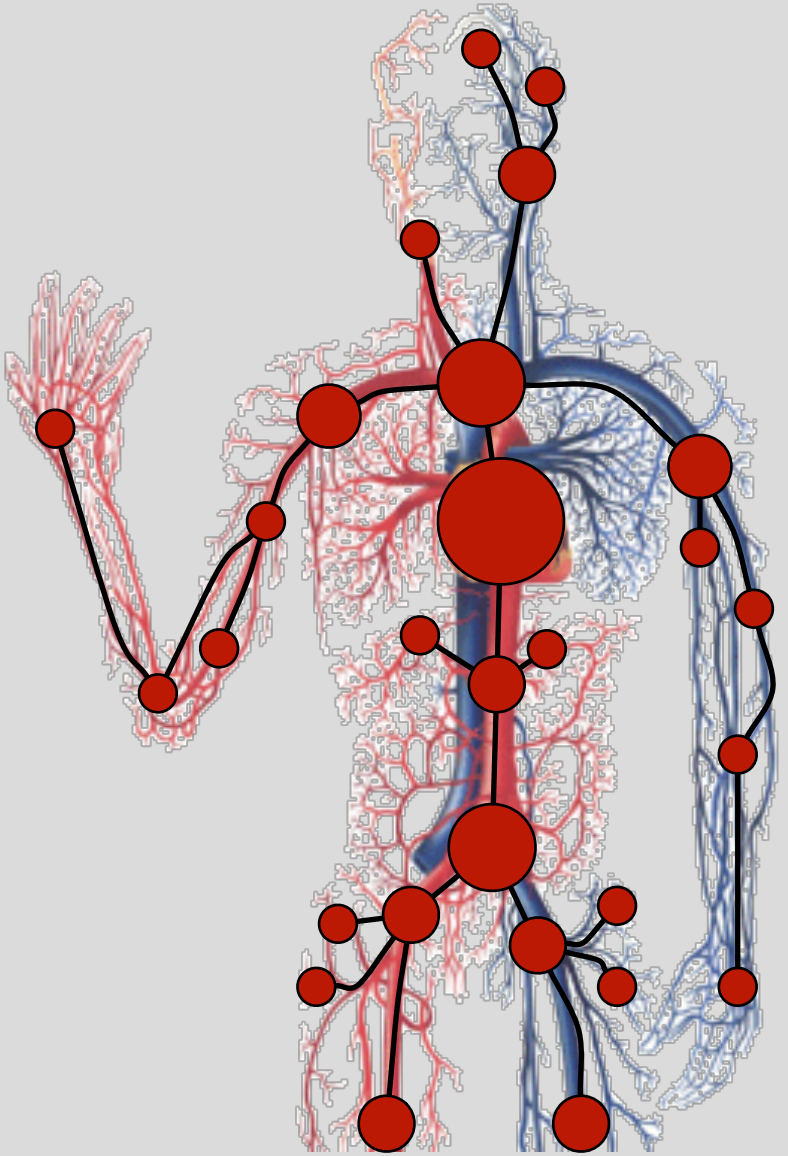
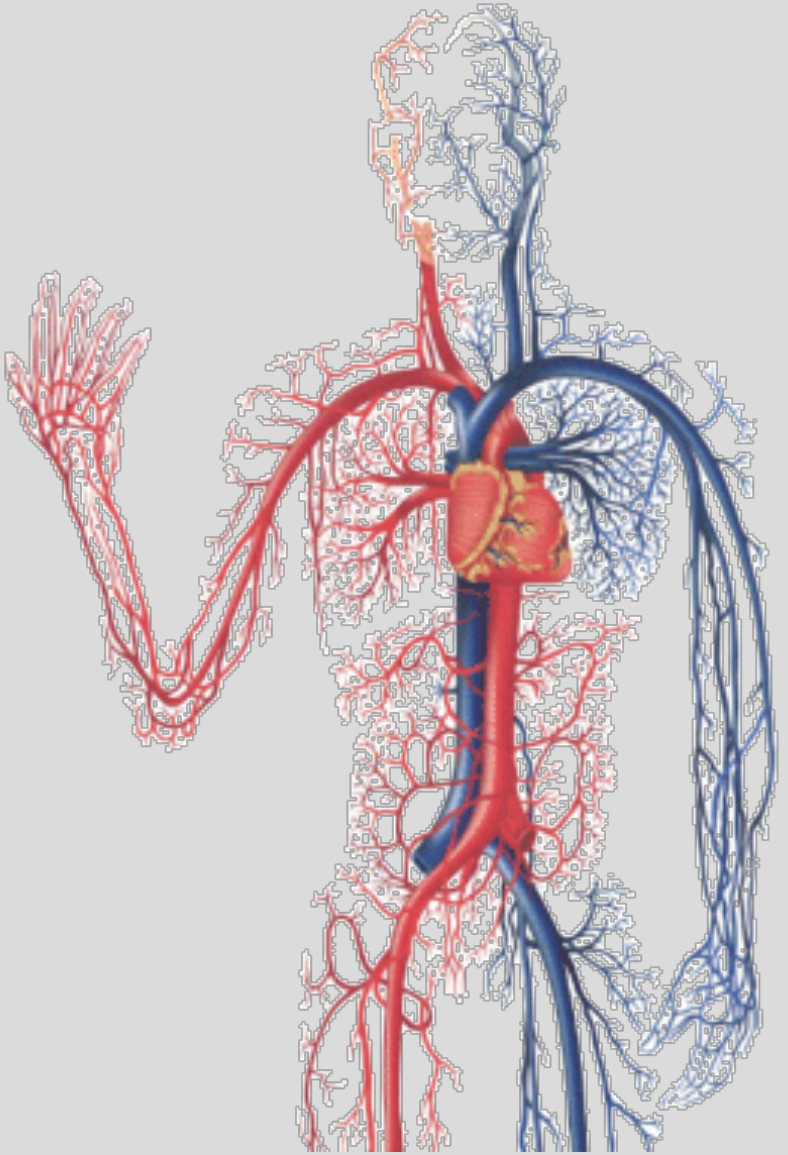


Vascular System



https://en.wikipedia.org/wiki/Circulatory_system

Vascular System



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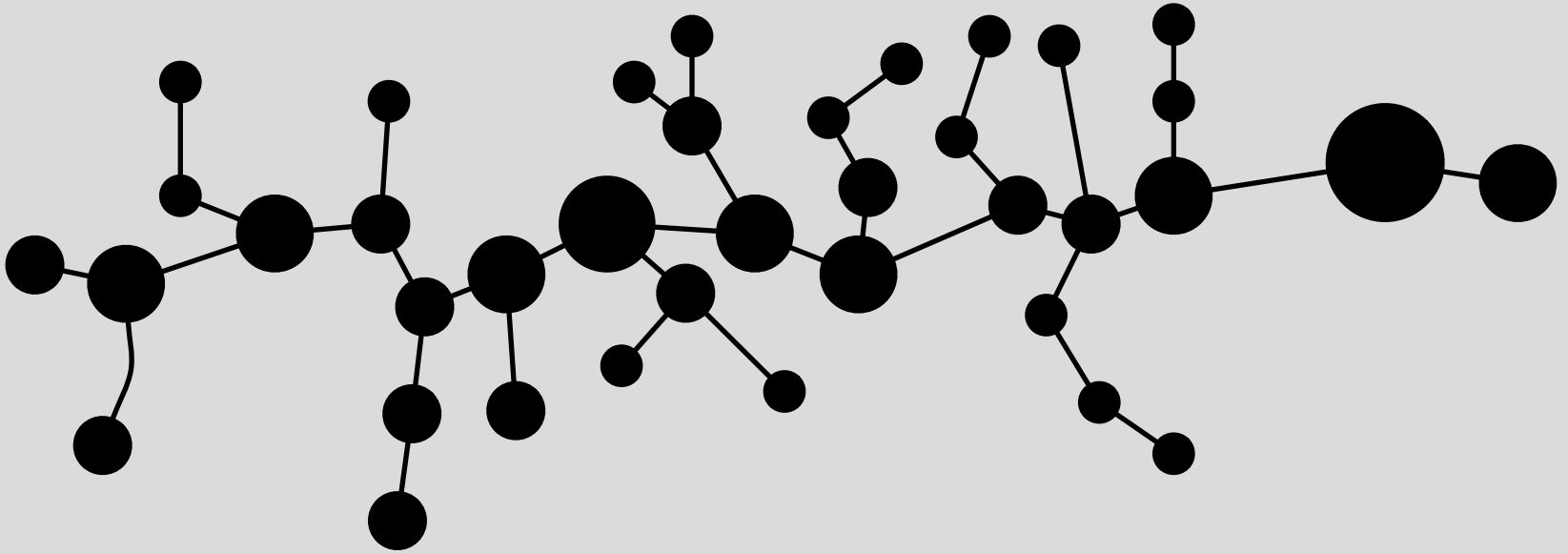
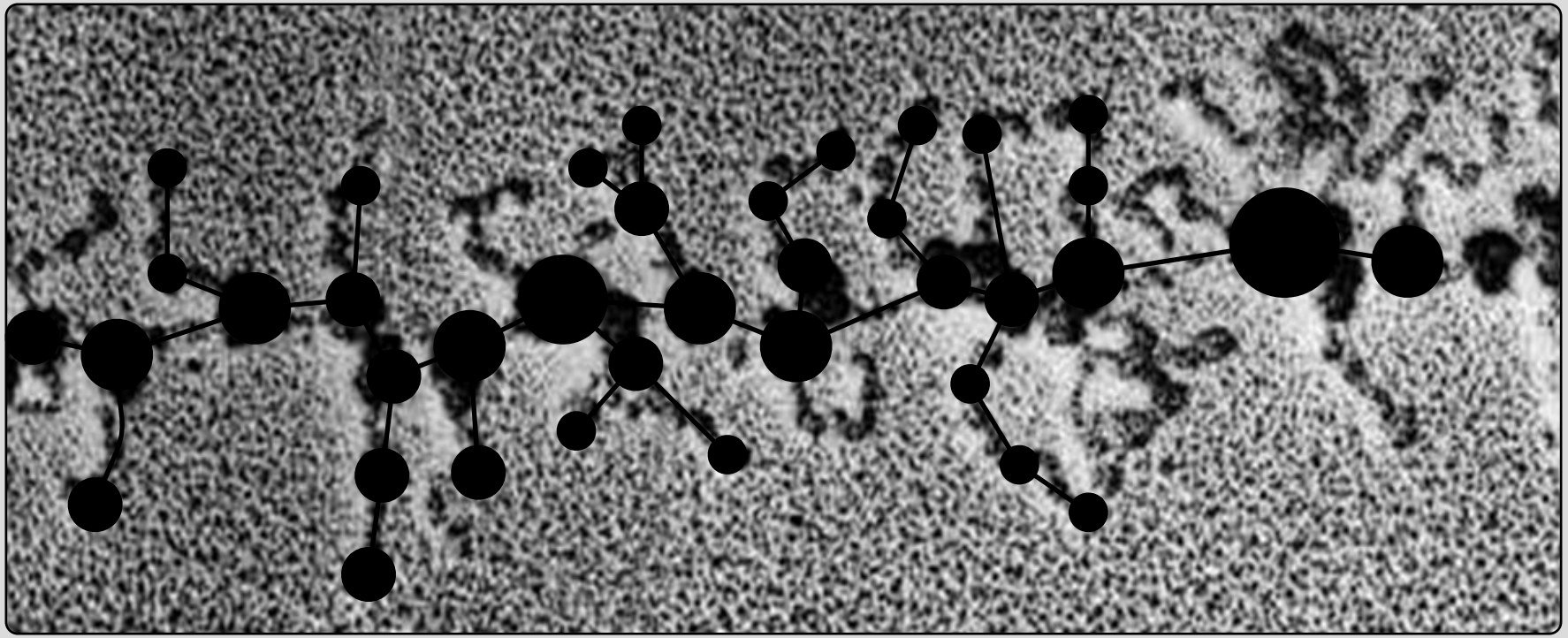
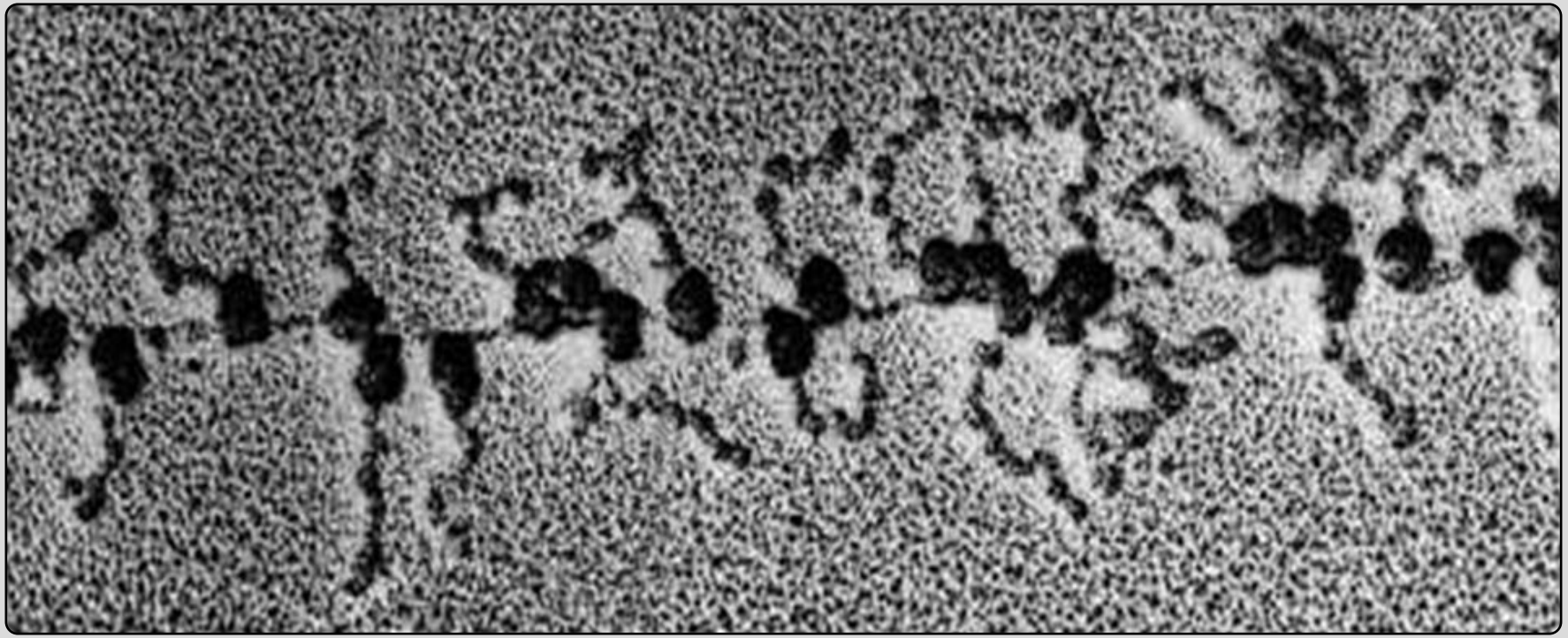


Protein Chains



https://en.wikipedia.org/wiki/Protein_complex

Protein Chains



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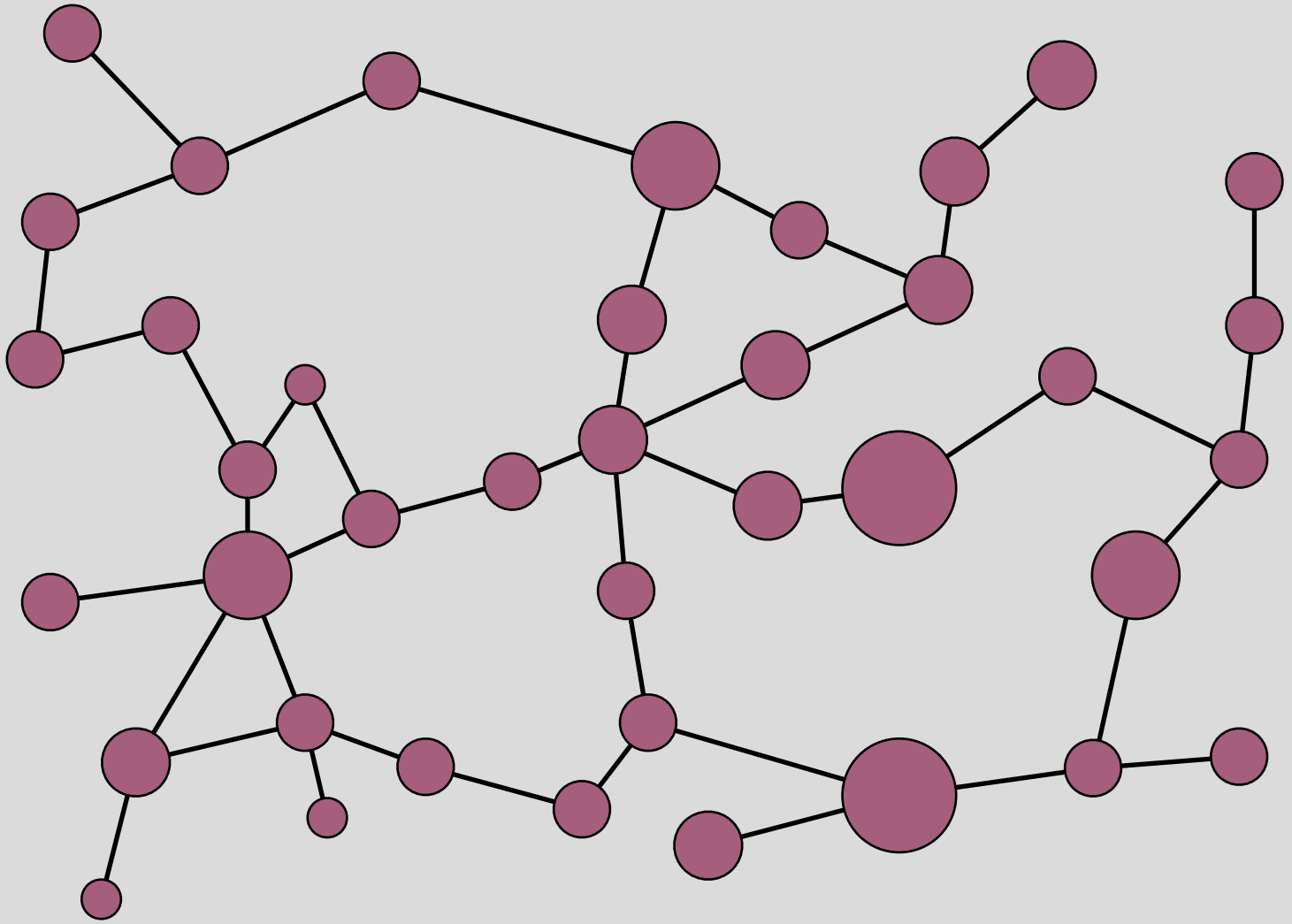
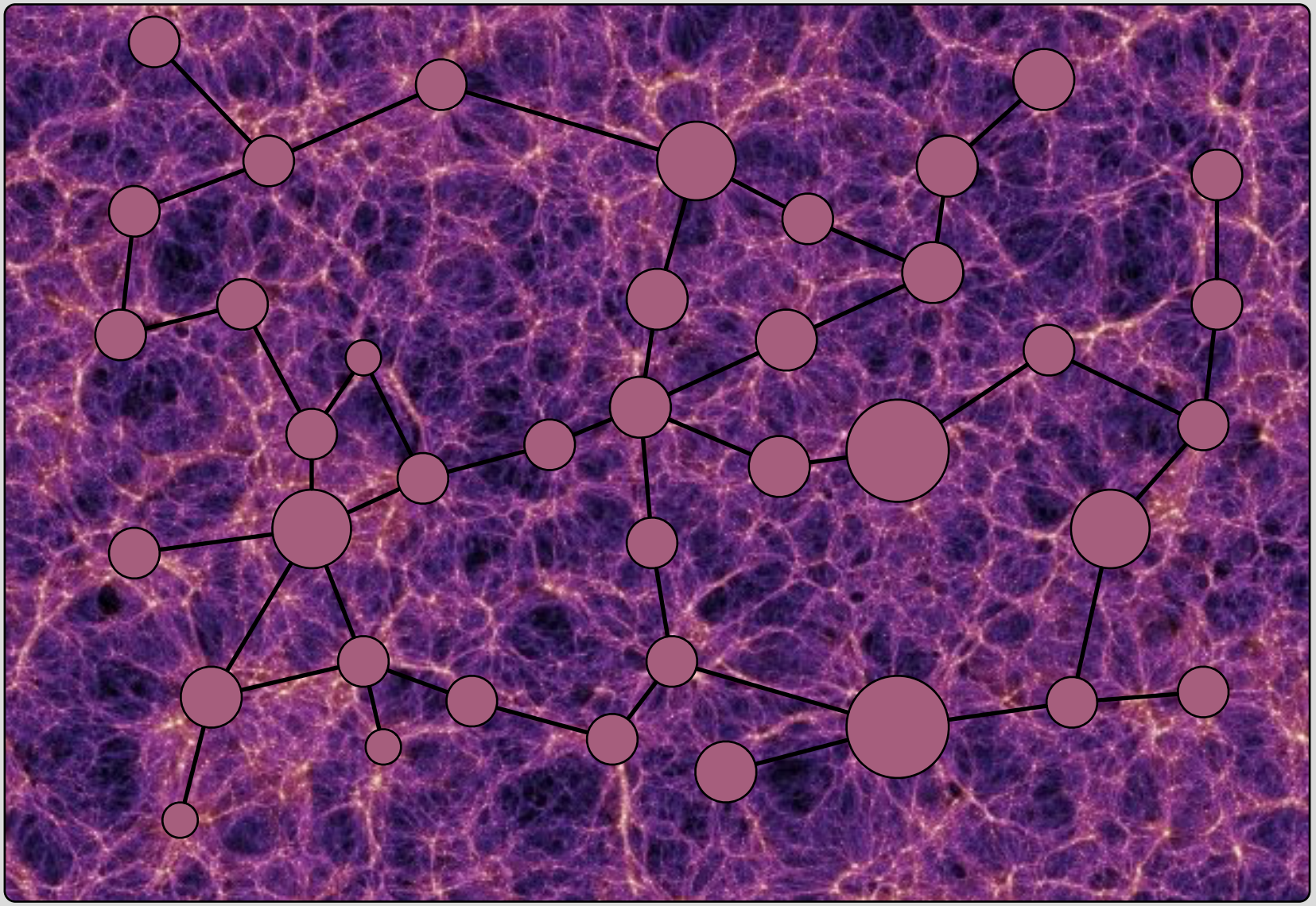


Galactic Filament



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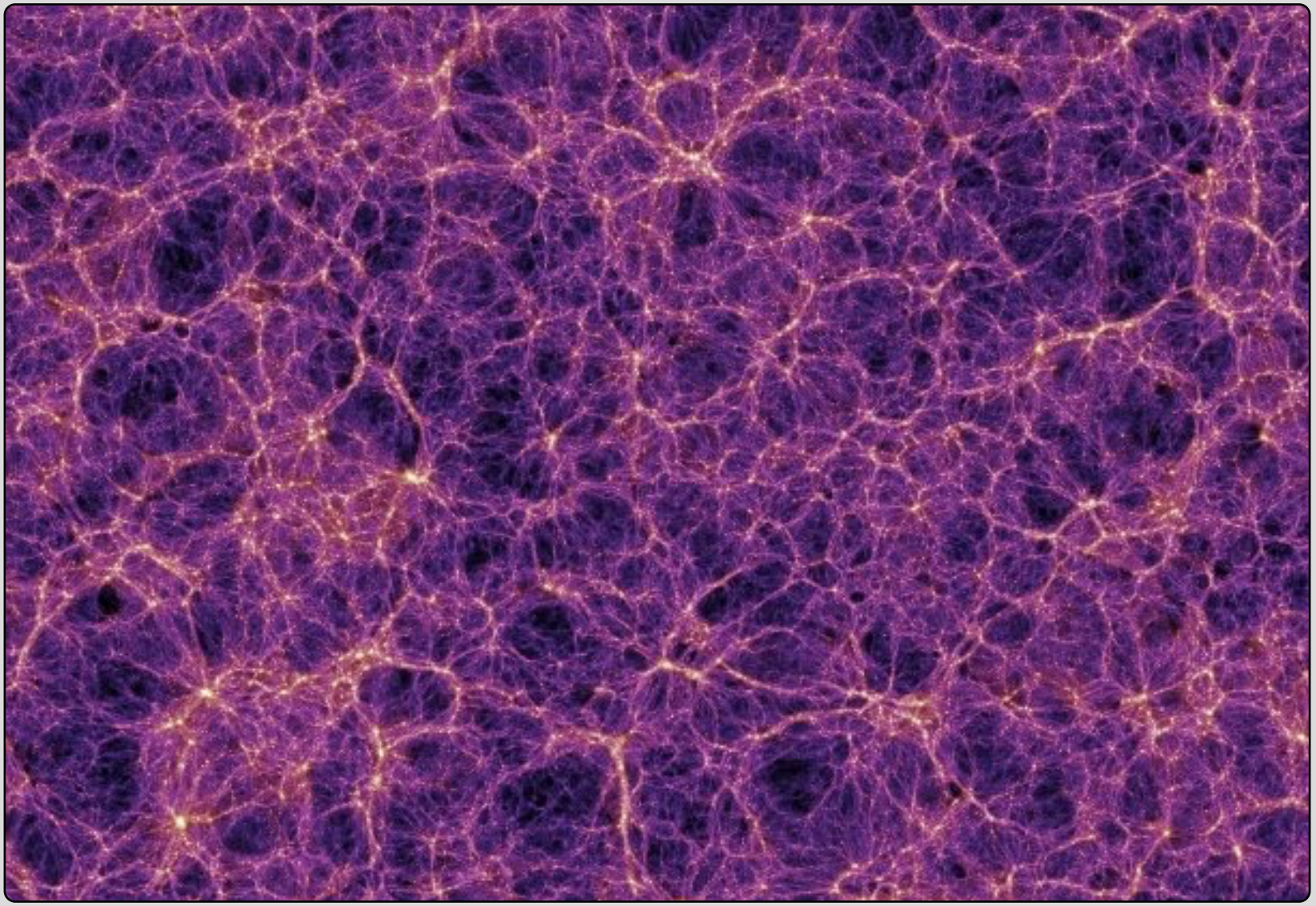
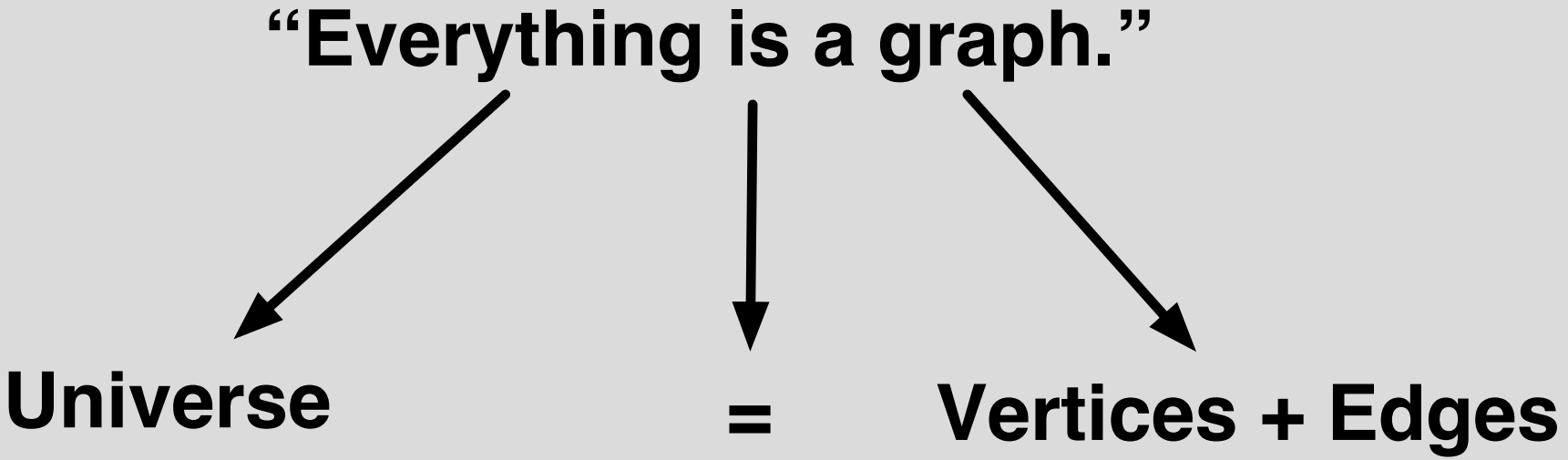
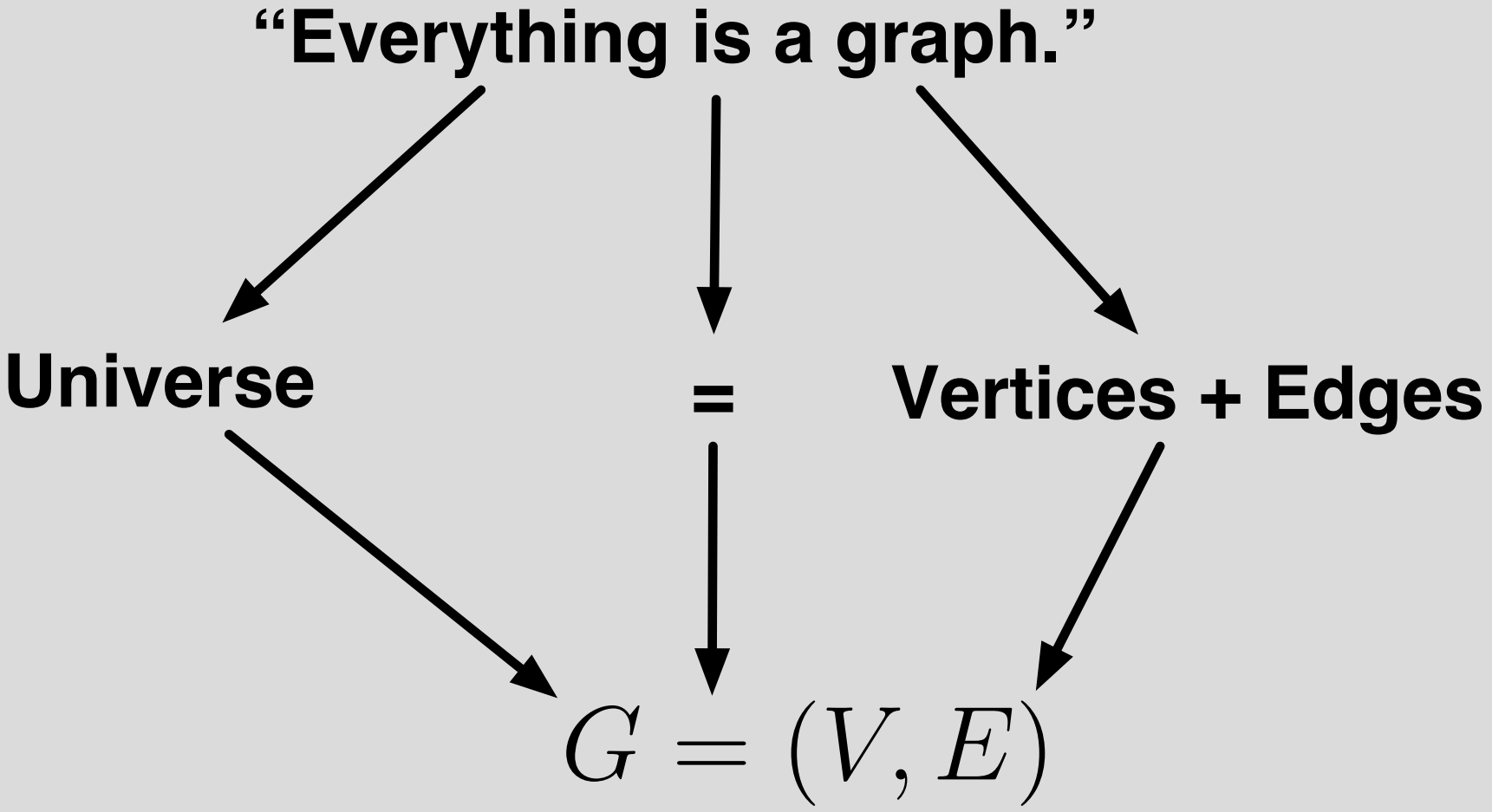
Galactic Filament



https://en.wikipedia.org/wiki/Galaxy_filament

“Everything is a graph.”


“Everything is a graph.”
Universe
=
Vertices + Edges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Universe
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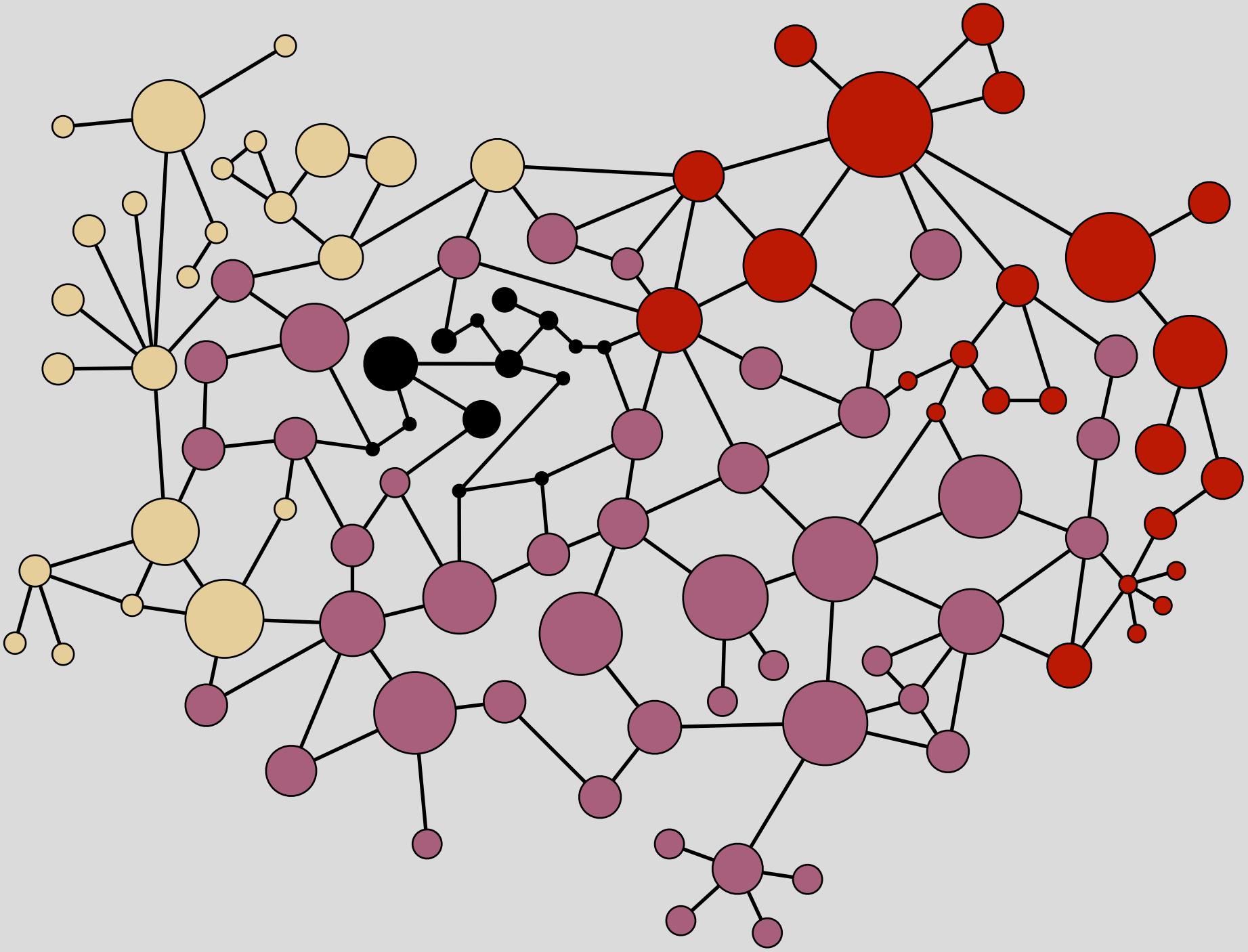
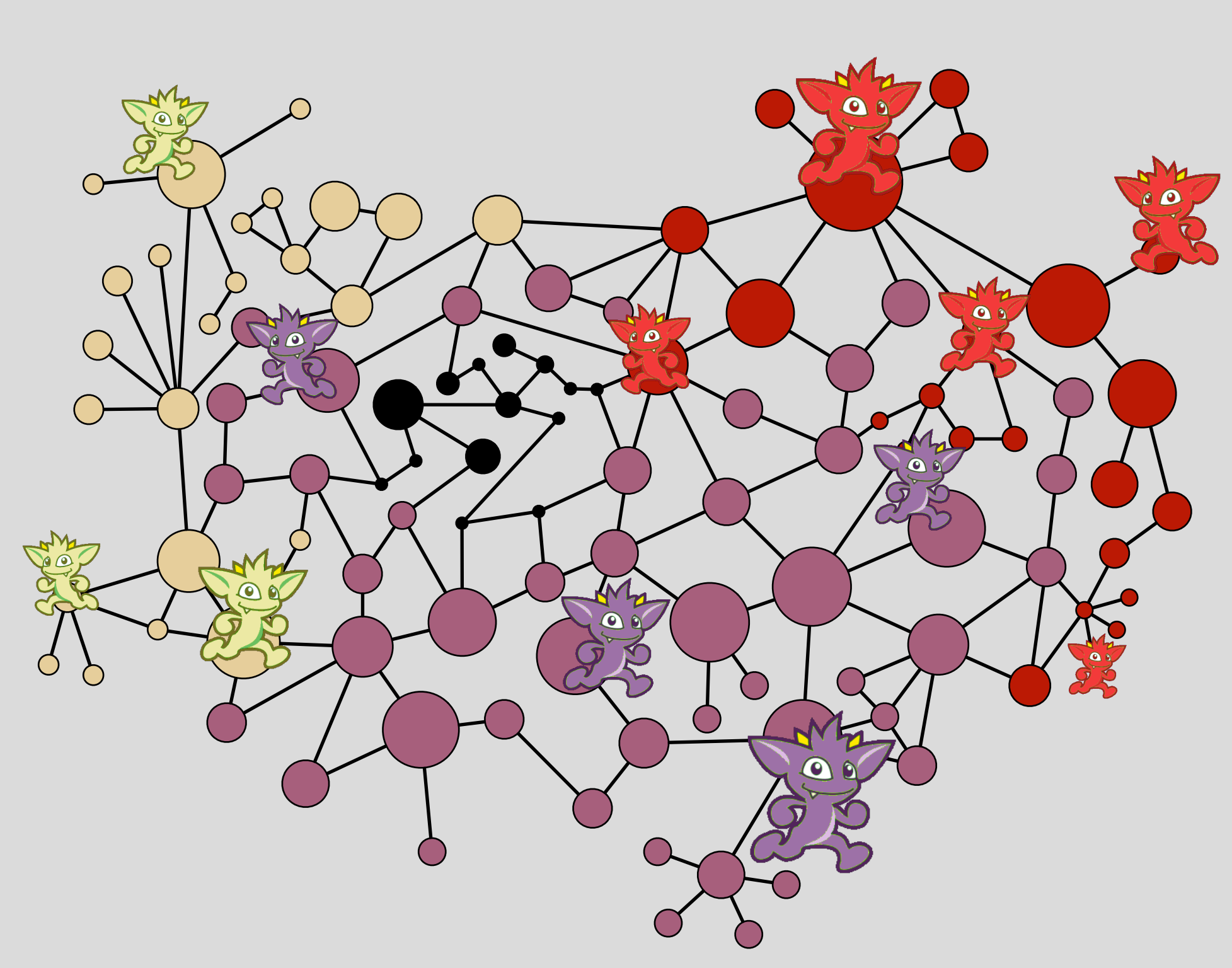
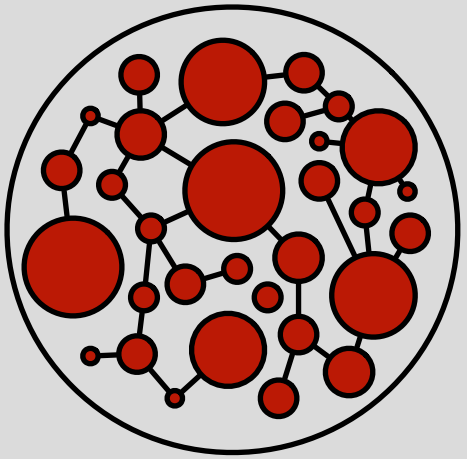
Vertices + Edges
$G = (V, E)$





Graph Computing

Graph



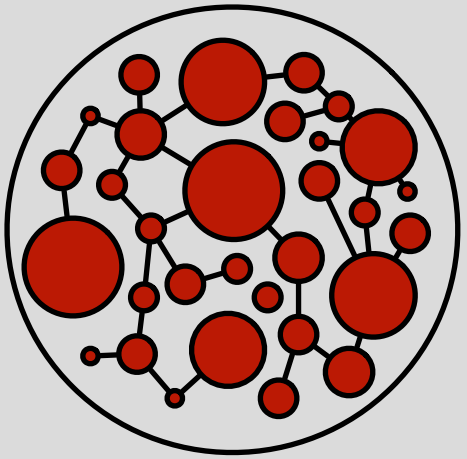
Structure

Traversal

Process

Graph Computing

Graph



Structure

Traversal

Process

?

$$G = (V, E)$$

“Everything is a graph.”

Time:

The Process of Change

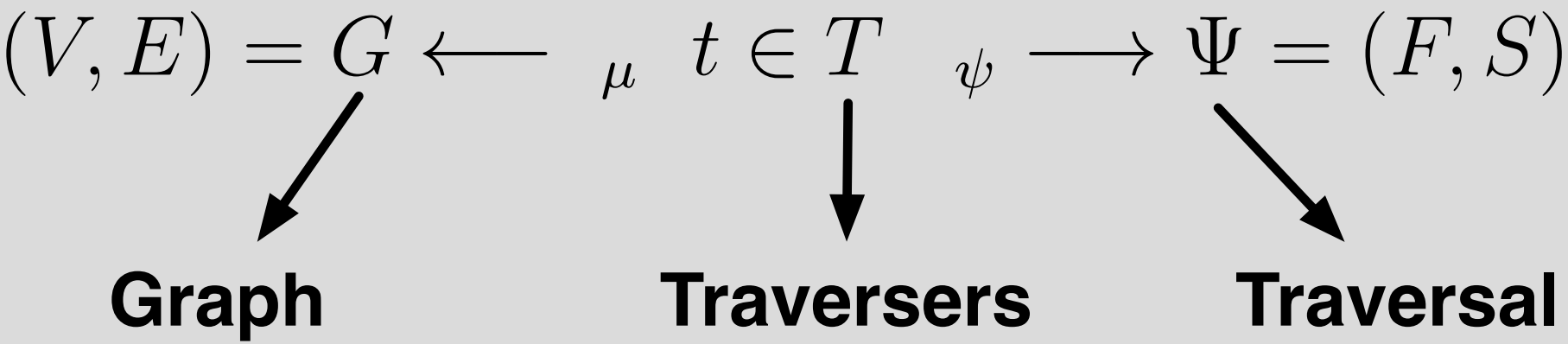
Gremlin Graph Traversal Machine

$$(V, E) = G \xleftarrow{\quad \mu \quad} t \in T \xrightarrow{\quad \psi \quad} \Psi = (F, S)$$

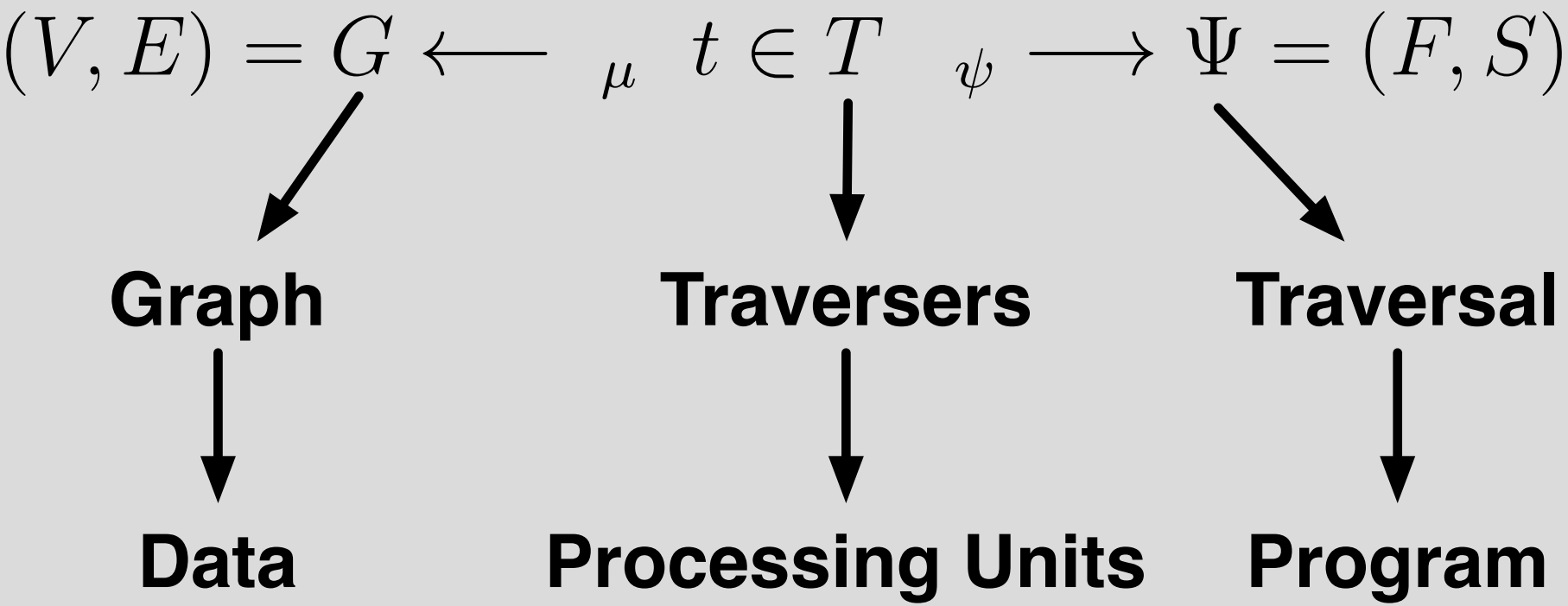
Rodriguez, M.A., “The Gremlin Graph Traversal Machine and Language,” Proceedings of the 15th Symposium on Database Programming Languages (DBPL 2015), pages 1–10, ISBN:978-1-4503-3902-5, doi:10.1145/2815072.2815073, ACM, October 2015.

http://arxiv.org/abs/1508.03843

Gremlin Graph Traversal Machine



Gremlin Graph Traversal Machine



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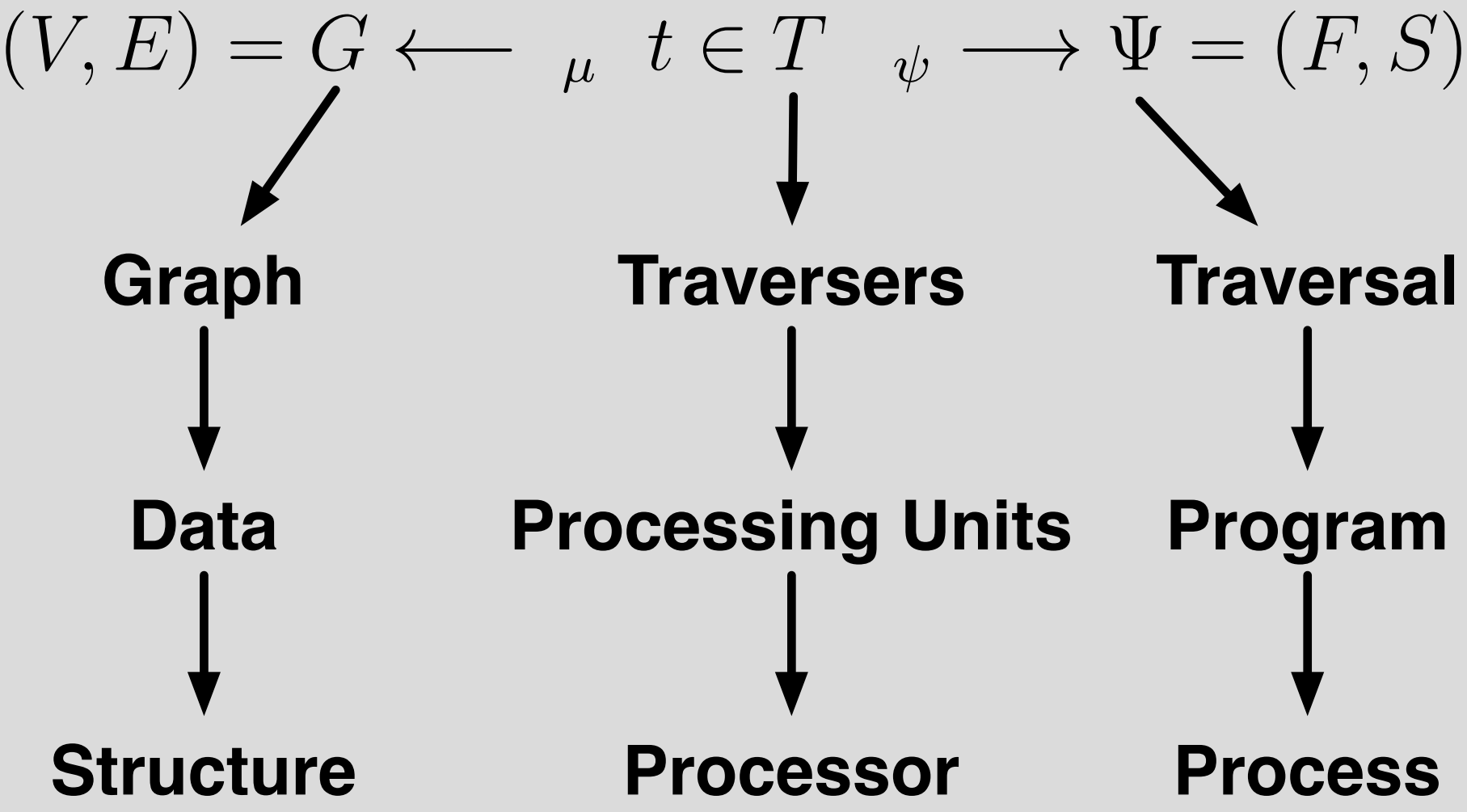
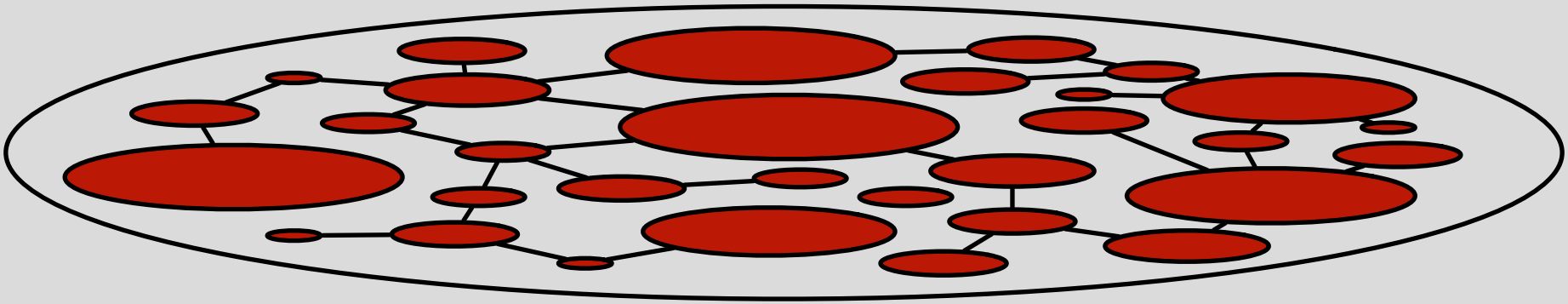
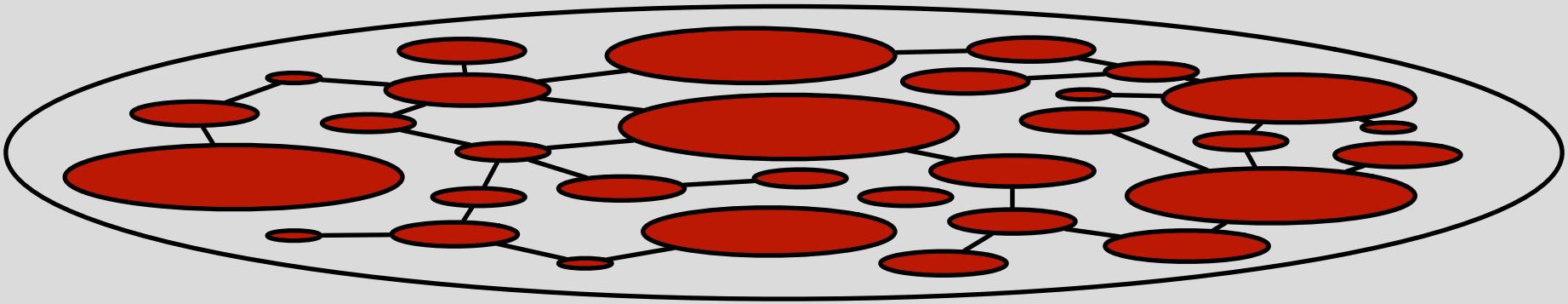




$$G = (V, E)$$

```
g.V(1).out('knows').out('created')
```



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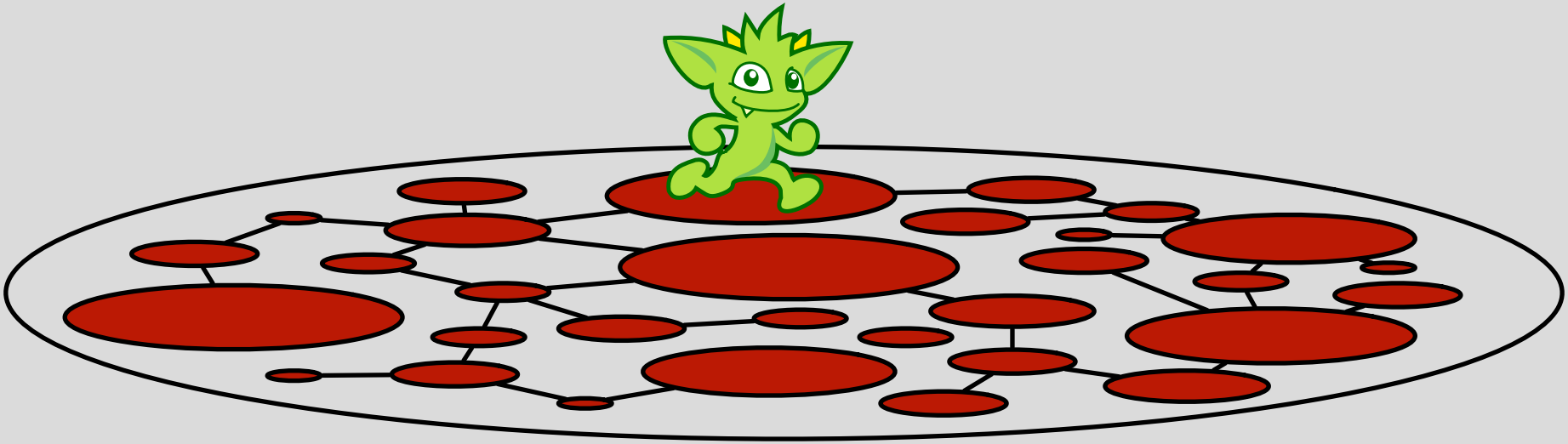

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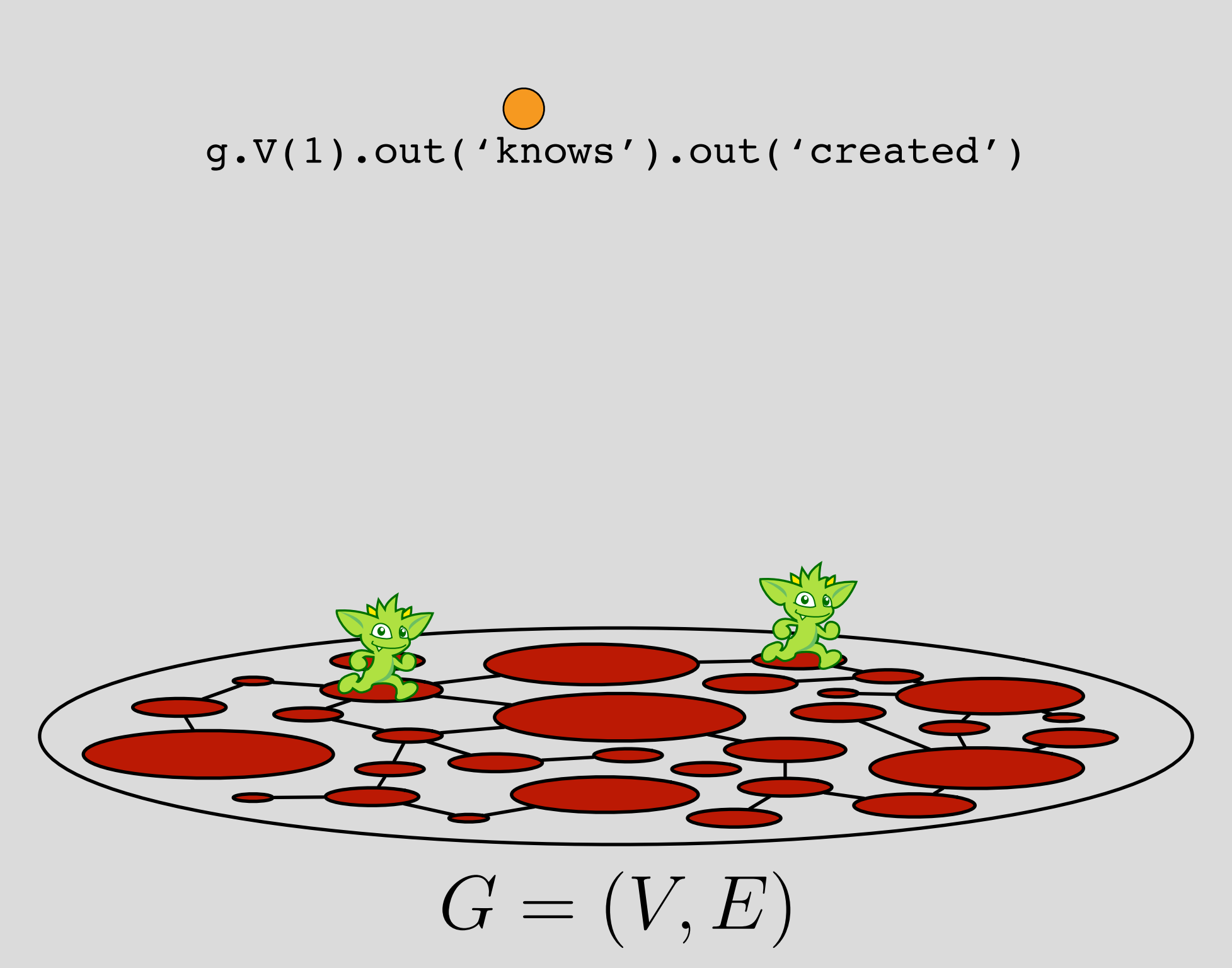
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$G = (V, E)$

```
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```
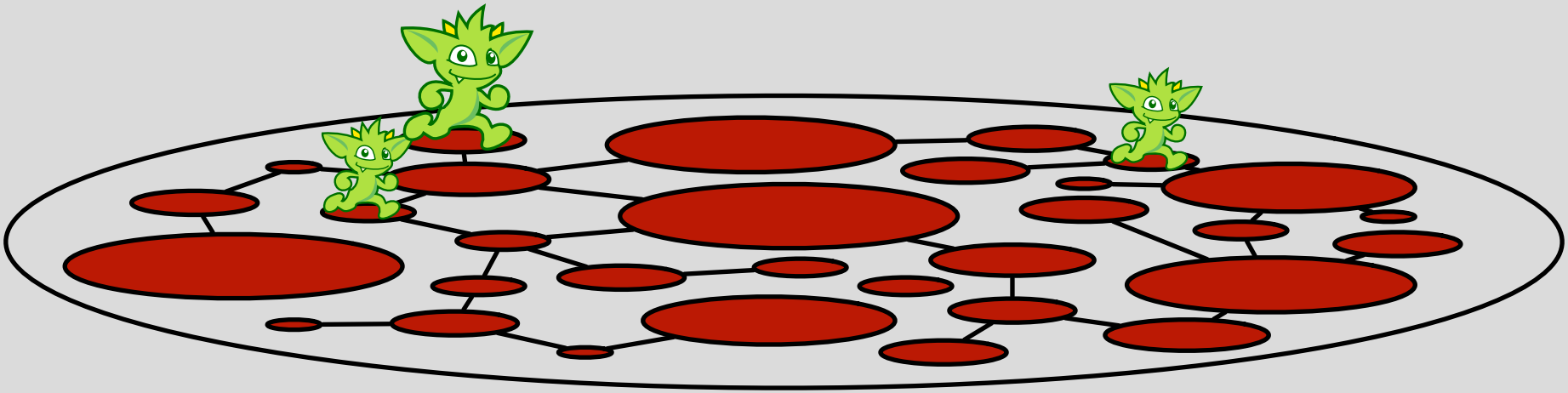
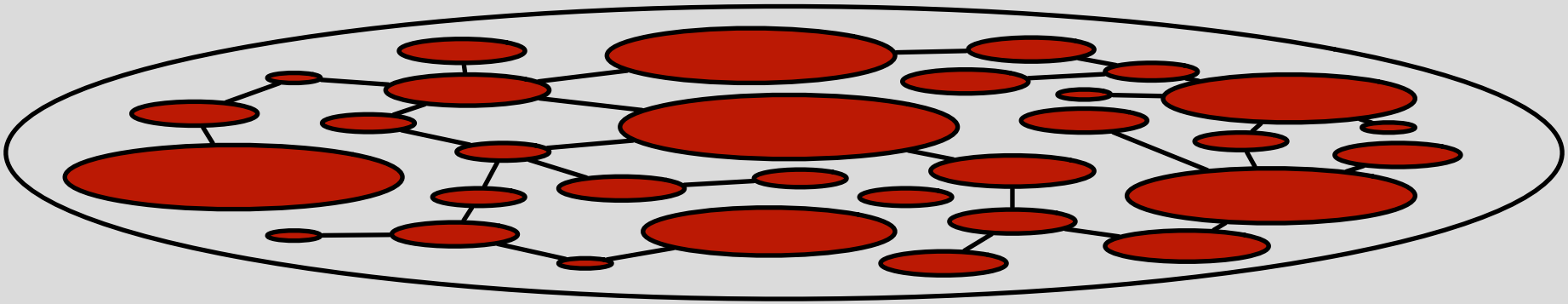



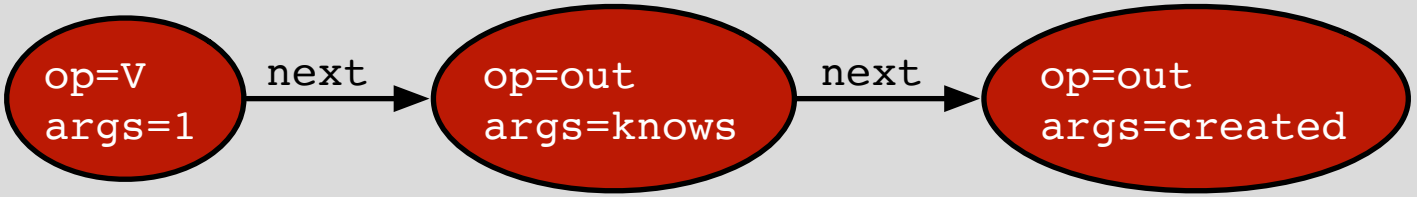
$$G = (V, E)$$

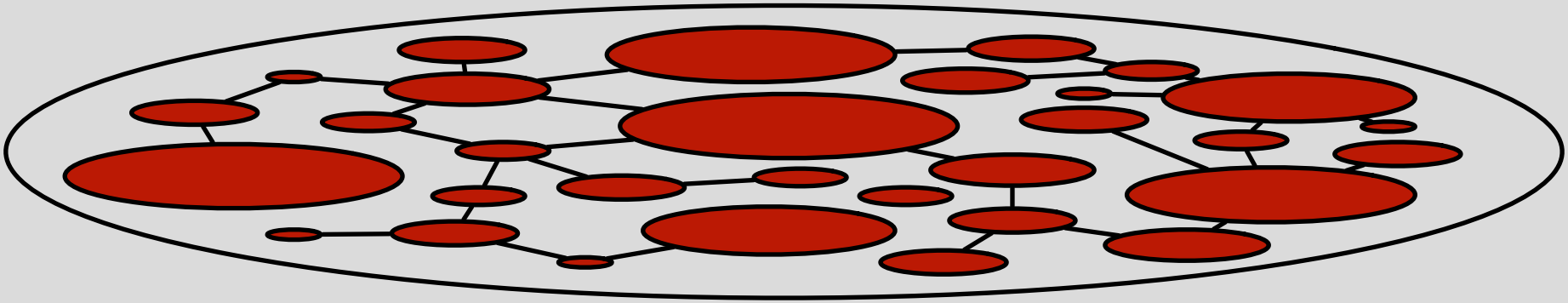
```
g.V(1).out('knows').out('created')
```



$$G = (V, E)$$

$$\Psi = (F, S)$$





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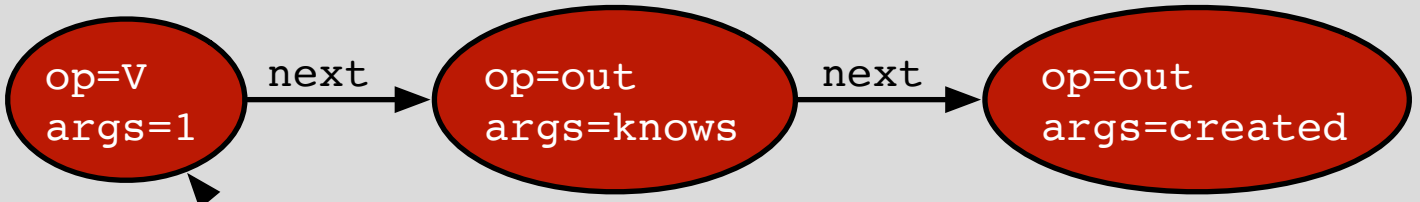

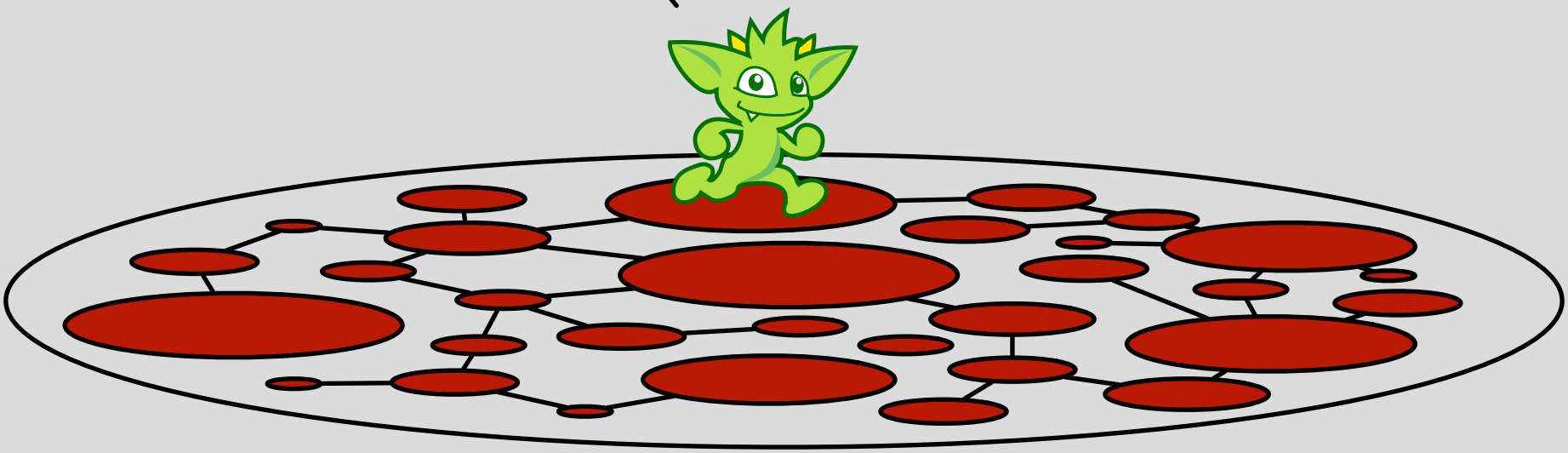

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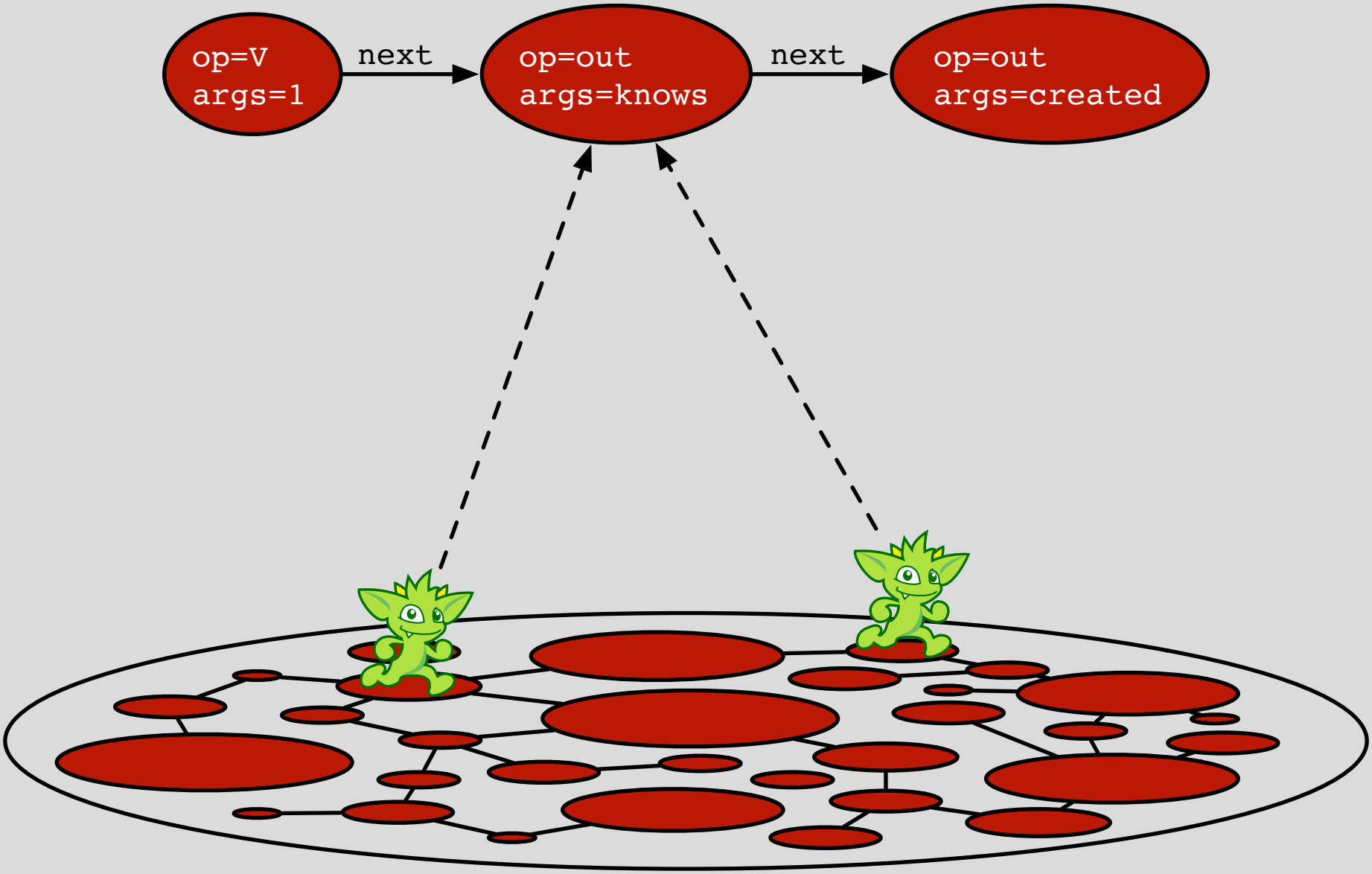

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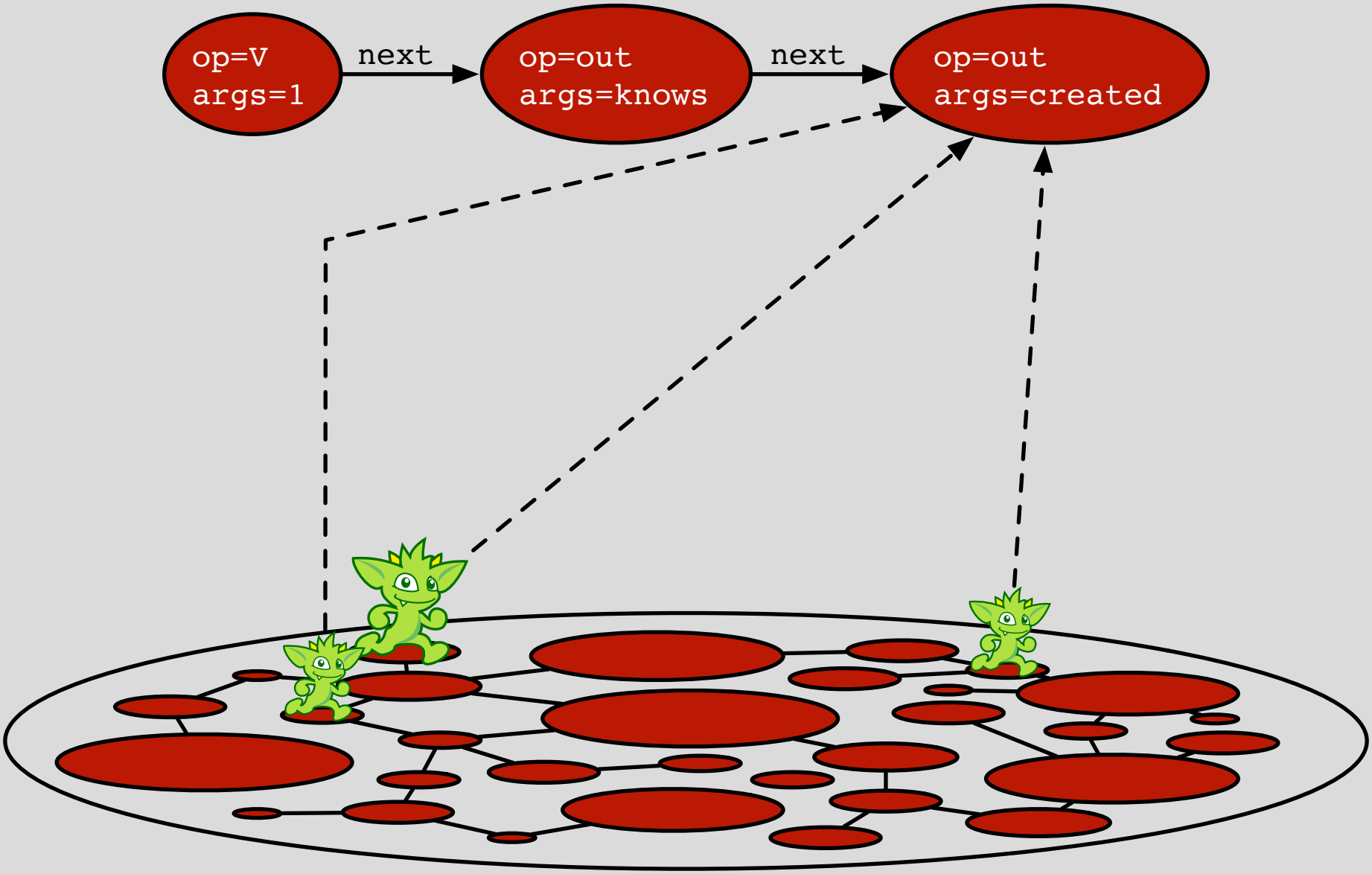

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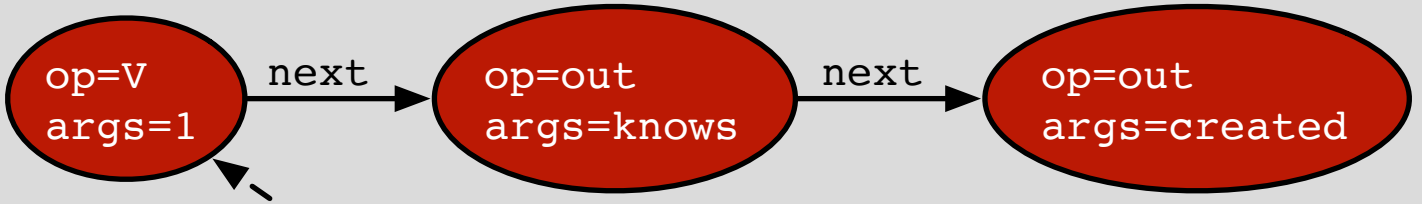
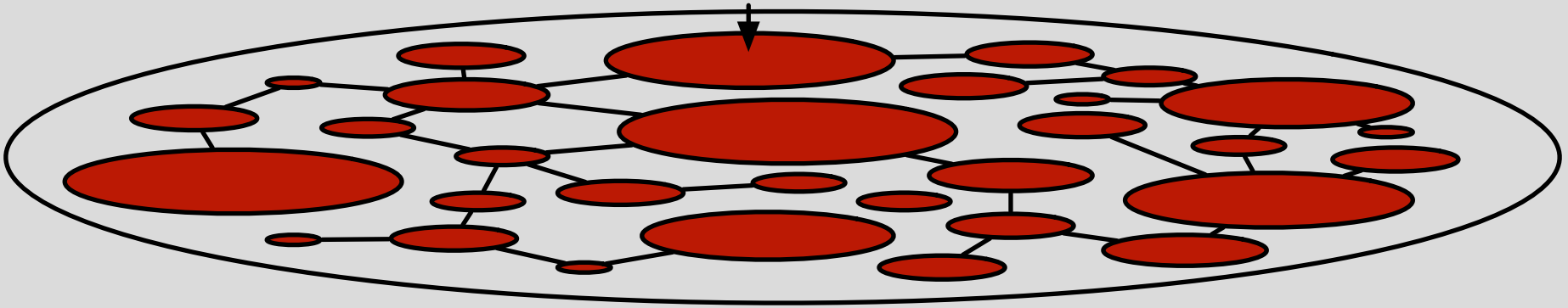
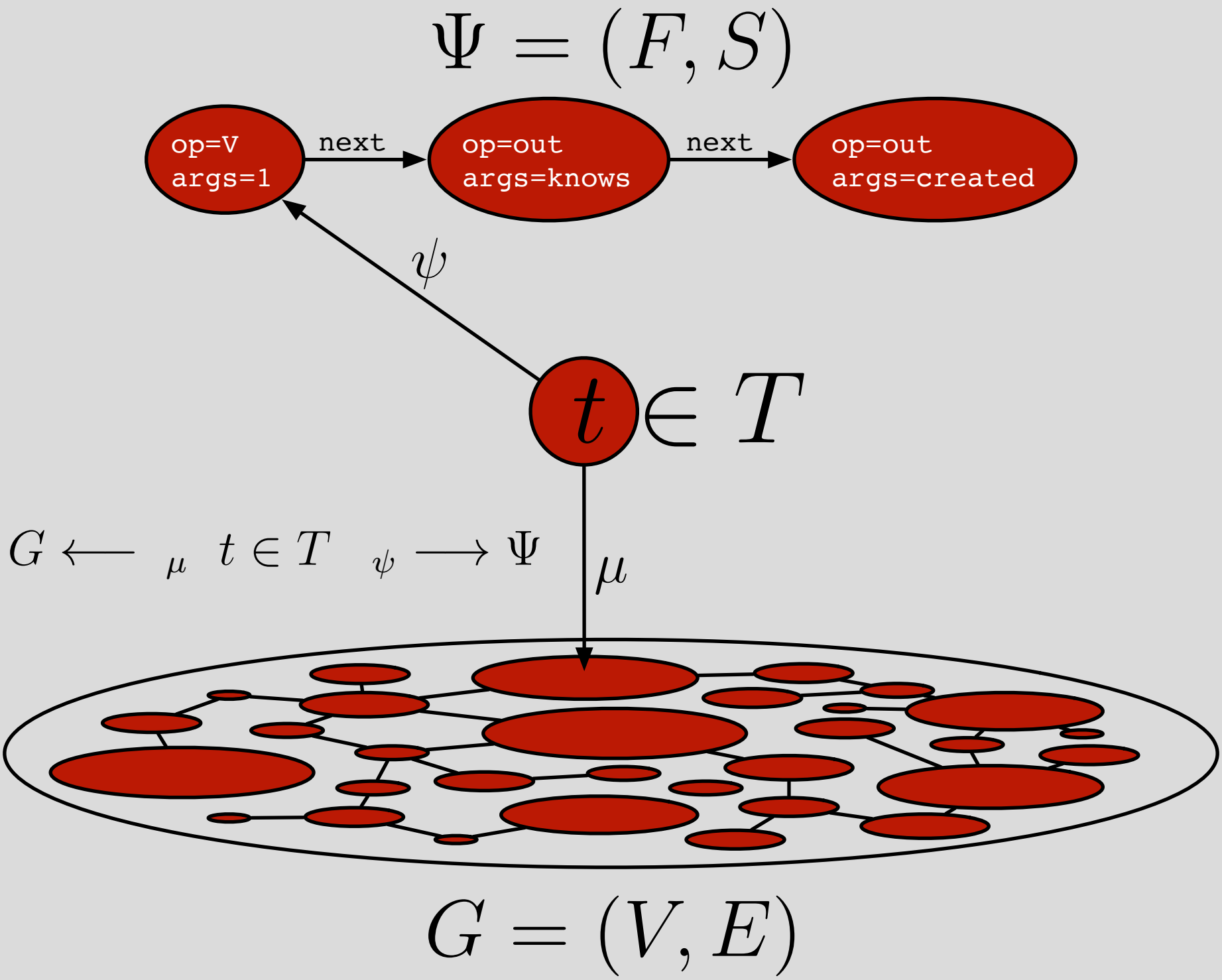
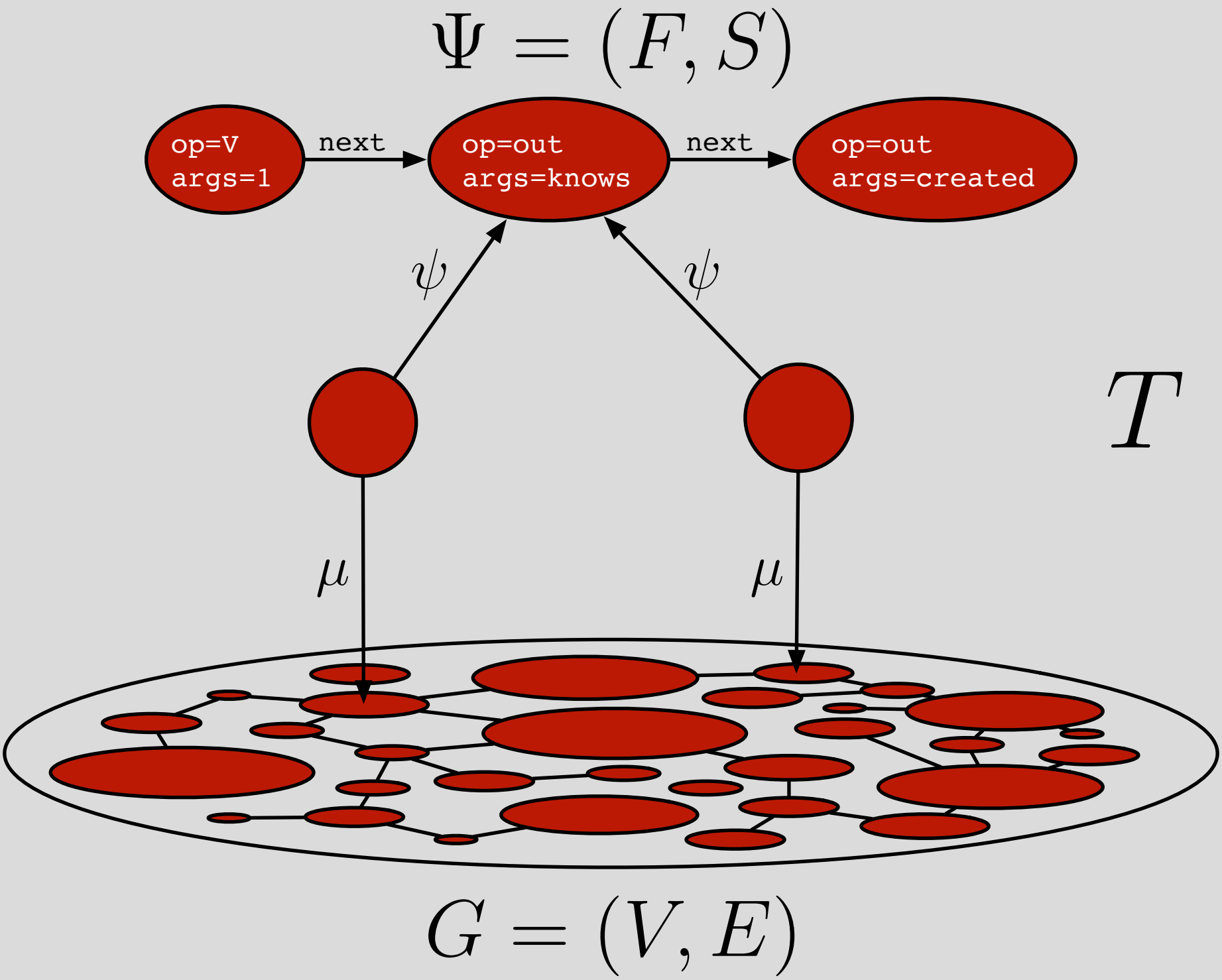


$$G \xleftarrow{\ \mu\ } t \in T \xrightarrow{\ \psi\ } \Psi$$



$$G = (V, E)$$


$\Psi = (F, S)$
op=V
args=1
next
op=out
args=knows
next
op=out
args=created
ψ
$t \in T$
$G \longleftarrow_{\mu} t \in T \longrightarrow_{\psi} \Psi$
μ
$G = (V, E)$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ψ
ψ
T
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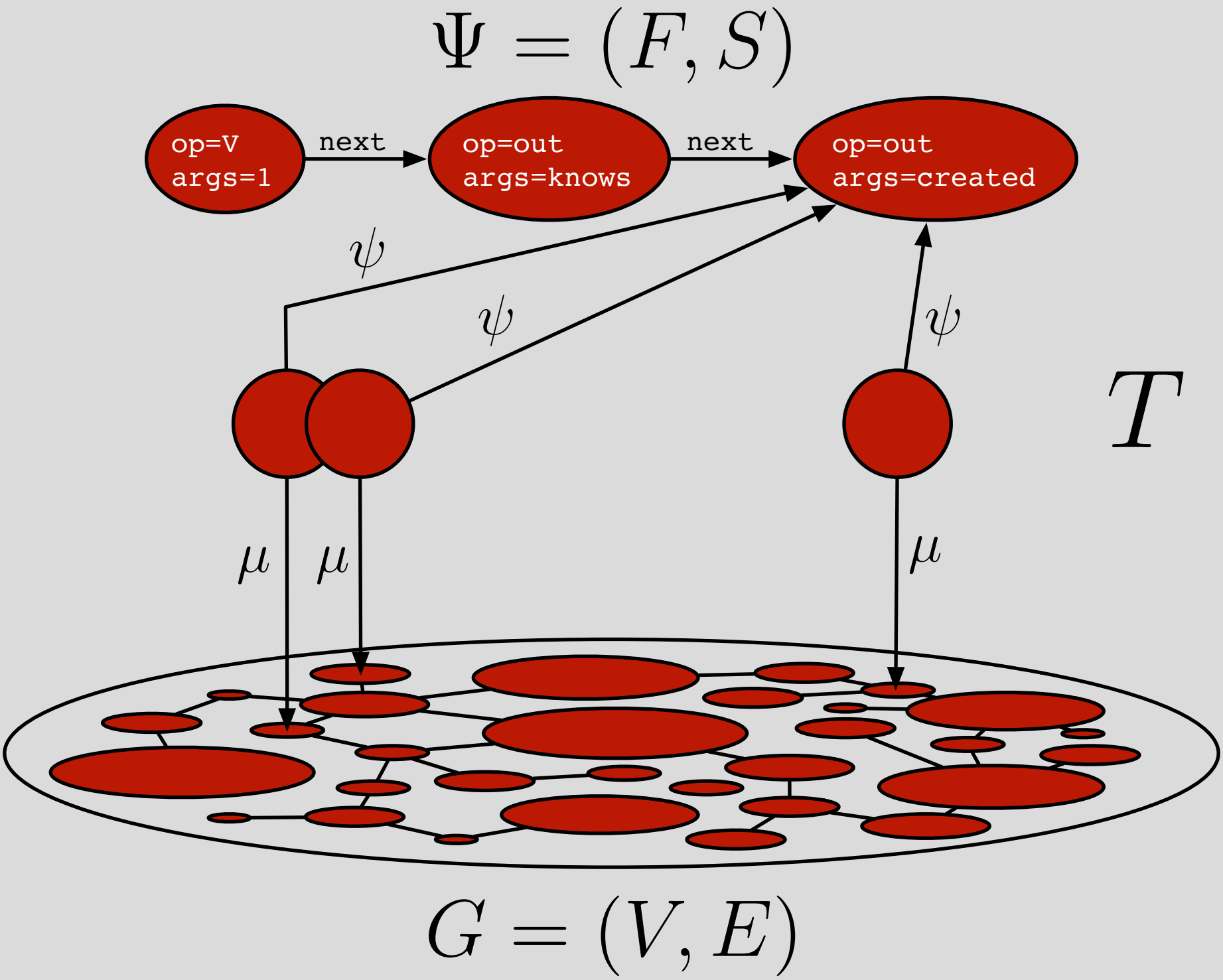
$G = (V, E)$


$\Psi = (F, S)$
op=V
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op=out
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op=out
args=created
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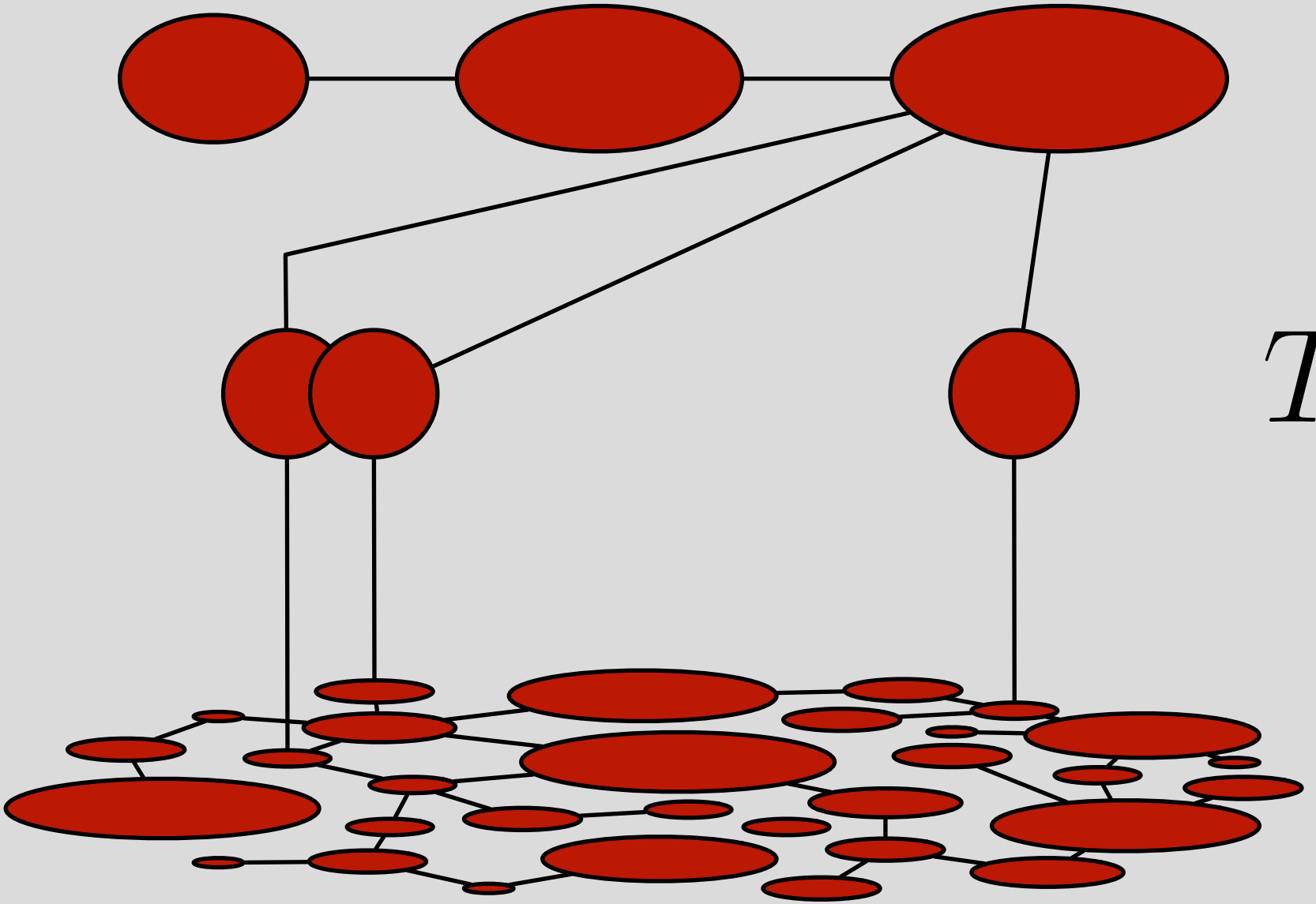
$G = (V, E)$

$\Psi = (F, S)$



T

$G = (V, E)$

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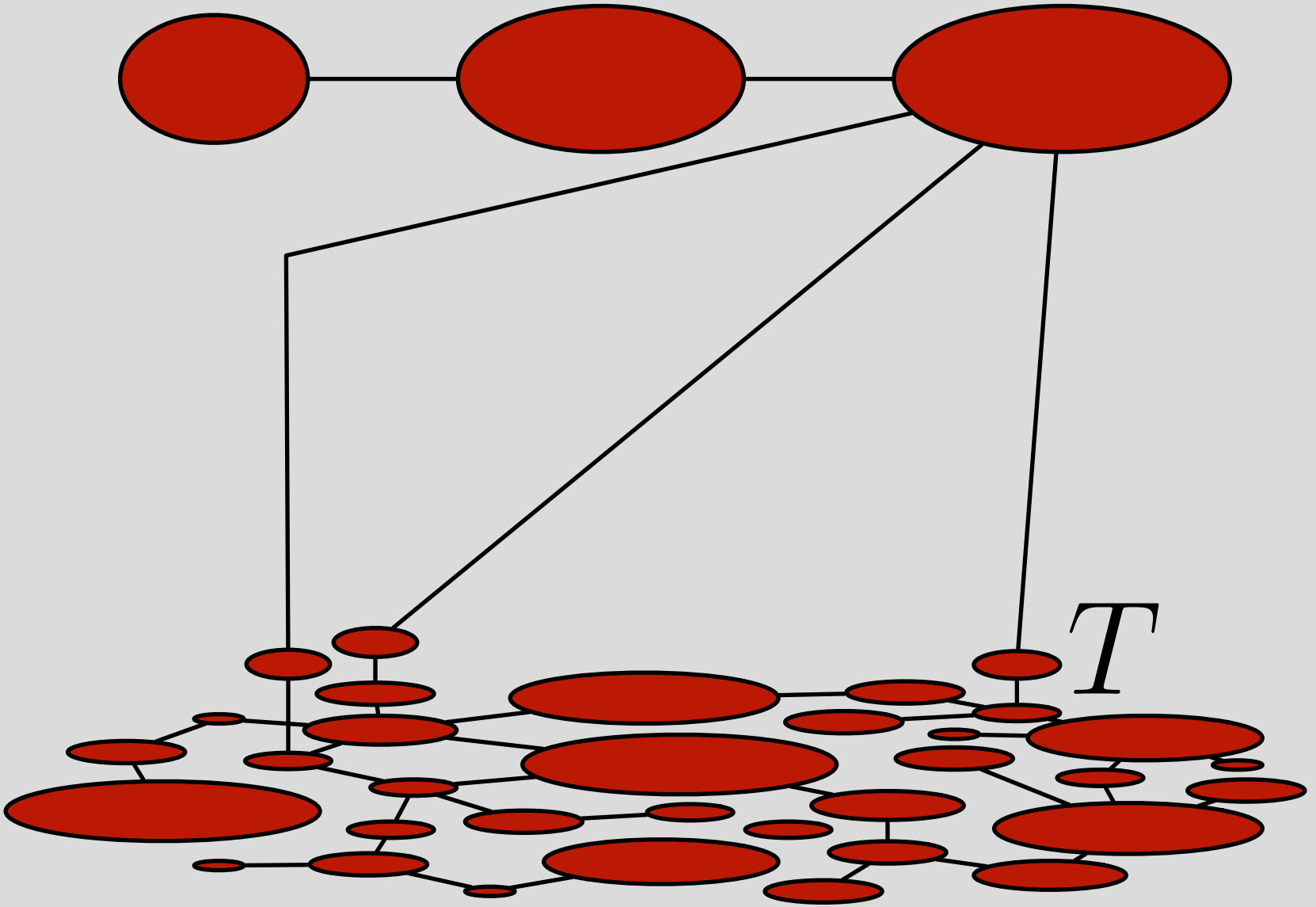

$G = (V, E)$

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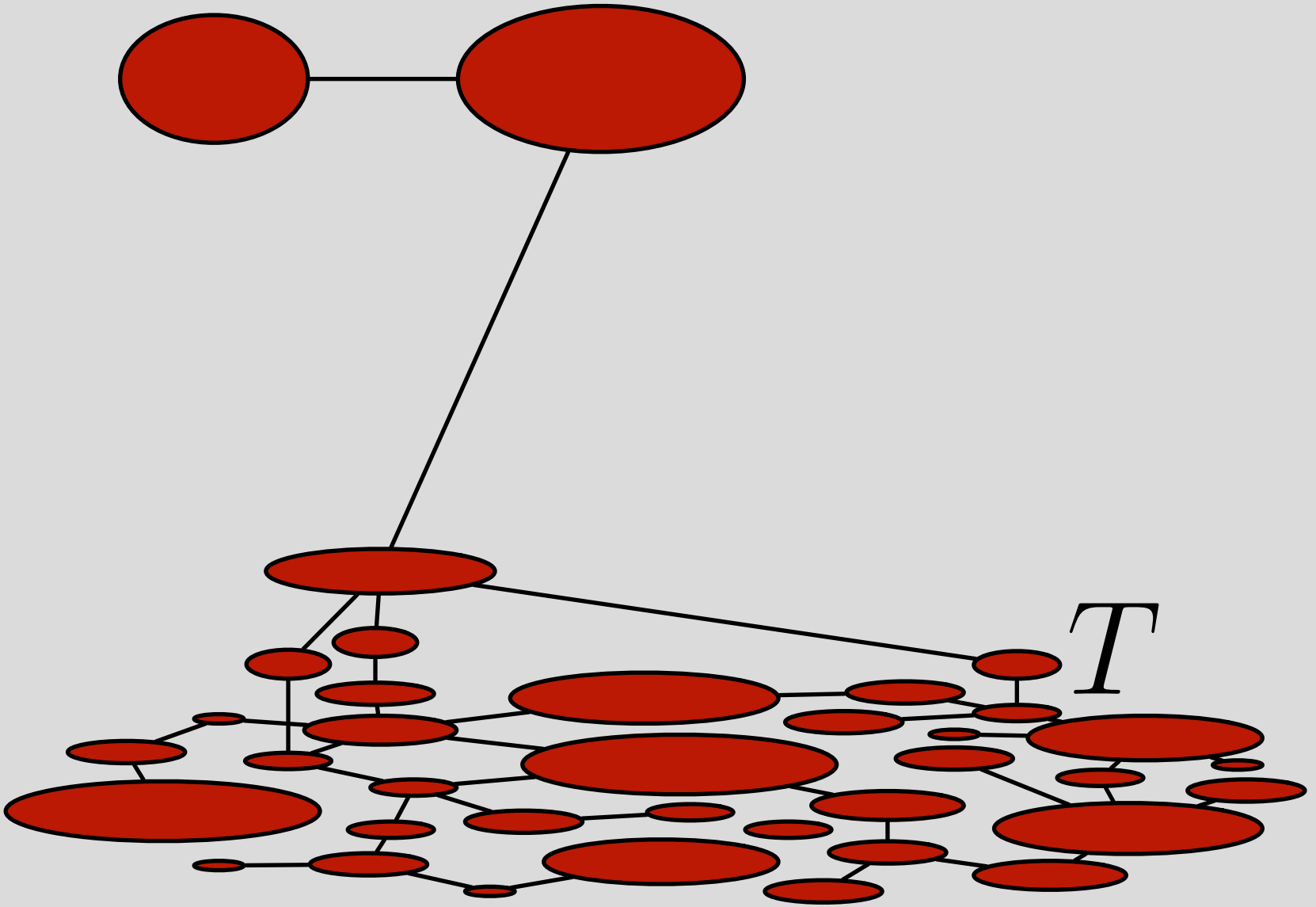

$$G = (V, E)$$

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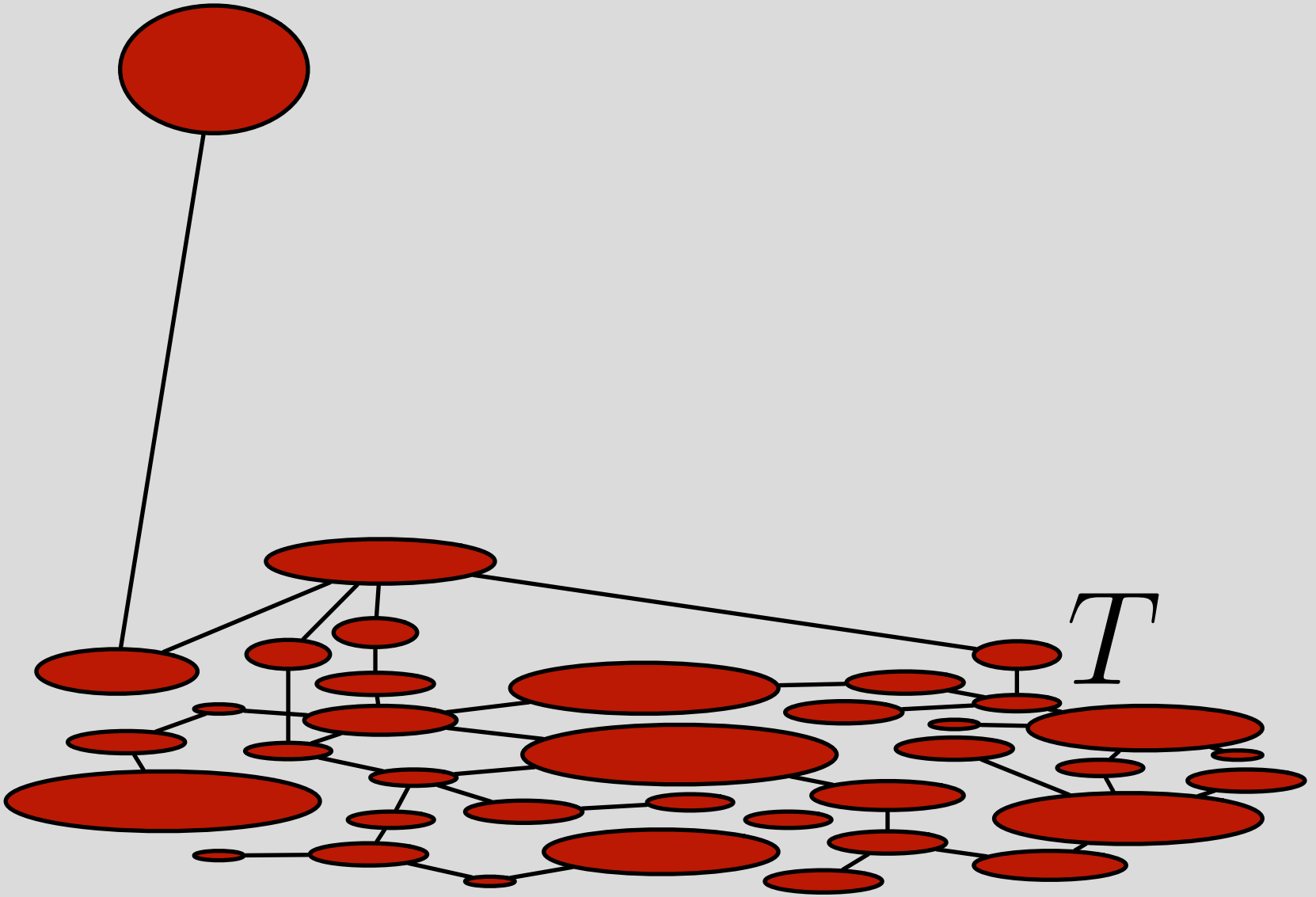
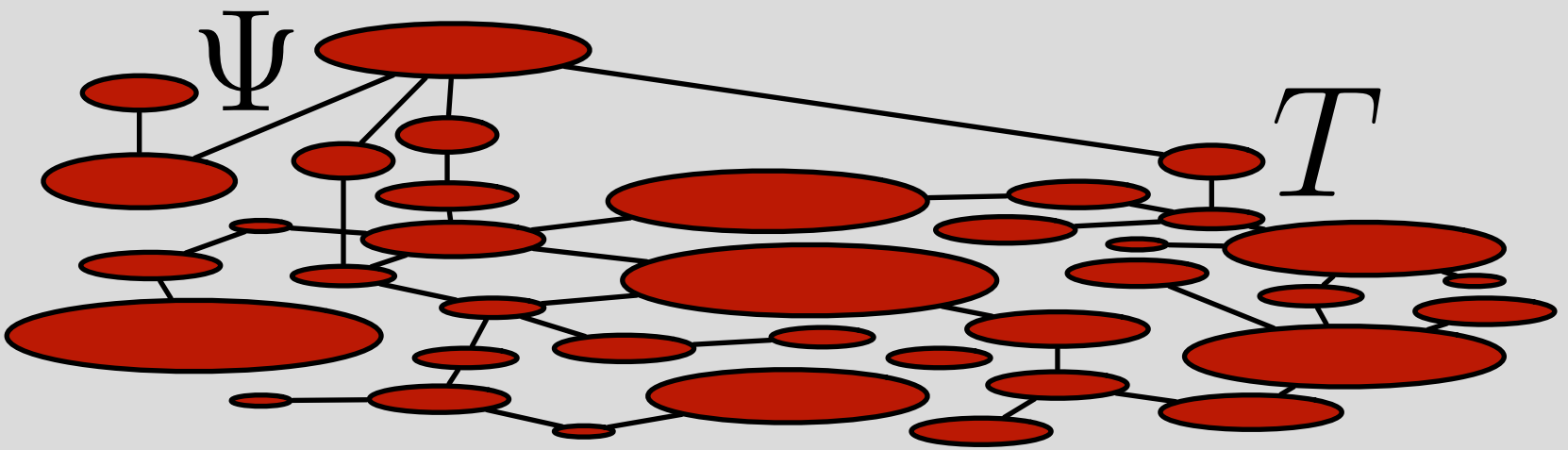


$$G = (V, E)$$

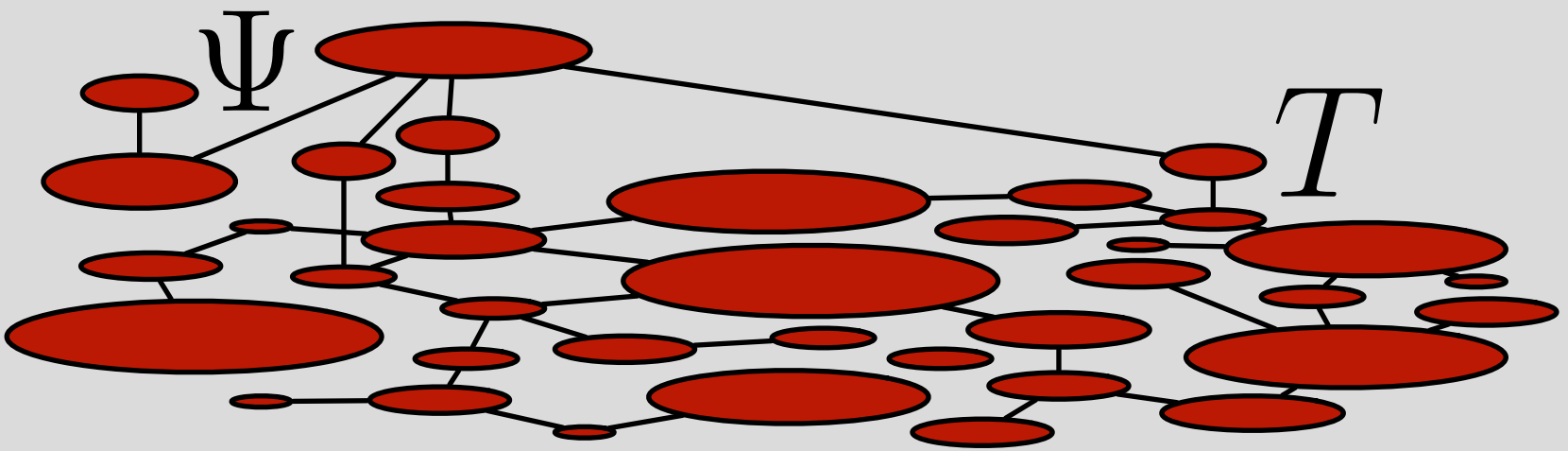
“Everything is a graph?”



$$G = (V, E)$$

“Everything is a graph?”

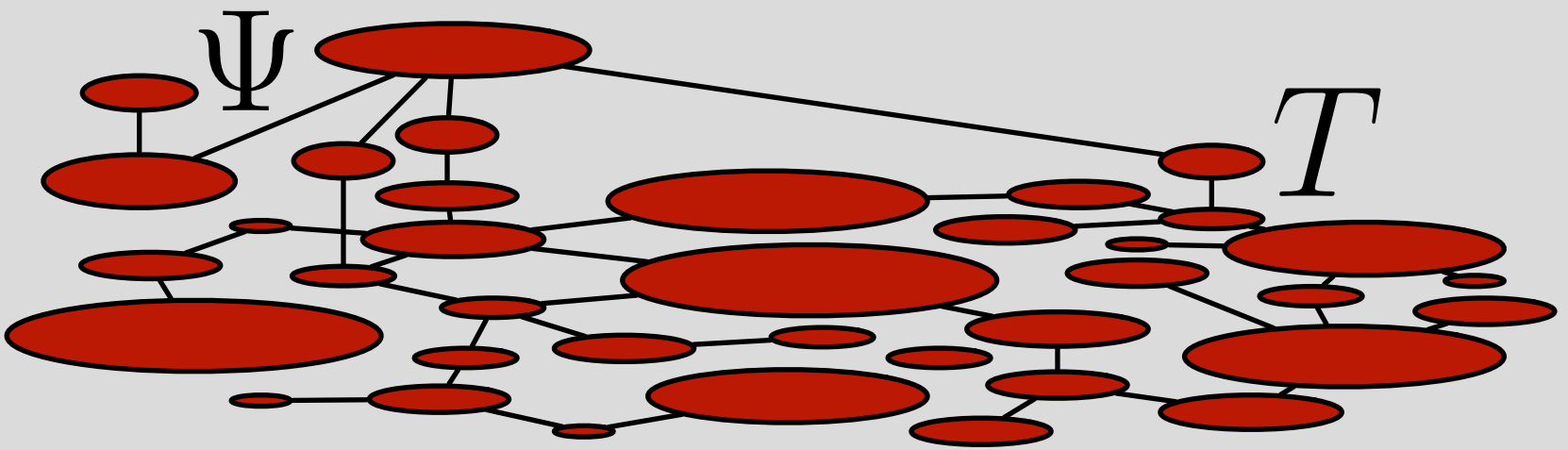
No — All that exists is a static structure.



$$G = (V, E)$$

“Everything is a graph?”

Fine — Create a traversal that executes the graph encoded traversal. Ψ'



$$G = (V, E)$$

Footnote #2

```
g.withSack(0).withSideEffect('drain',[1]).withSideEffect('fill',[]).
  V().has('source','g').as('parent').
  repeat(out('next').as('step').
    map(values('arg').fold()).as('args').
    sideEffect(select('drain').unfold().
    choose(select(last,'args').count(local).is(0),
      choose(select(last,'step').by('op')).
        option('V',V().hasLabel(not(within('step','traversal')))).
        option('out',out()).
        option('in',in()).
        option('both',both()).
        option('outE',outE()).
        option('inE',inE()).
        option('bothE',bothE()).
        option('inV',inV()).
        option('outV',outV()).
        option('otherV',otherV()).
        option('values',values()).
        option('barrier',barrier()).
        option('dedup',dedup()).
        option(none,identity()).
      choose(select(last,'step').by('op')).
        option('V', V().hasLabel(not(within('step','traversal'))).
          where(within('args')).by(id).by()).
        option('has',filter(union(label(),properties().
          where(within('args')).by(key).by().value()).
            filter(predicate("it.path(last,'args')[1].test(it.get())")))).
        option('out',outE().where(within('args')).by(label).by().inV()).
        option('in',inE().where(within('args')).by(label).by().outV()).
        option('both',bothE().where(within('args')).by(label).by().otherV()).
        option('outE',outE().where(within('args')).by(label).by()).
        option('inE',inE().where(within('args')).by(label).by()).
        option('bothE',bothE().where(within('args')).by(label).by()).
        option('values',properties().where(within('args')).by(key).by().value()).
        option('barrier',barrier()).
        option(none,identity())).
      store('fill')).
```

Ψ'

...

Footnote #2

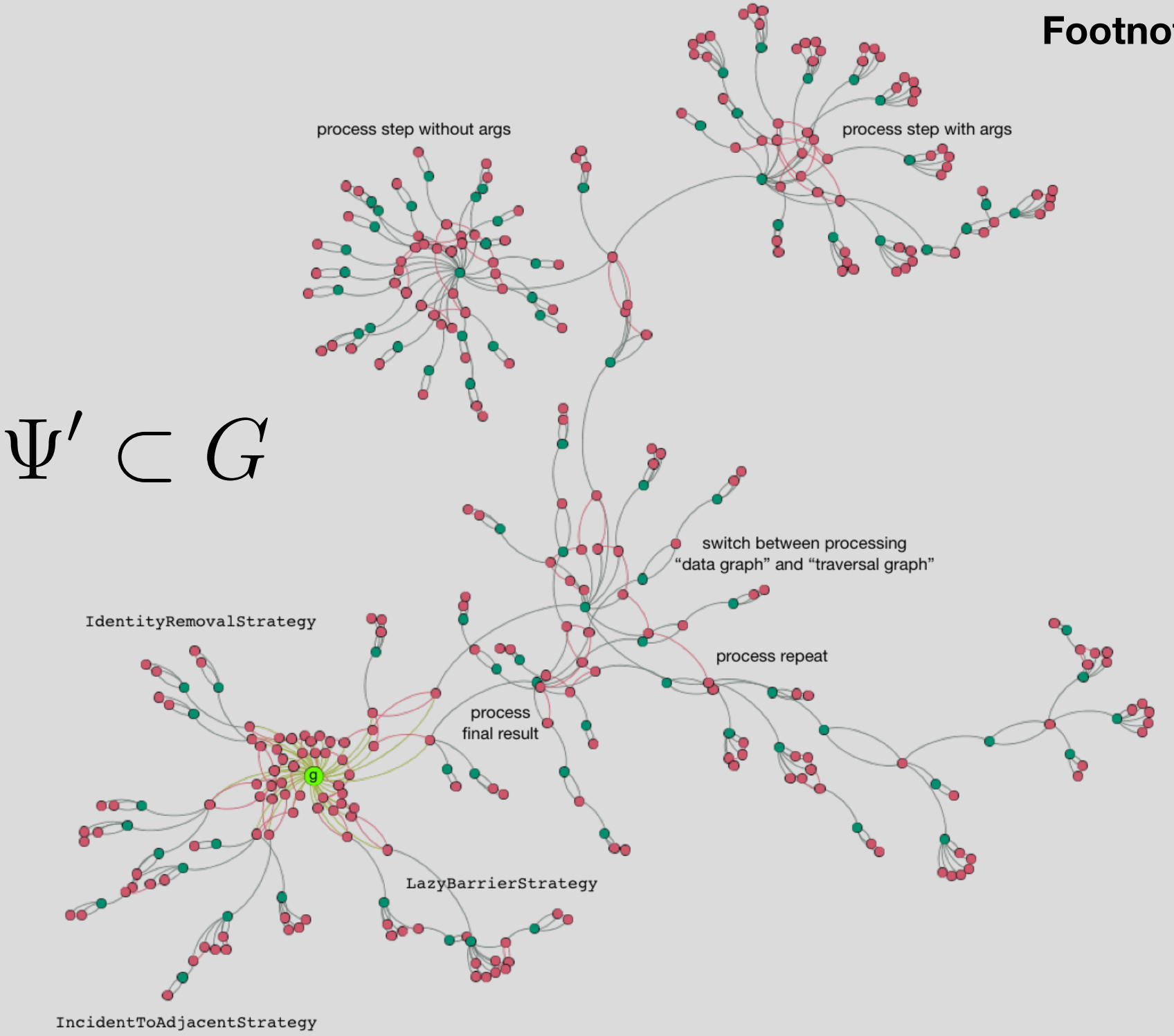
...

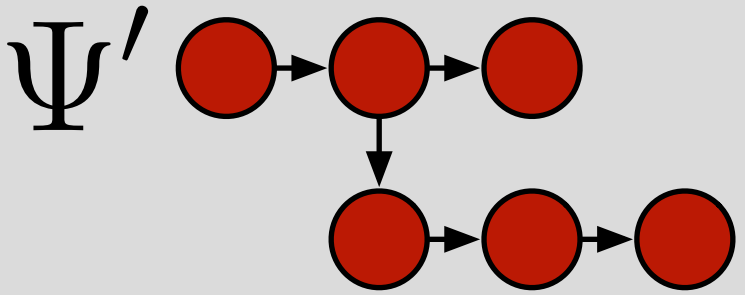
```
sideEffect(consumer("it.sideEffects('drain').clear()")).
    sideEffect(select('fill').unfold().store('drain')).
    sideEffect(consumer("it.sideEffects('fill').clear()")).
    select(last,'step').
    choose(has('op','repeat').and().out('next').has('op','times'),
      select(last,'step').as('parent').
        sack(assign).by(out('next').values('arg')).out('child').as('step'),
      choose(select(last,'parent').has('op','repeat').and().out('next').count().is(0),
        choose(sack().is(gt(1)),
          sack(minus).by(constant(1)).select(last,'parent').out('child').as('step'),
          select(last,'parent').as('step').out('parent').as('parent').select(last,'step')),
        identity()))).
  until(out('next').count().is(0)).
  select('drain').
  choose(select(last,'step').has('op',within('fold','sum','mean','min','max','count','groupCount')),
    choose(select(last,'step').by('op')).
      option('fold',identity()).
      option('sum',map(unfold().sum())).
      option('mean',map(unfold().mean())).
      option('min',map(unfold().min())).
      option('max',map(unfold().max())).
      option('count',map(unfold().count())).
      option('groupCount',map(unfold().groupCount())),
    unfold())
```

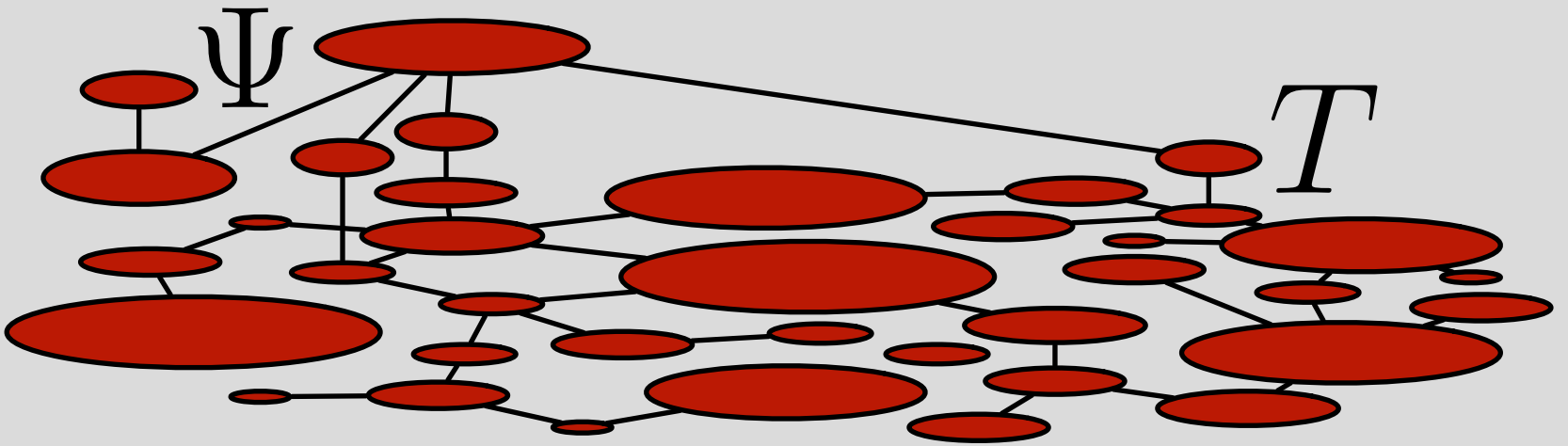
Rodriguez, M.A., “A Gremlin Implementation of the Gremlin Traversal Machine,” DataStax Engineering Blog, October 2016.

https://www.datastax.com/dev/blog/a-gremlin-implementation-of-the-gremlin-traversal-machine

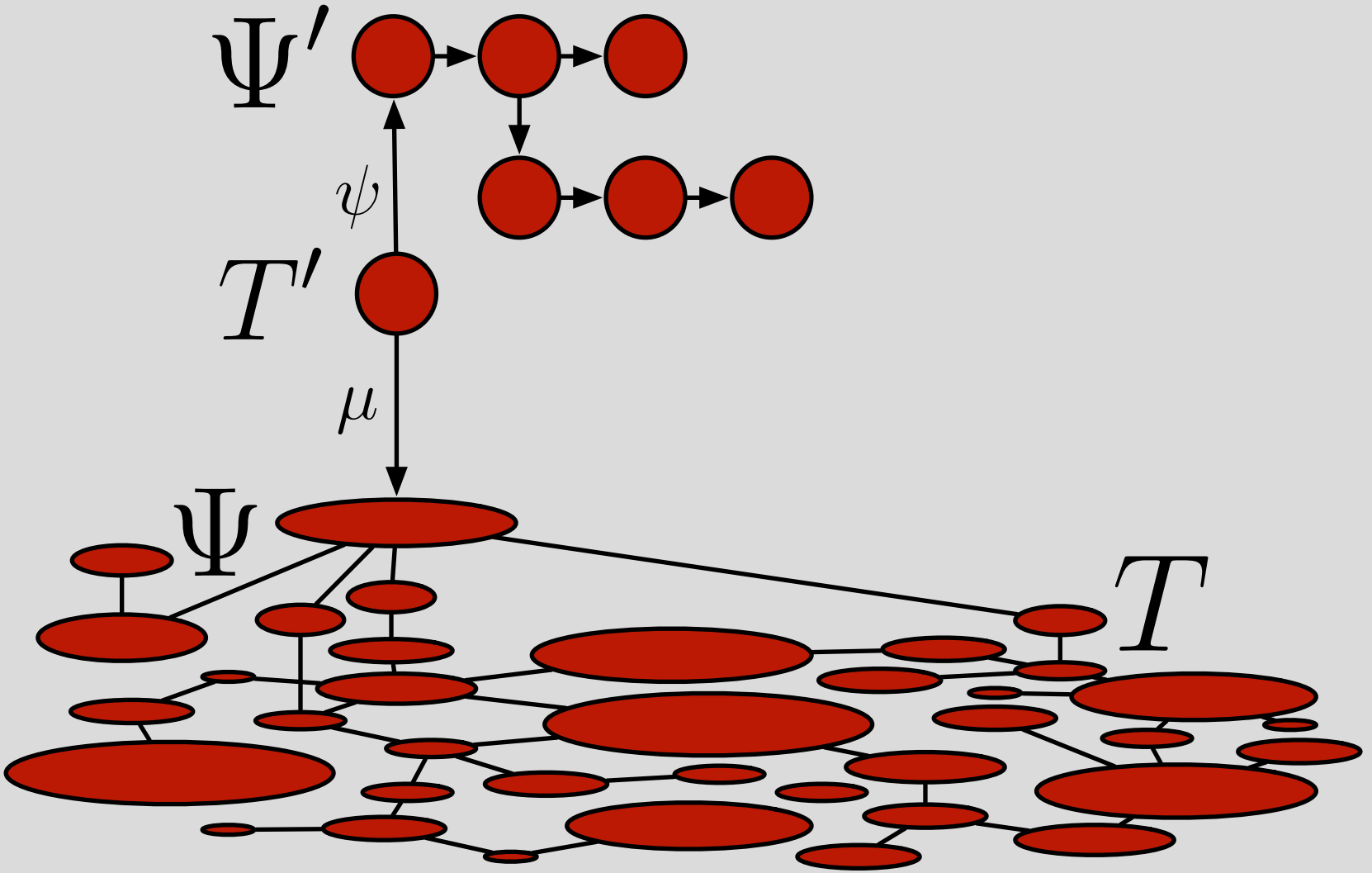
Footnote #2


process step without args
process step with args
$\Psi' \subset G$
switch between processing
“data graph” and “traversal graph”
IdentityRemovalStrategy
process repeat
process
final result
g
LazyBarrierStrategy
IncidentToAdjacentStrategy



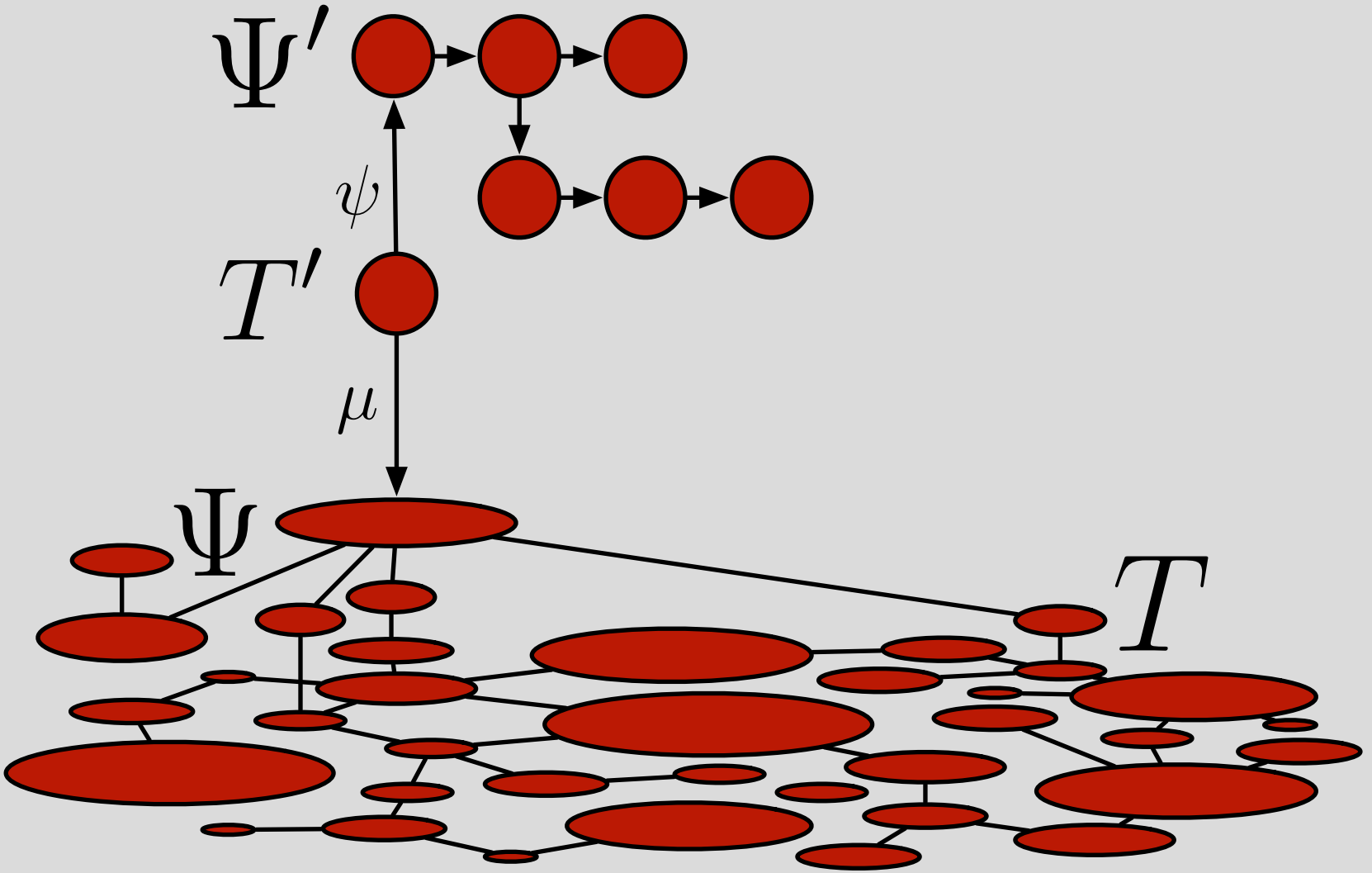


$$G = (V, E)$$



$$G = (V, E)$$

“Everything is a graph?”



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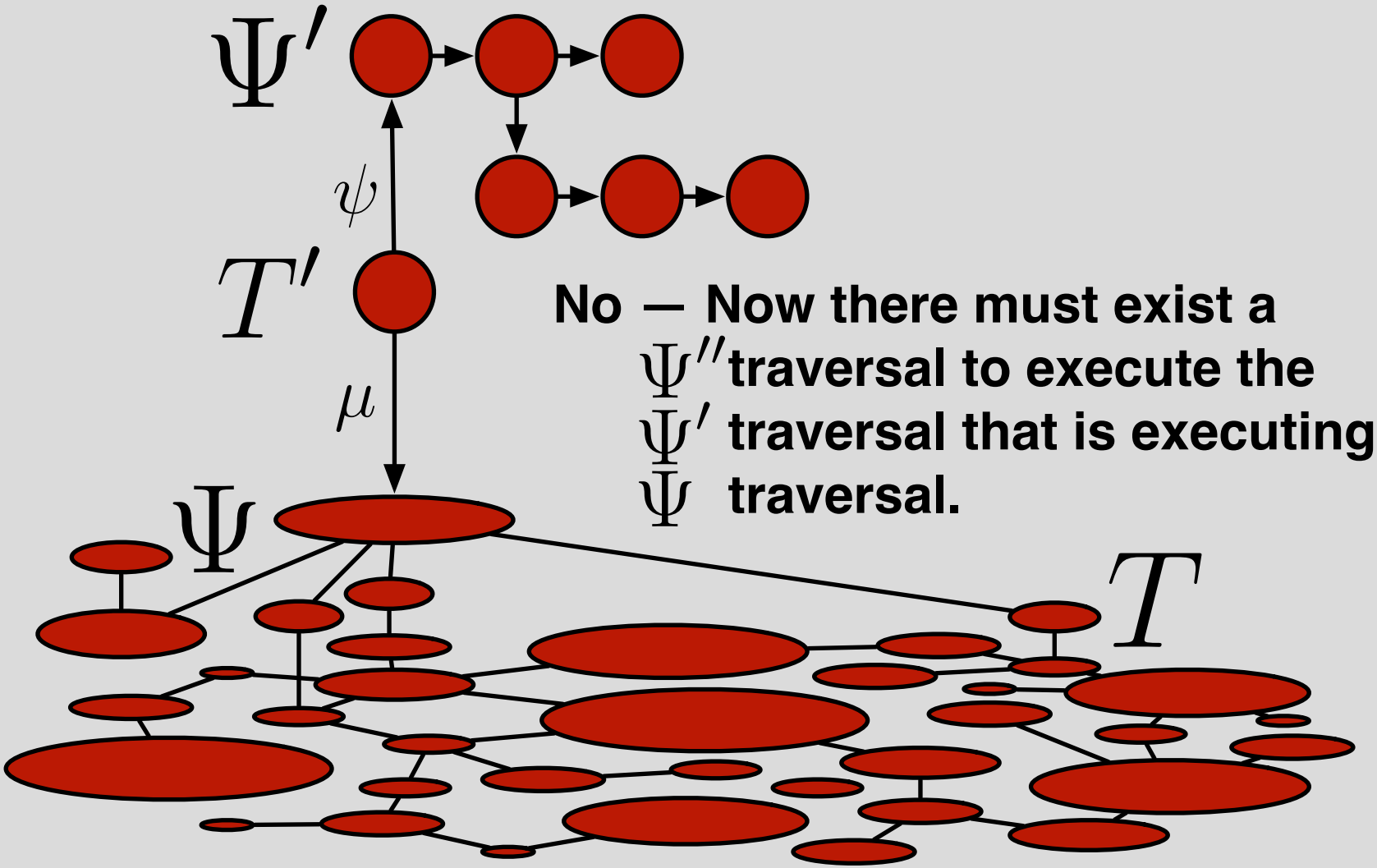
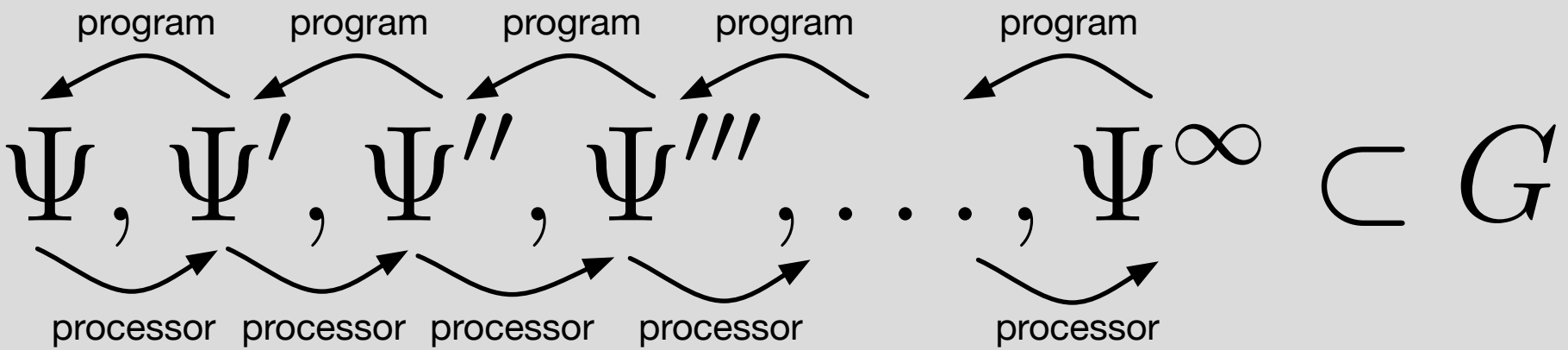
“Everything is a graph?”

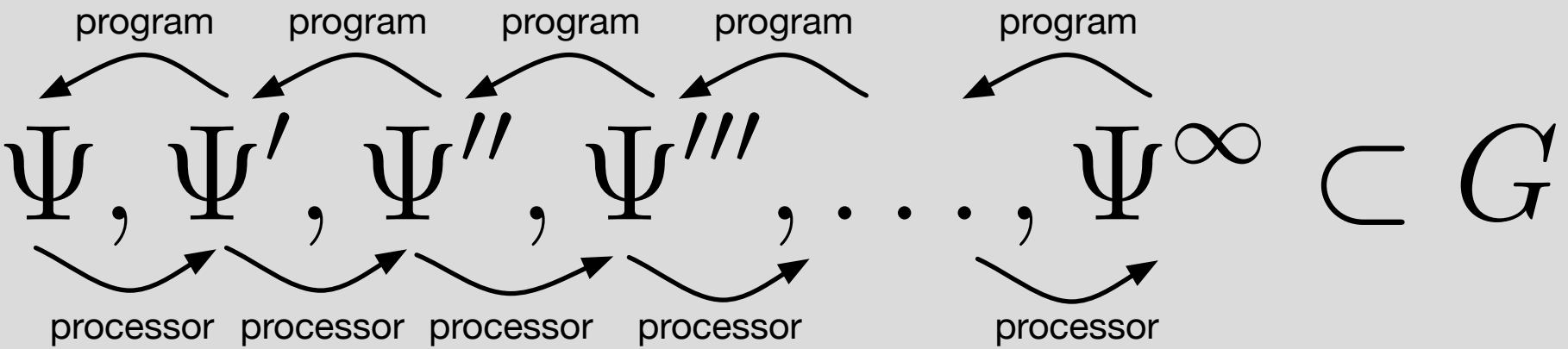


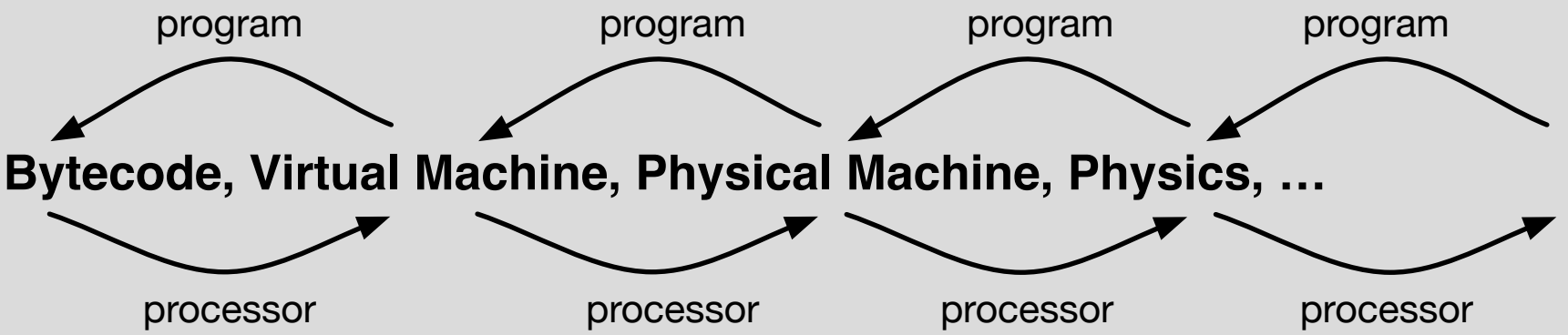
No — Now there must exist a Ψ'' traversal to execute the Ψ' traversal that is executing the Ψ traversal.

$$G = (V, E)$$

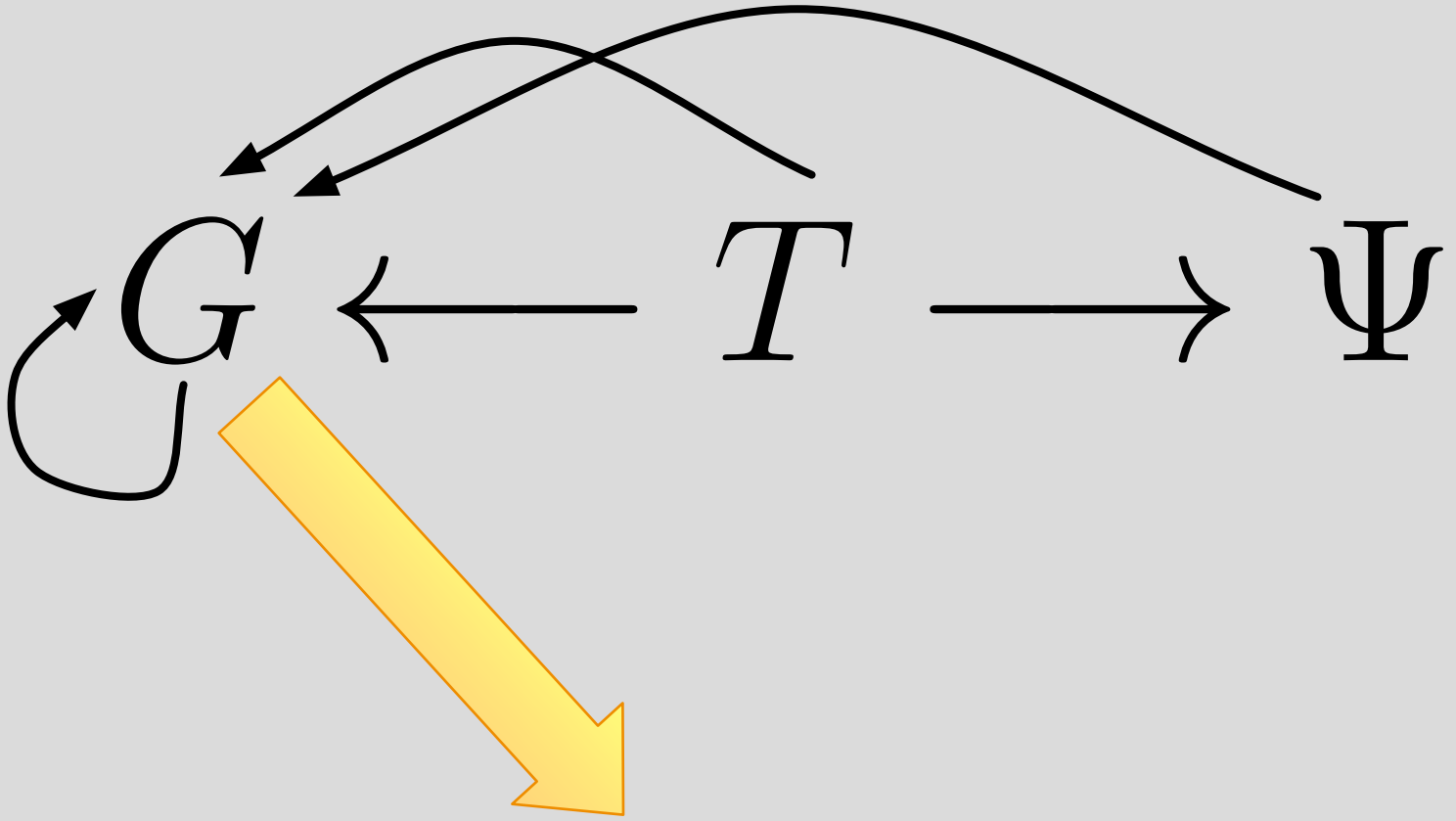
$$\Psi, \Psi', \Psi'', \Psi''', \ldots, \Psi^{\infty} \subset G$$


program
program
program
program
program
$\Psi, \Psi', \Psi'', \Psi''', \ldots, \Psi^{\infty} \subset G$
processor
processor
processor
processor
processor


program
program
program
program
program
$\Psi, \Psi', \Psi'', \Psi''', \ldots, \Psi^{\infty} \subset G$
processor
processor
processor
processor
processor


program
program
program
program
Bytecode, Virtual Machine, Physical Machine, Physics, …
processor
processor
processor
processor

Folding Process into Structure



$$G = (V, E)$$

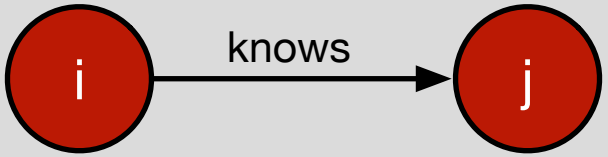
“Everything is a graph.”

Open Problem #1

How can the universal graph evolve without requiring processes to exist “outside” itself?

Footnote #1

directed labeled graph

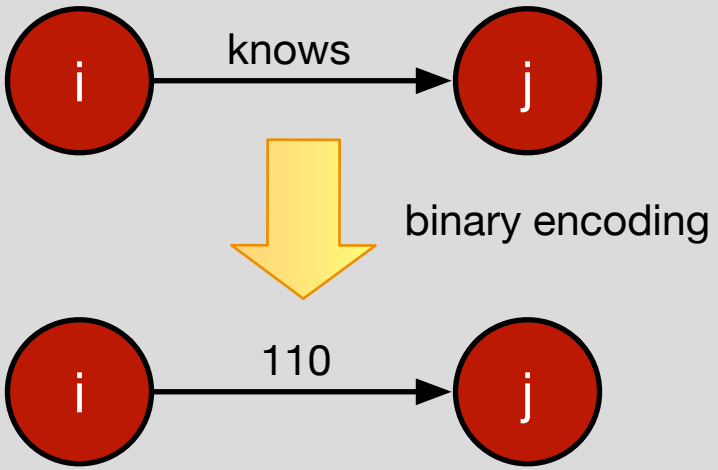


Rodriguez, M.A., “Mapping Semantic Networks to Undirected Networks,” International Journal of Applied Mathematics and Computer Sciences, 5(1), pages 39-42, ISSN:2070-3902, World Academy of Science Engineering and Technology, 2009.

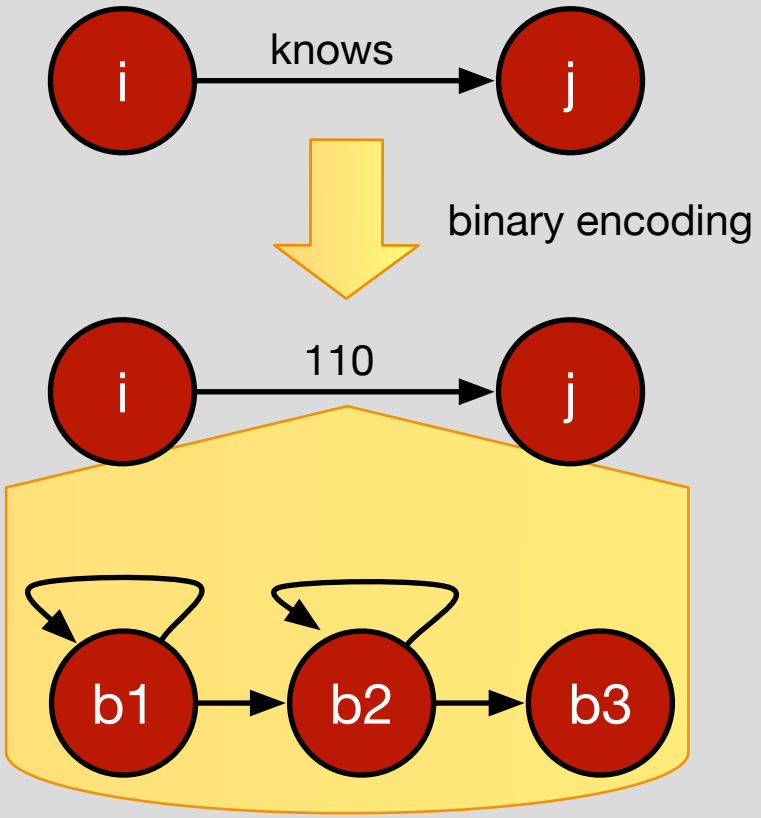
http://arxiv.org/abs/0804.0277

Footnote #1

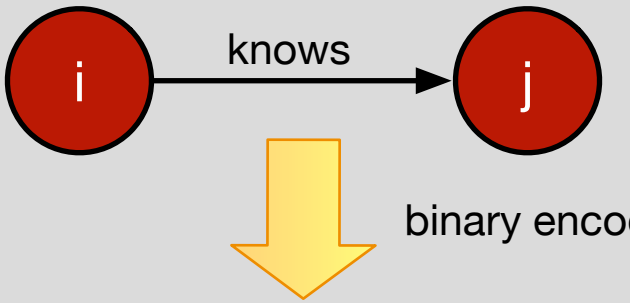
directed labeled graph

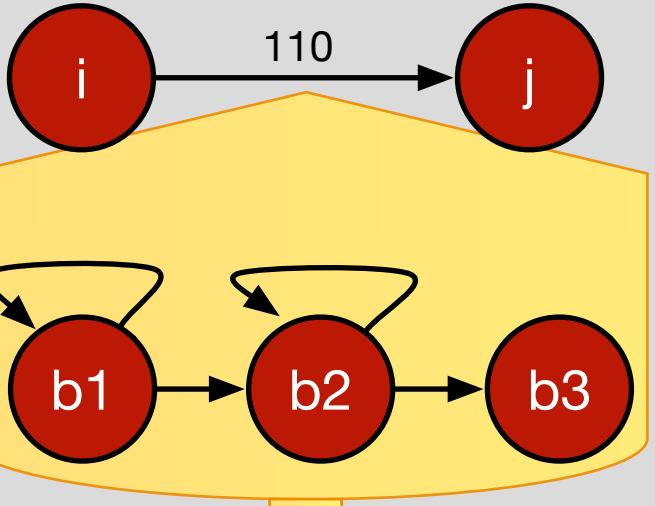


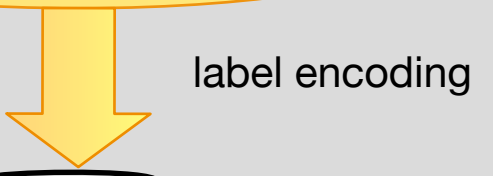
directed labeled graph



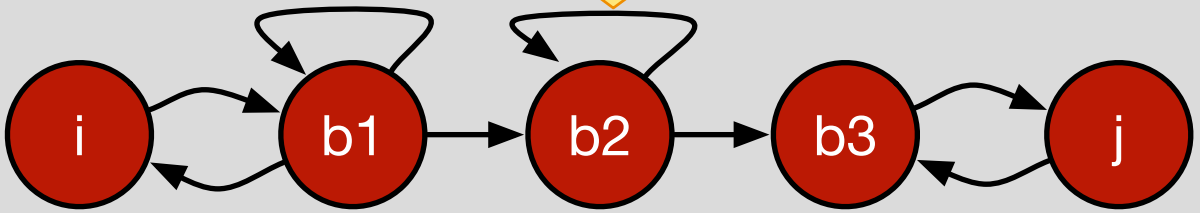
directed labeled graph



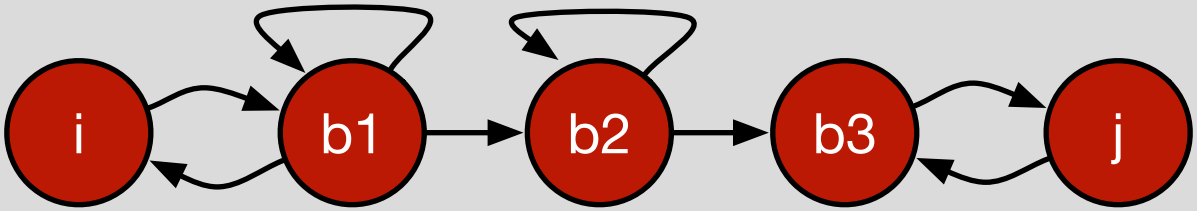




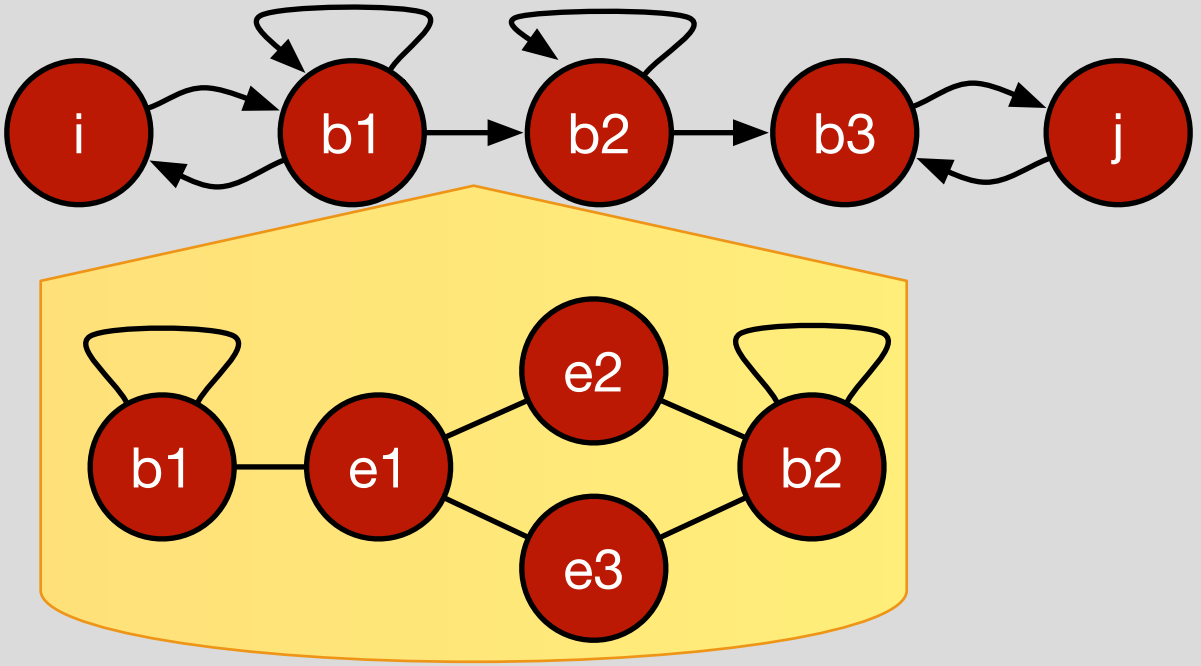
directed graph



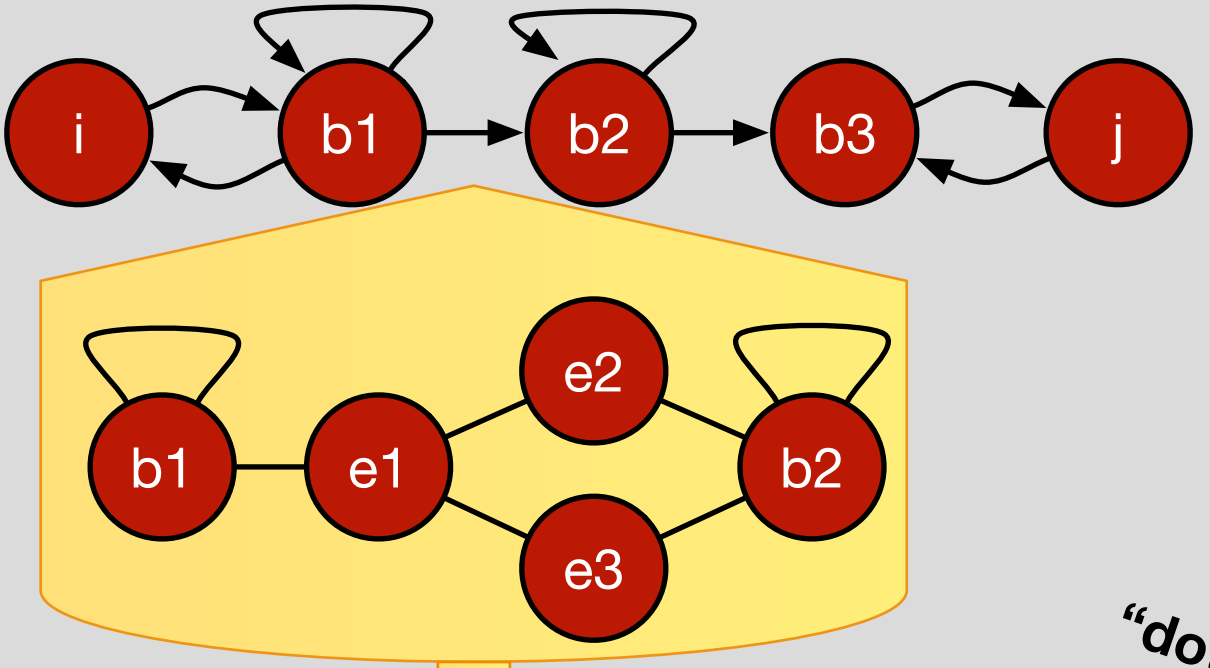
directed graph



directed graph



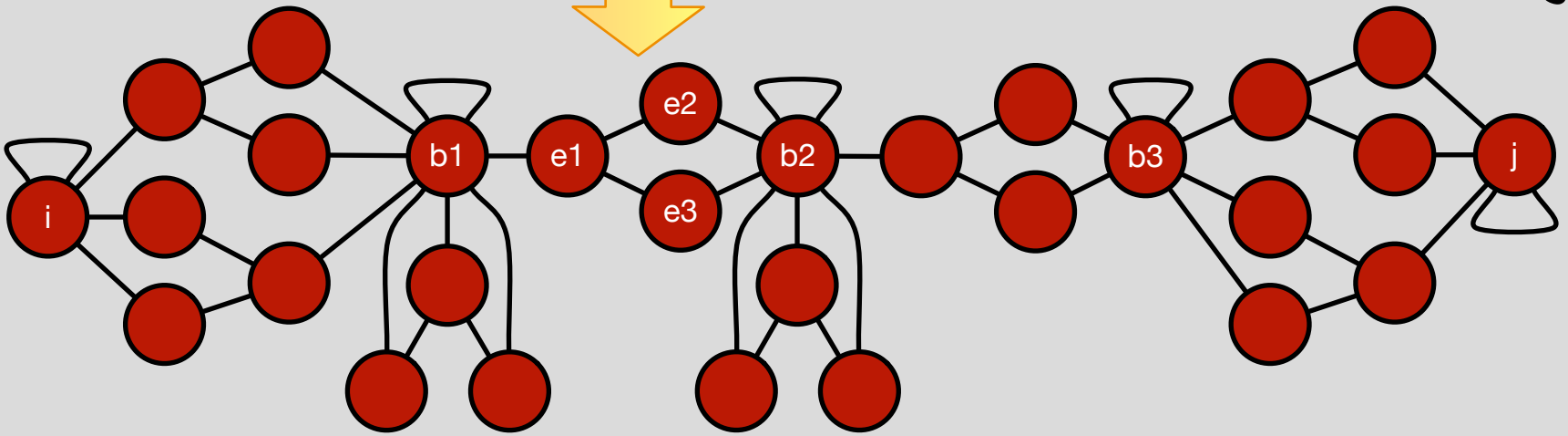
directed graph



direction encoding

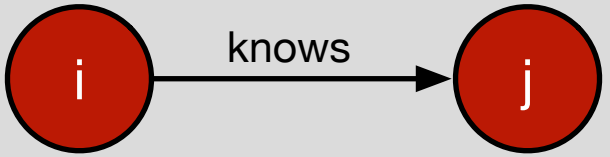
“dots and lines”

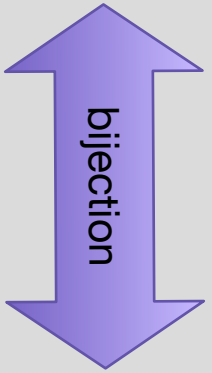
undirected graph



Footnote #1

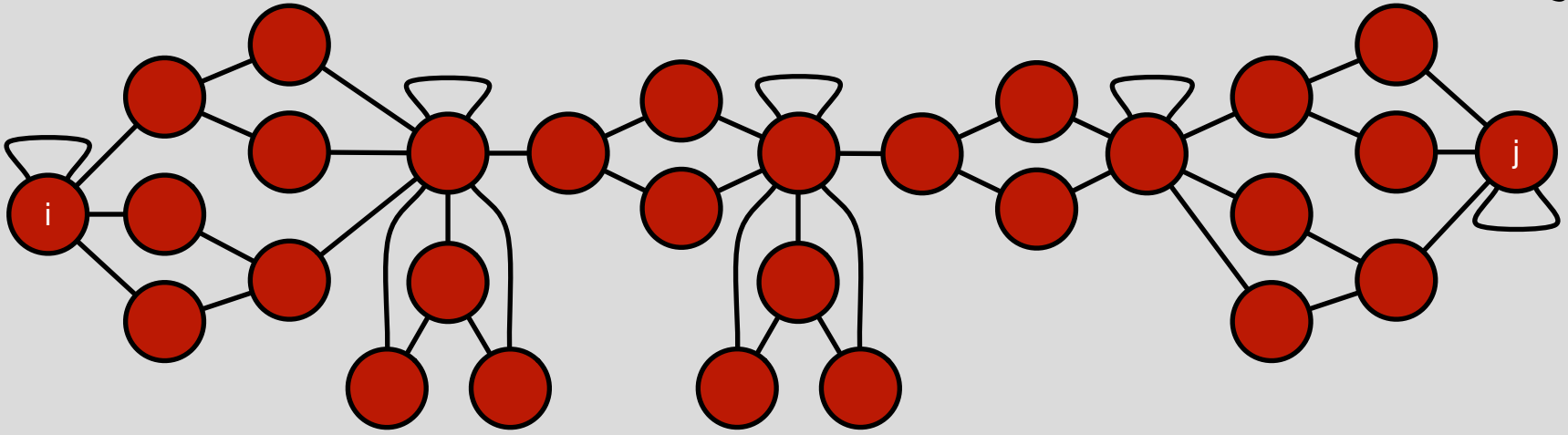
directed labeled graph





undirected graph

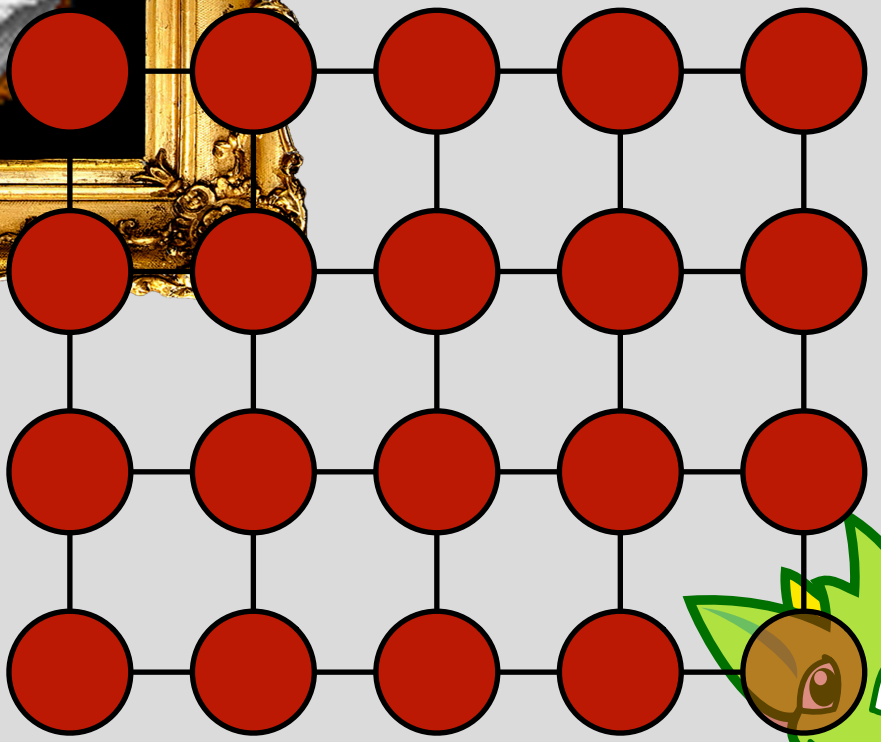
“dots and lines”



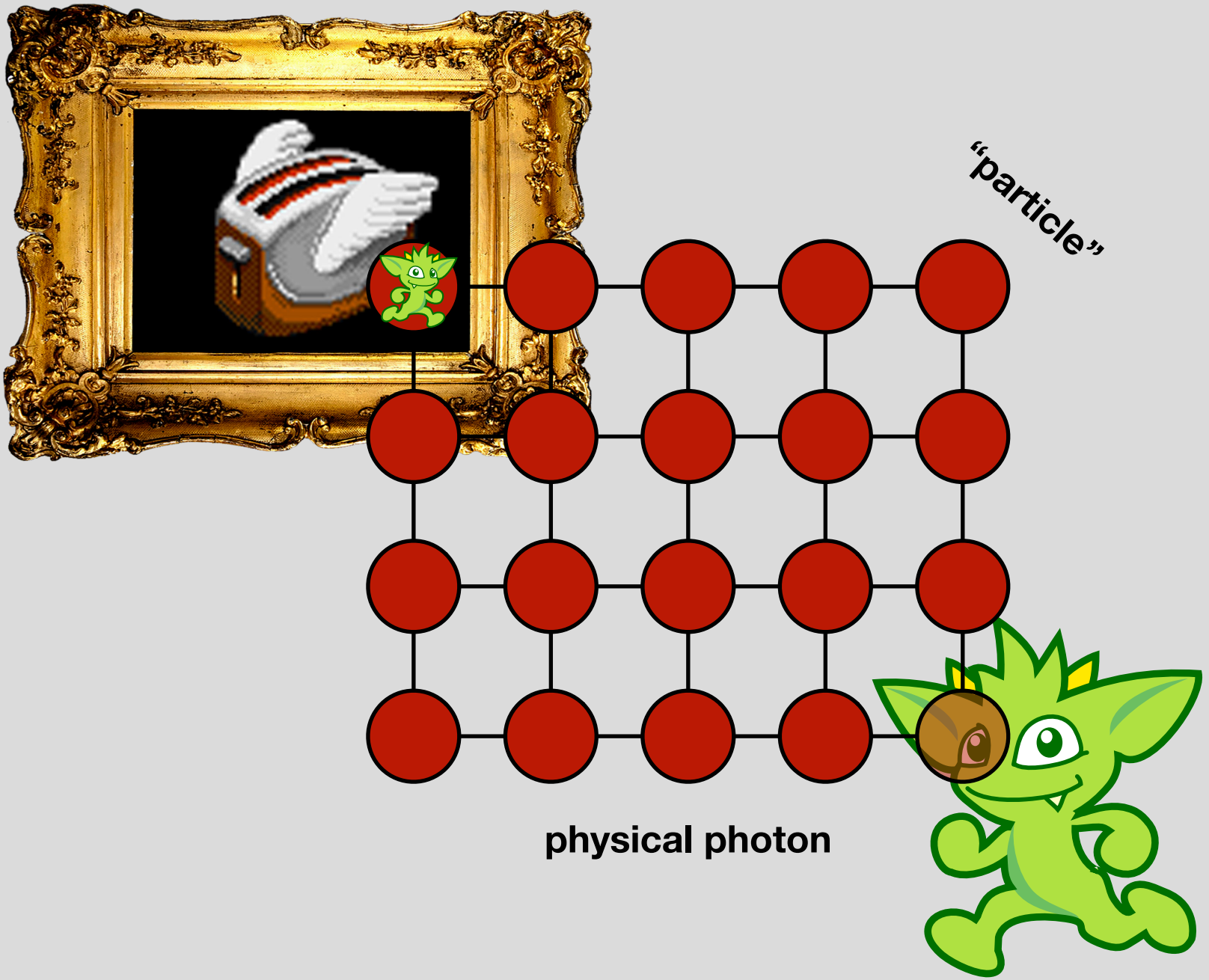
Thought:
The Structure of Experience

physical object

physical object

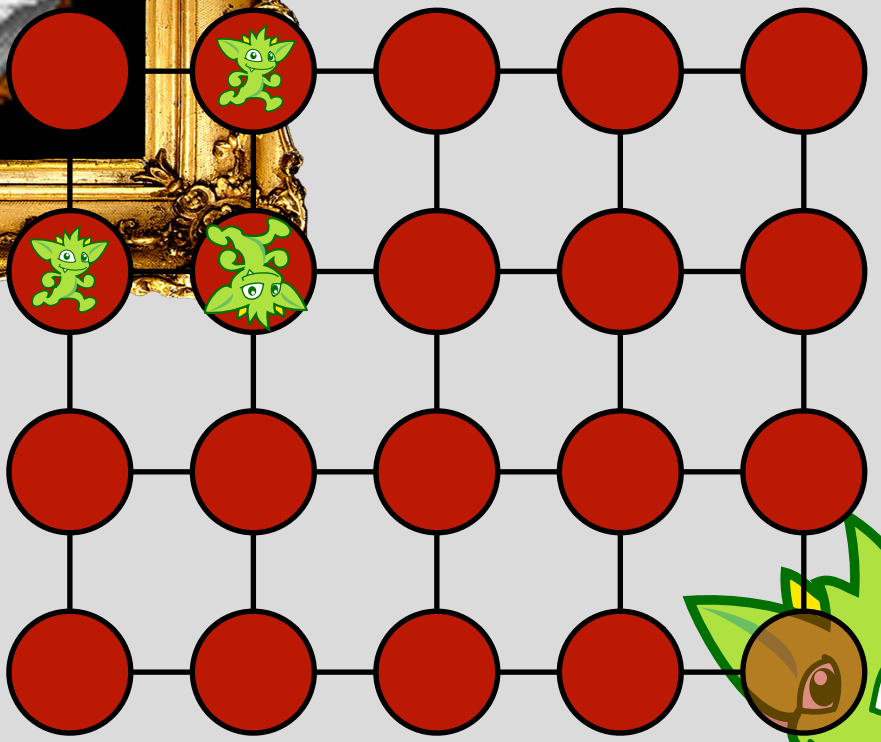


physical spacetime



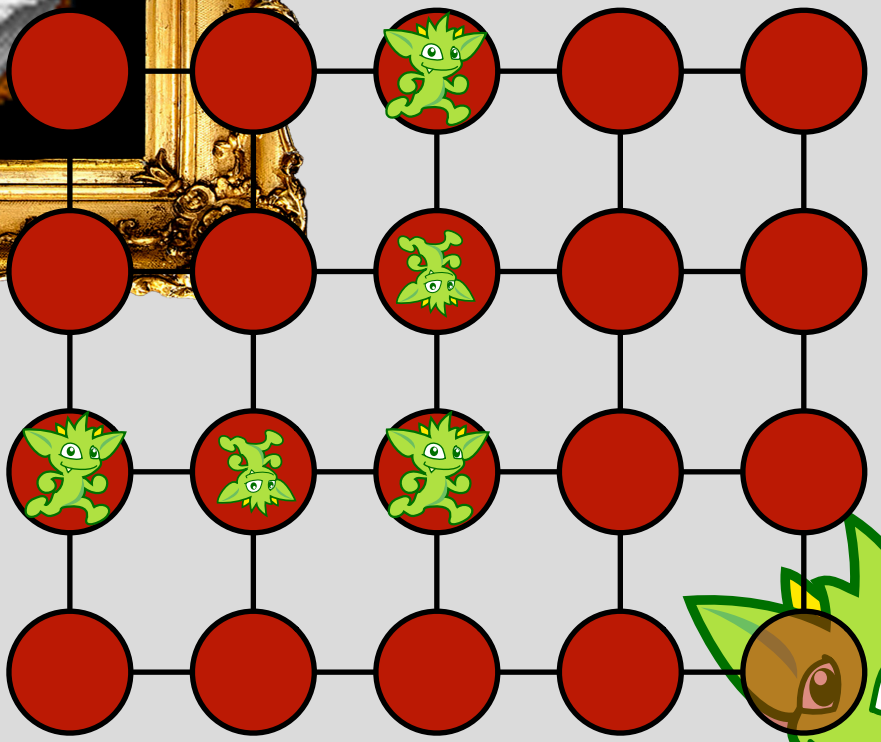
Rodriguez, M.A., Watkins, J.H., "Quantum Walks with Gremlin," Proceedings of GraphDay '16, pages 1-16, Austin, TX, January 2016.

http://arxiv.org/abs/1511.06278



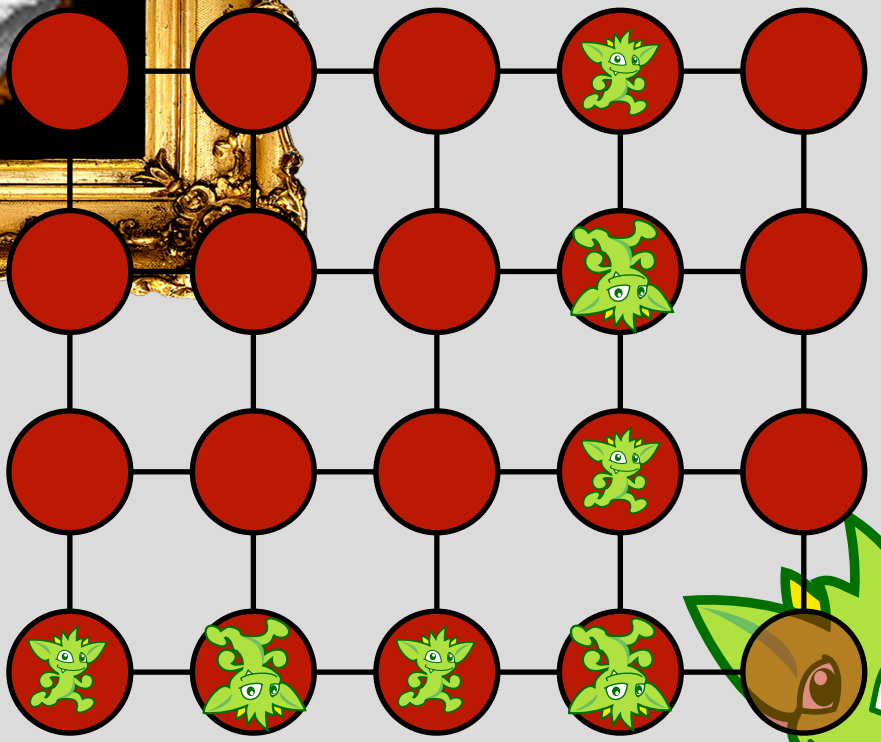
“wave”

photon in
quantum superposition



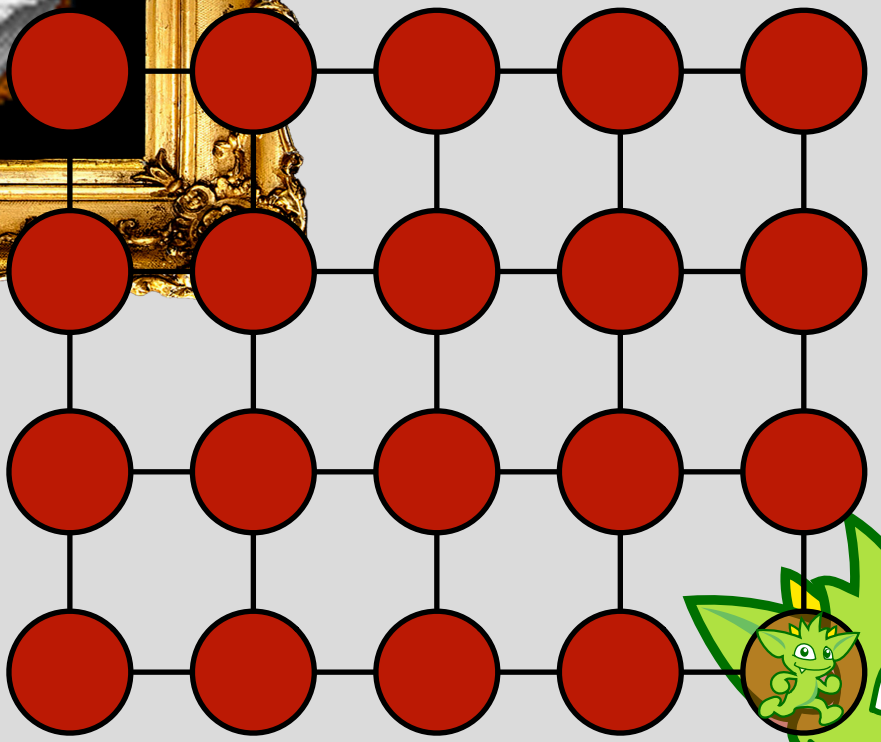
"wave"

photon in
quantum superposition



"wave"

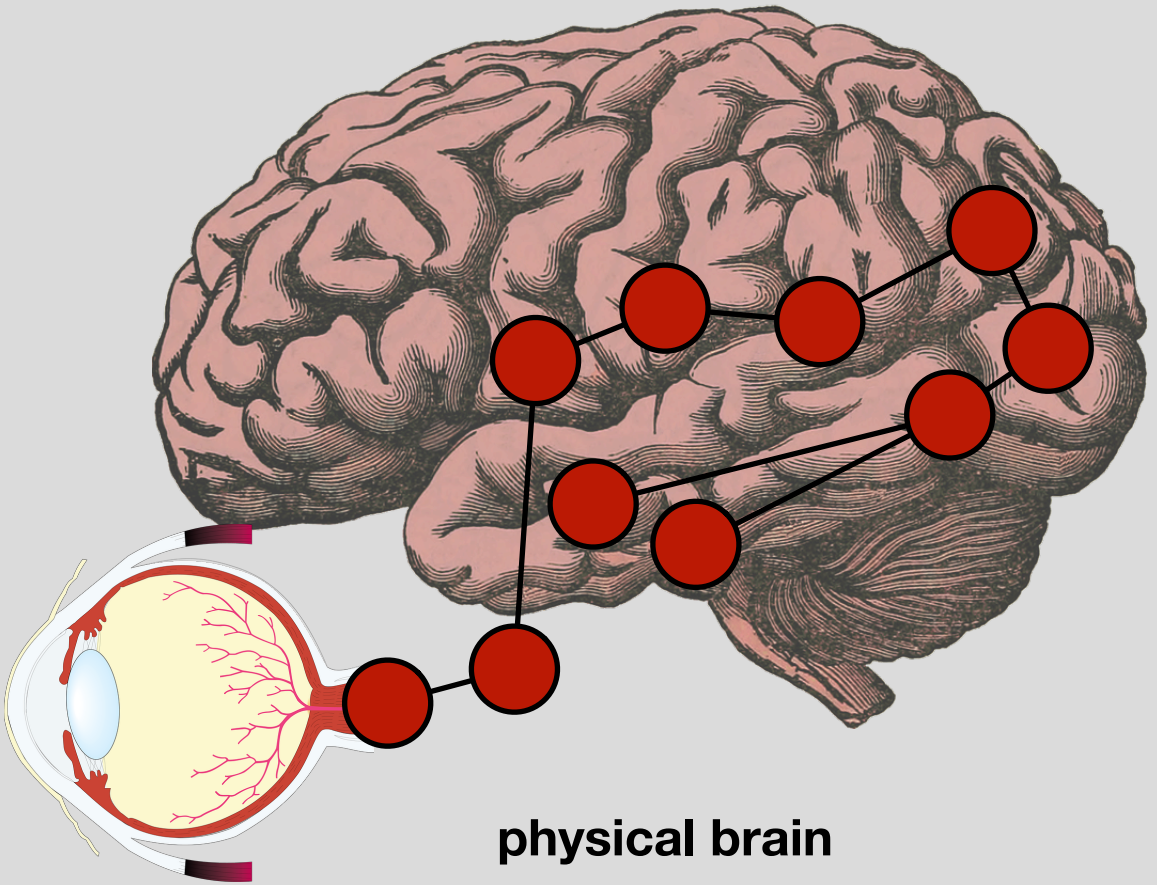
photon in
quantum superposition



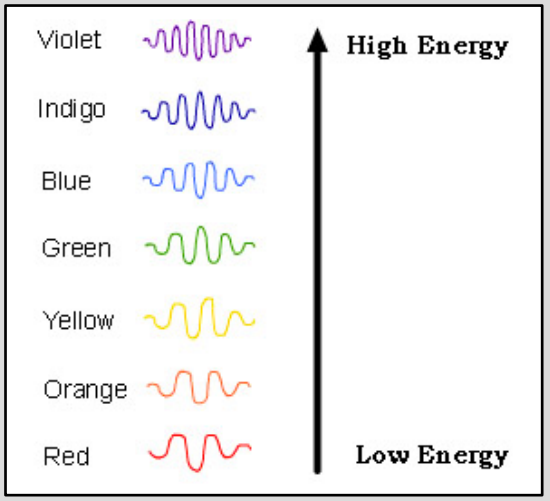
“particle”

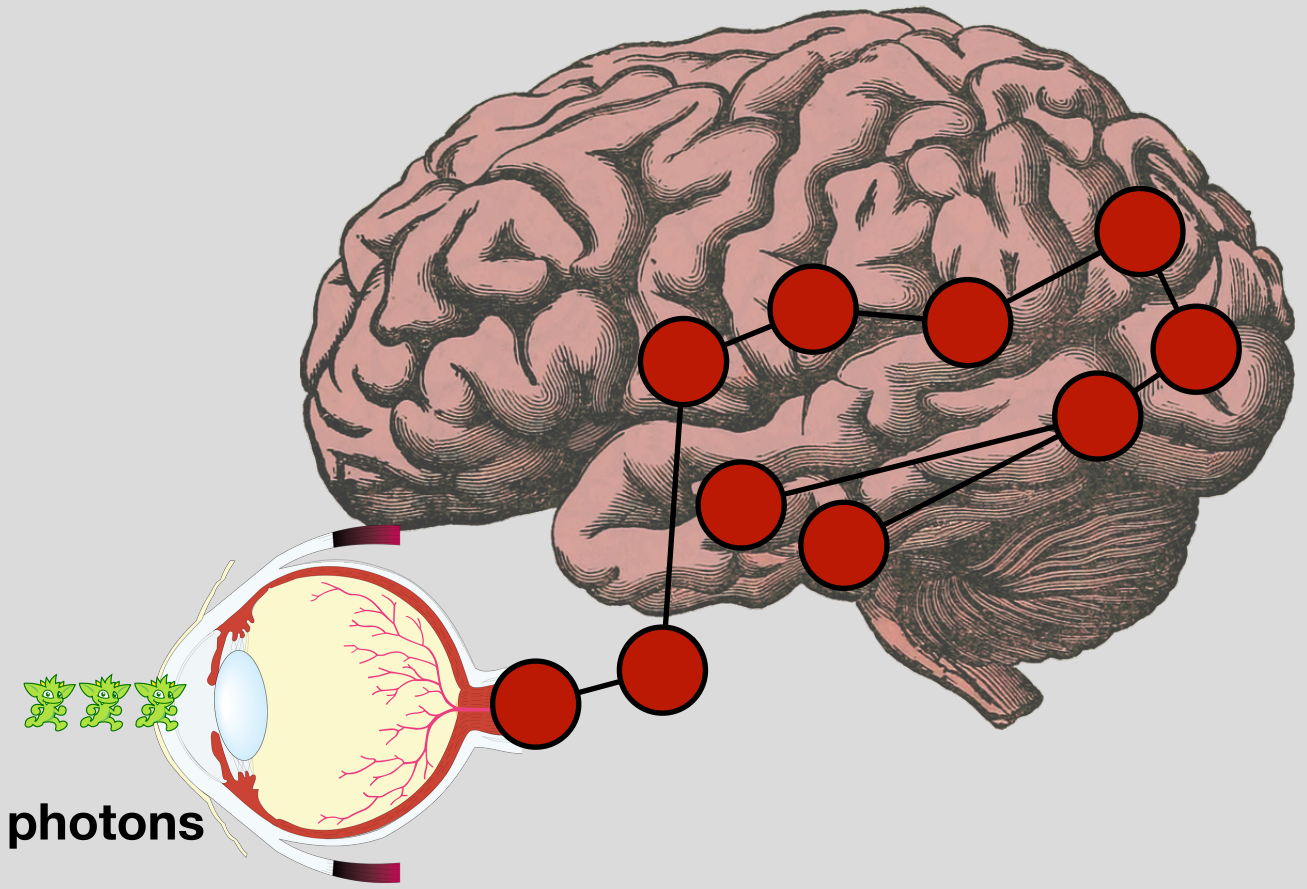
physical photon

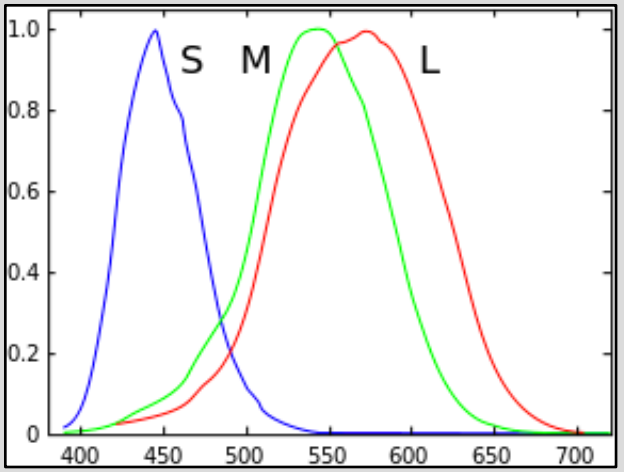
To be continued…

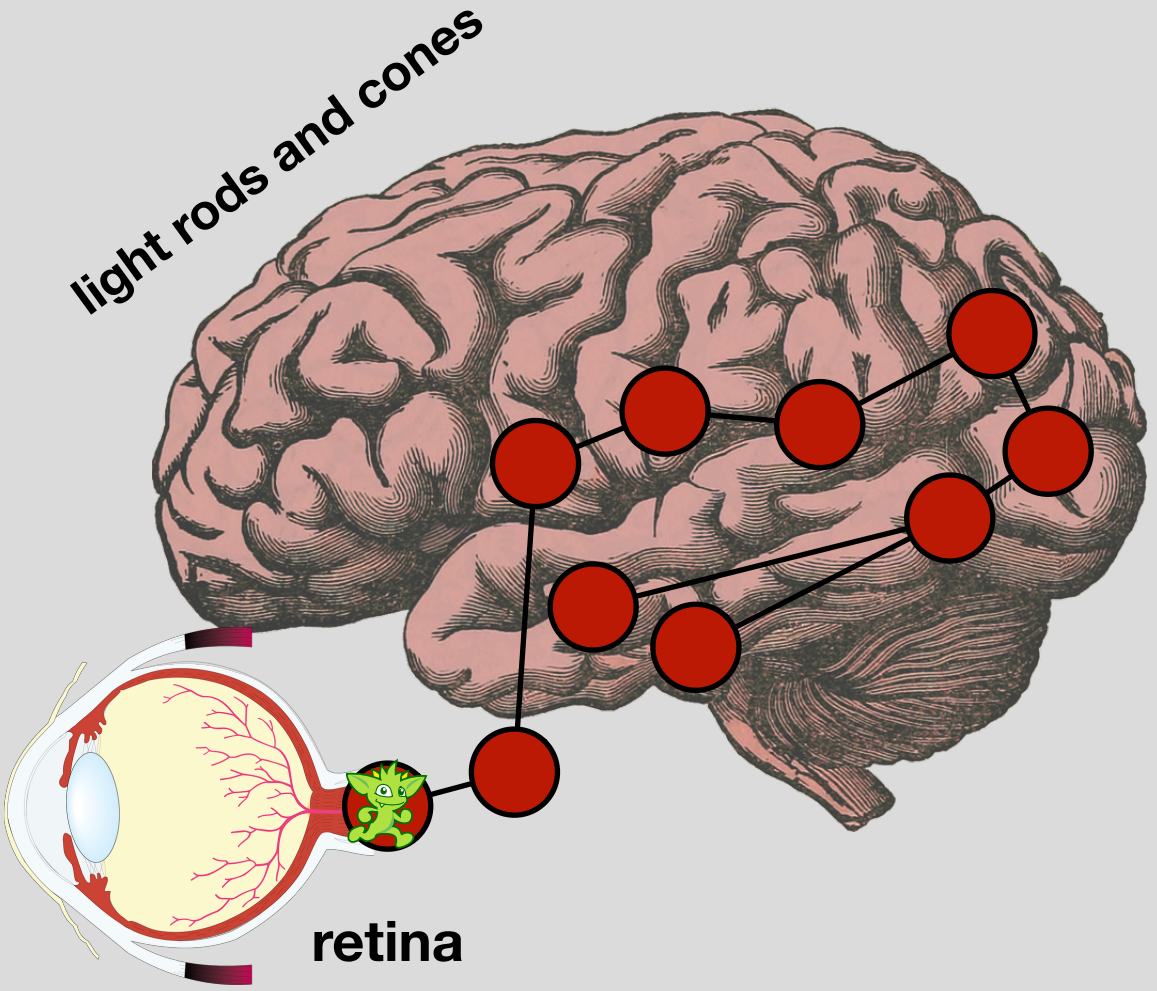


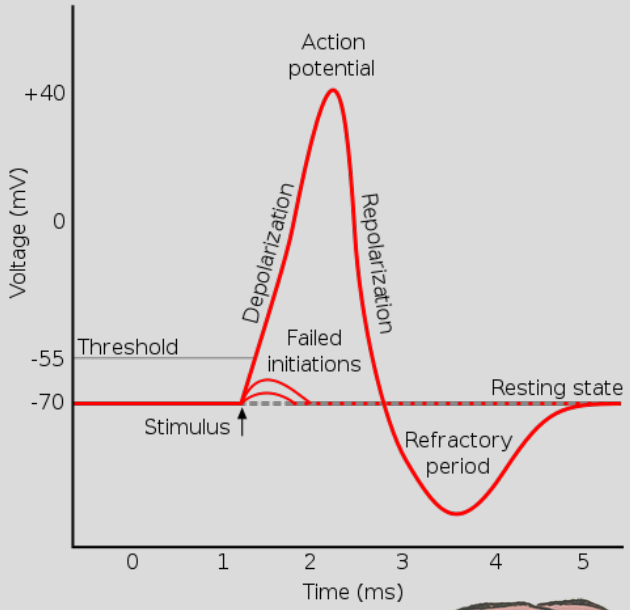
physical brain

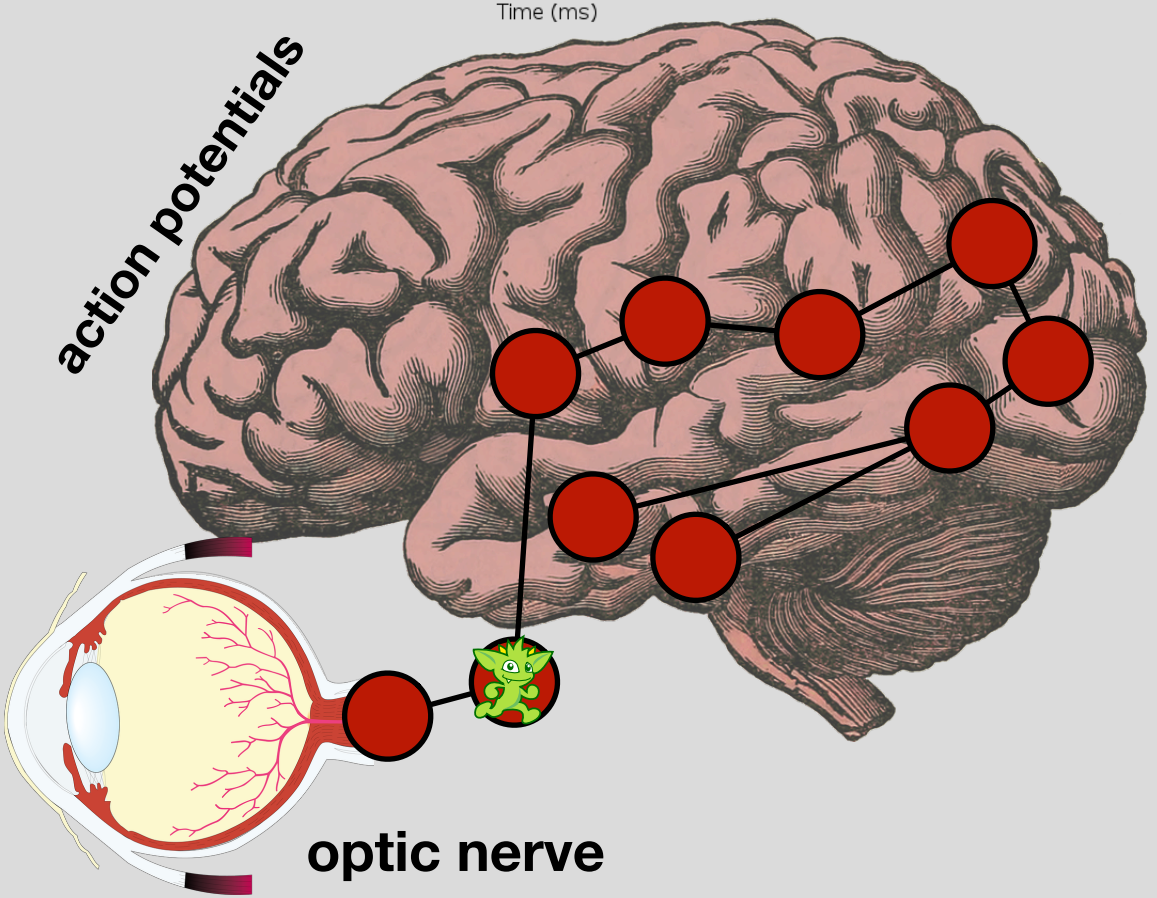

Violet
Indigo
Blue
Green
Yellow
Orange
Red
High Energy
Low Energy

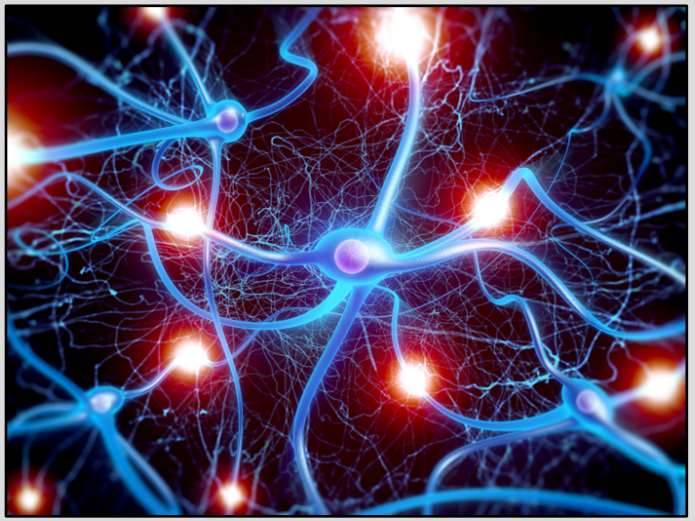

photons

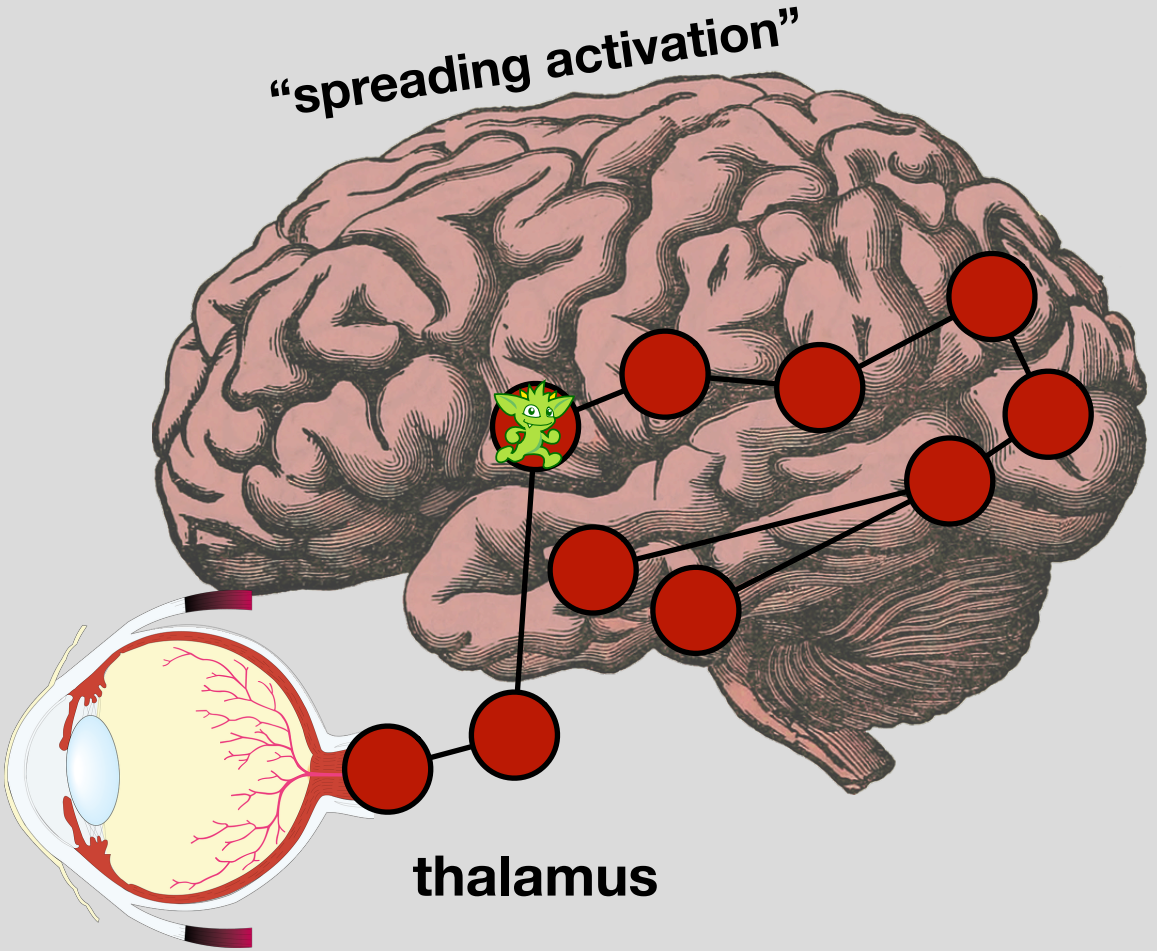

S
M
L
1.0
0.8
0.6
0.4
0.2
0
400
450
500
550
600
650
700

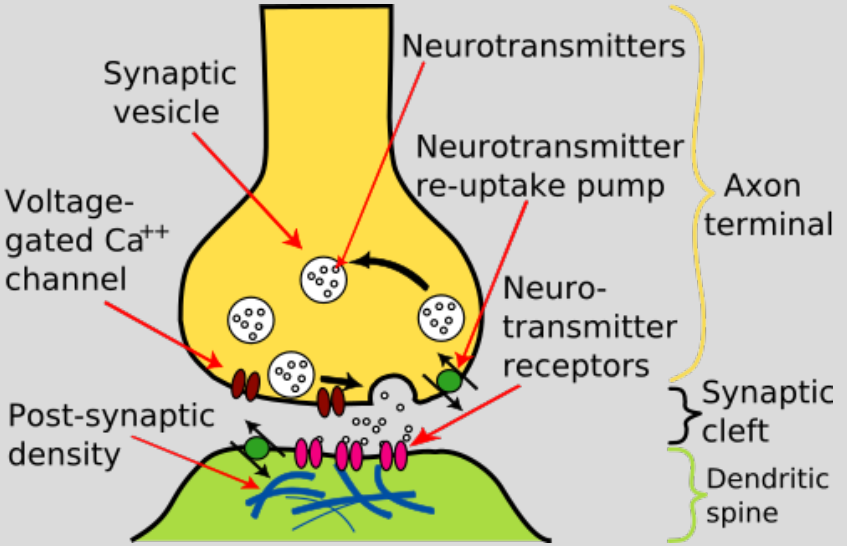

light rods and cones
retina


Action potential
+40
0
-55
-70
Voltage (mV)
Depolarization
Repolarization
Threshold
Failed initiations
Resting state
Stimulus
Refractory period
0
1
2
3
4
5
Time (ms)

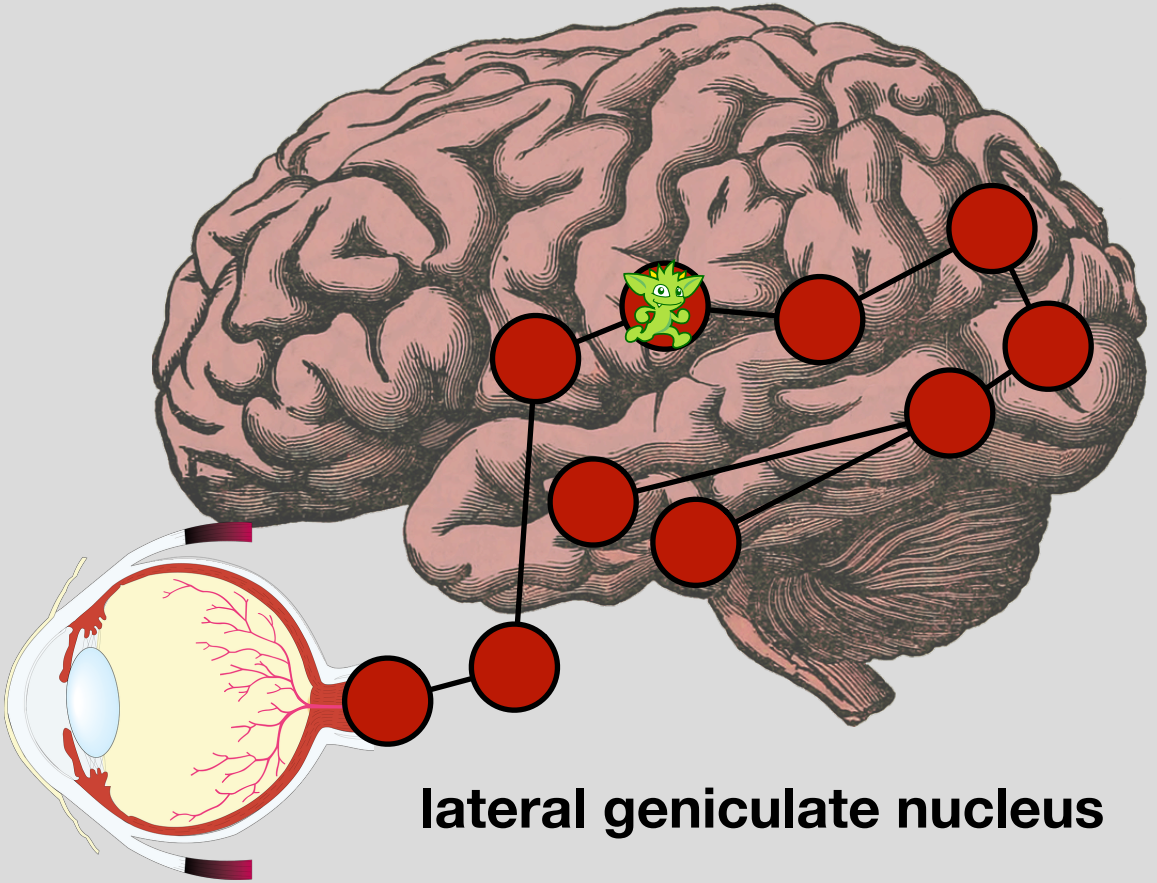

action potentials
optic nerve



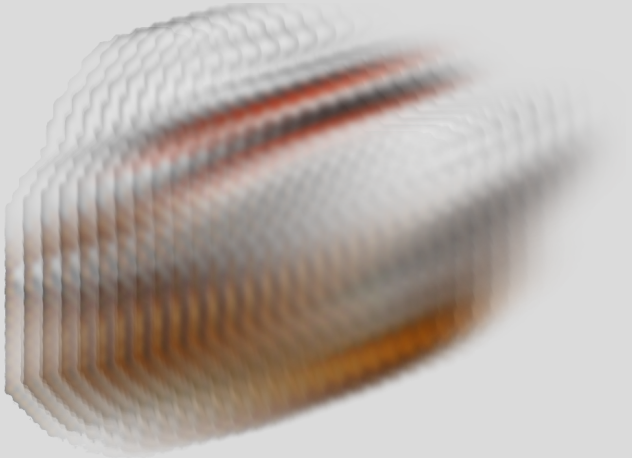

"spreading activation"
thalamus



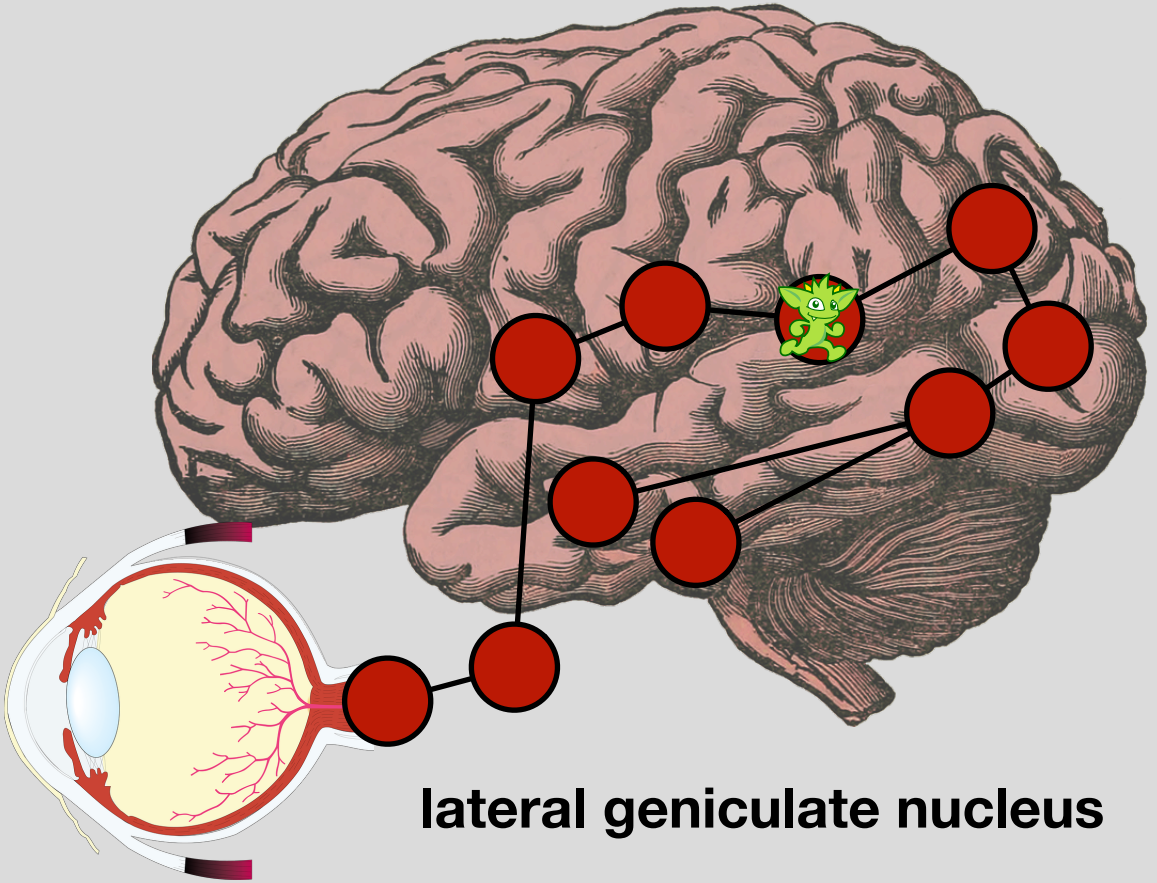
“neurotransmitter mediated energy diffusion”



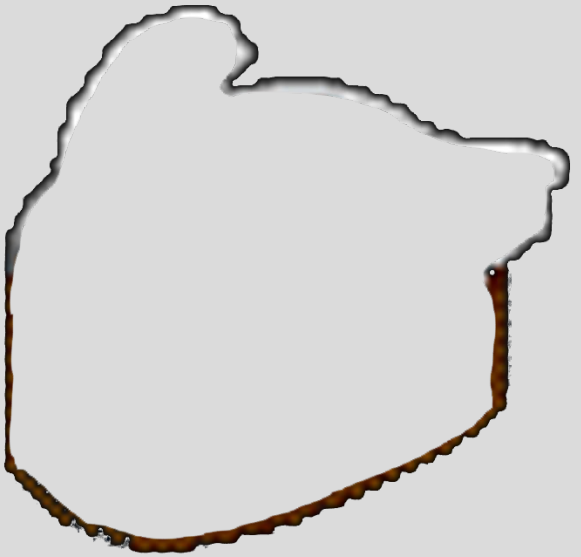
lateral geniculate nucleus



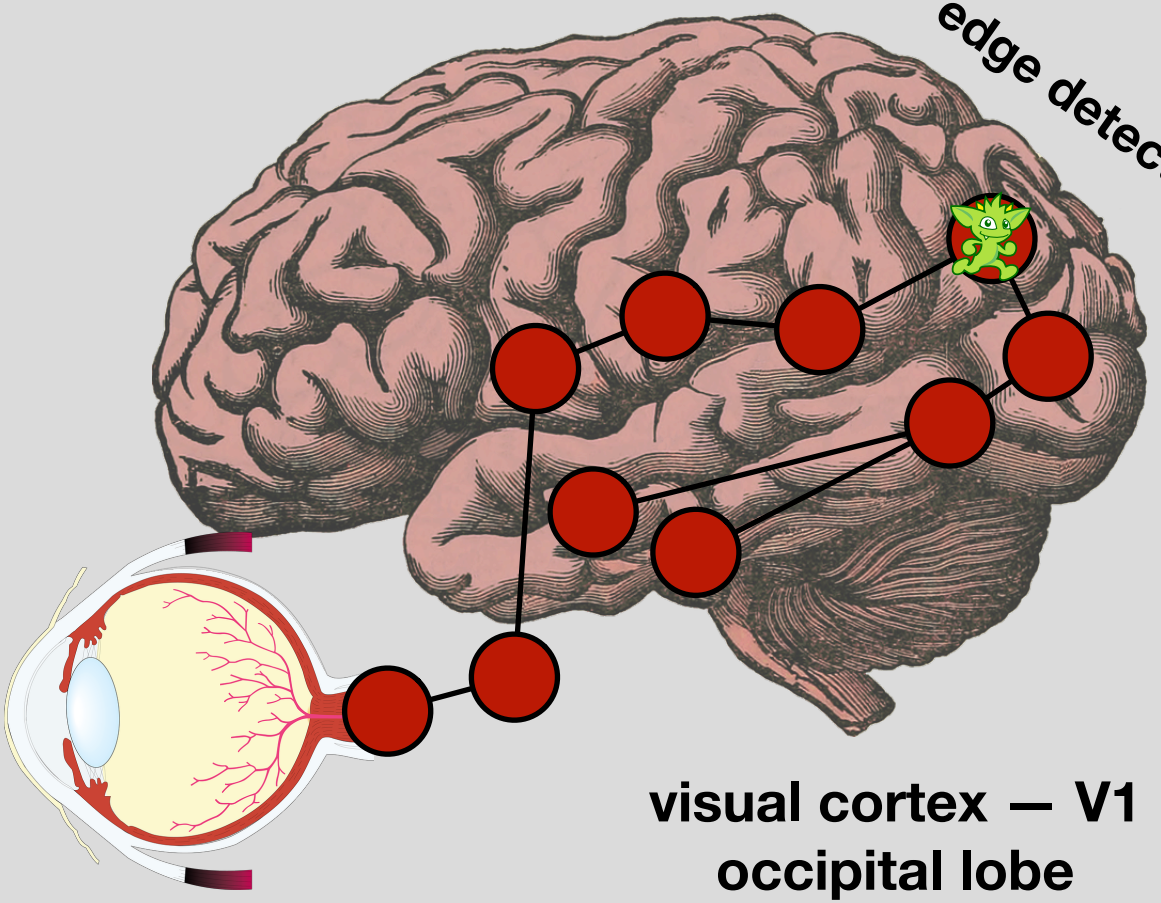
velocity of movement



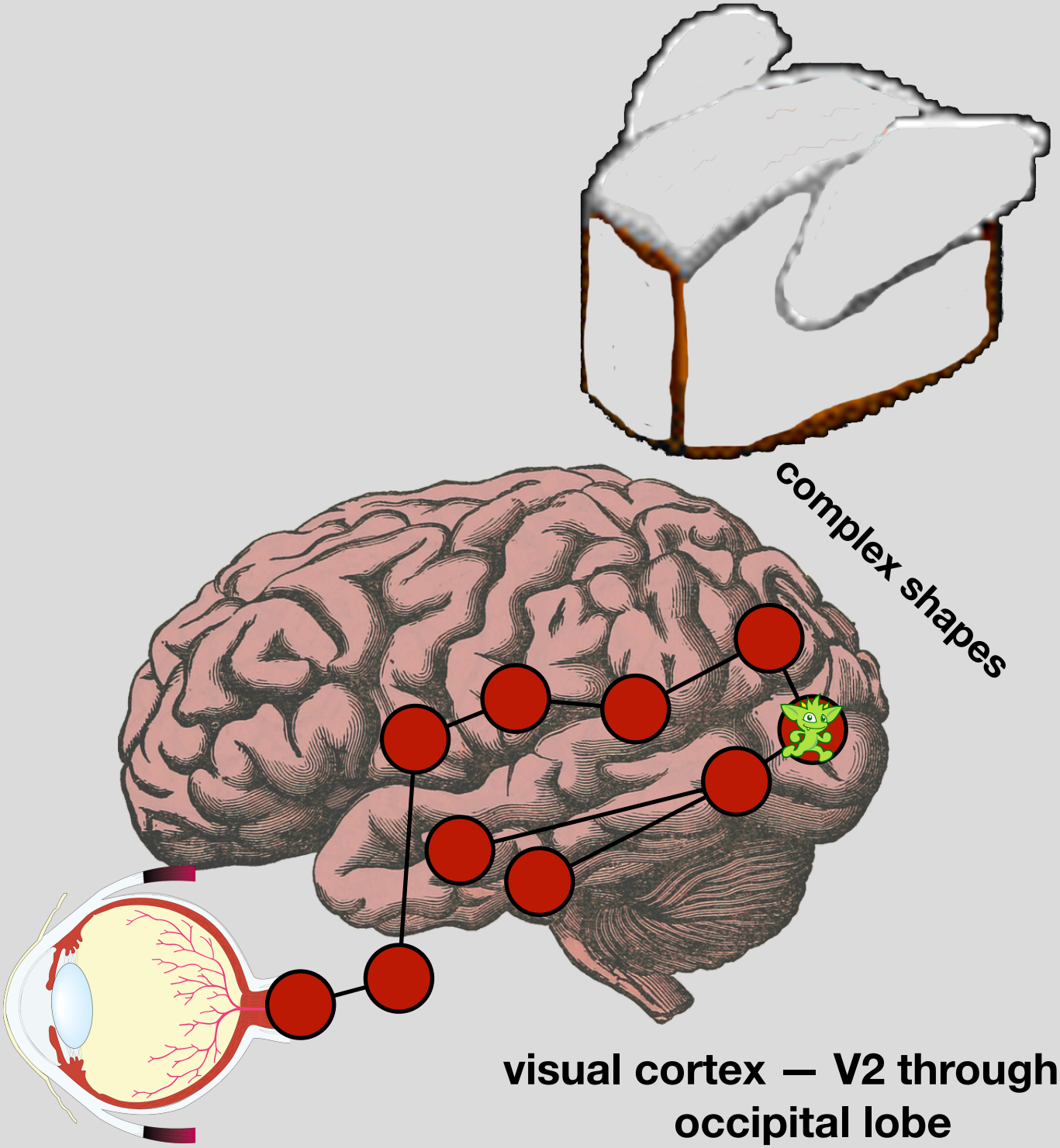
lateral geniculate nucleus

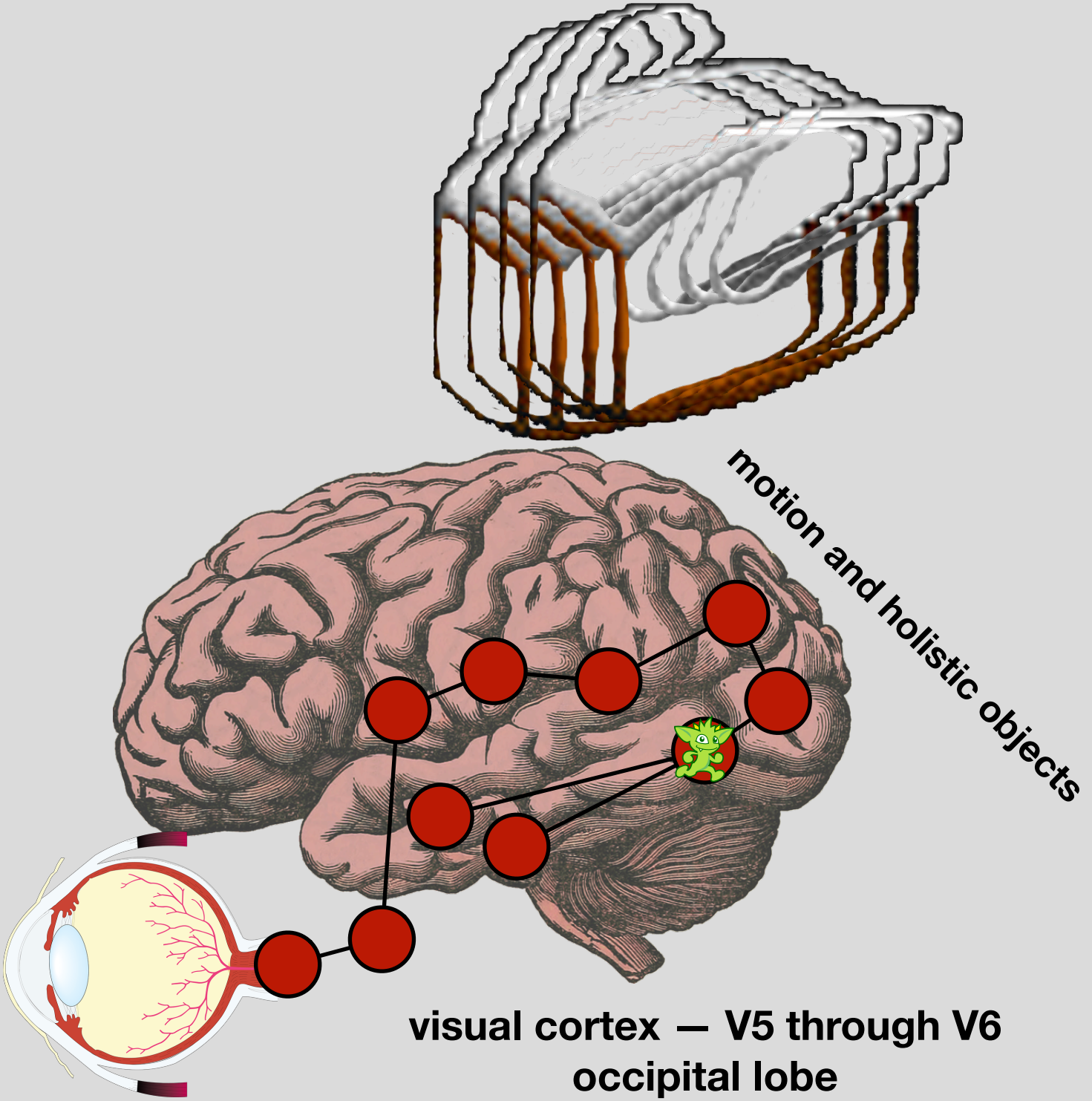


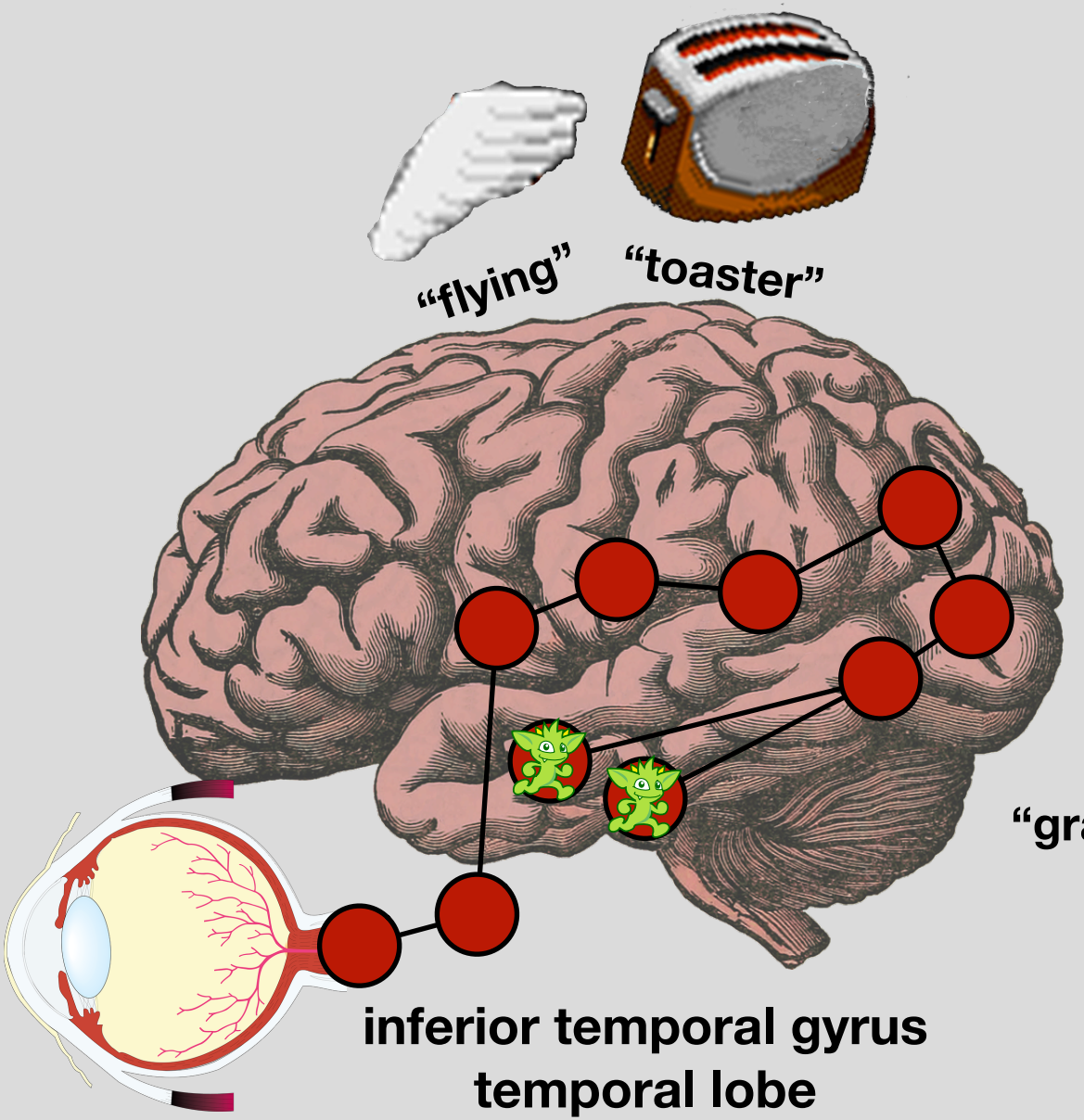
edge detection

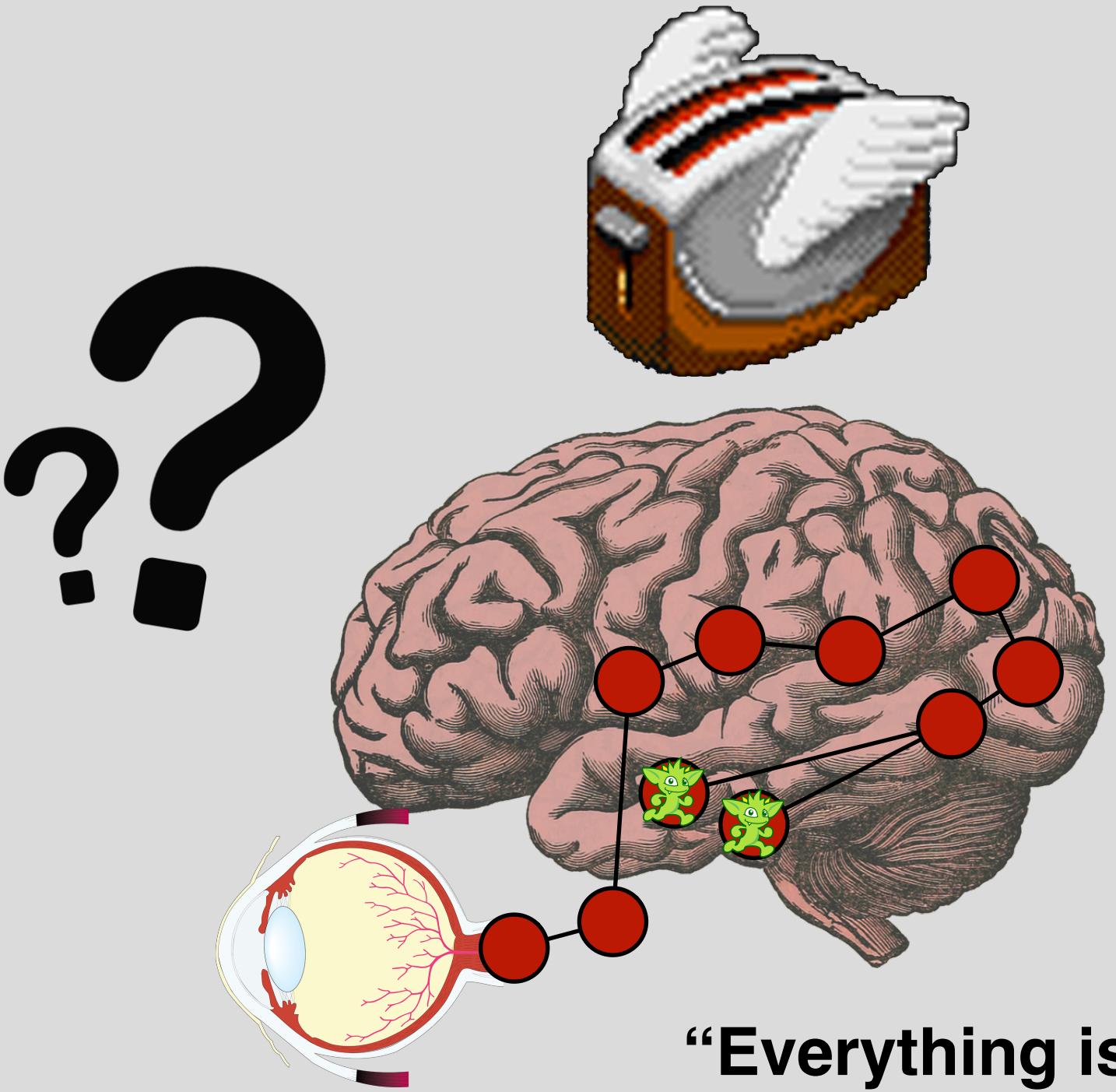


visual cortex — V1
occipital lobe

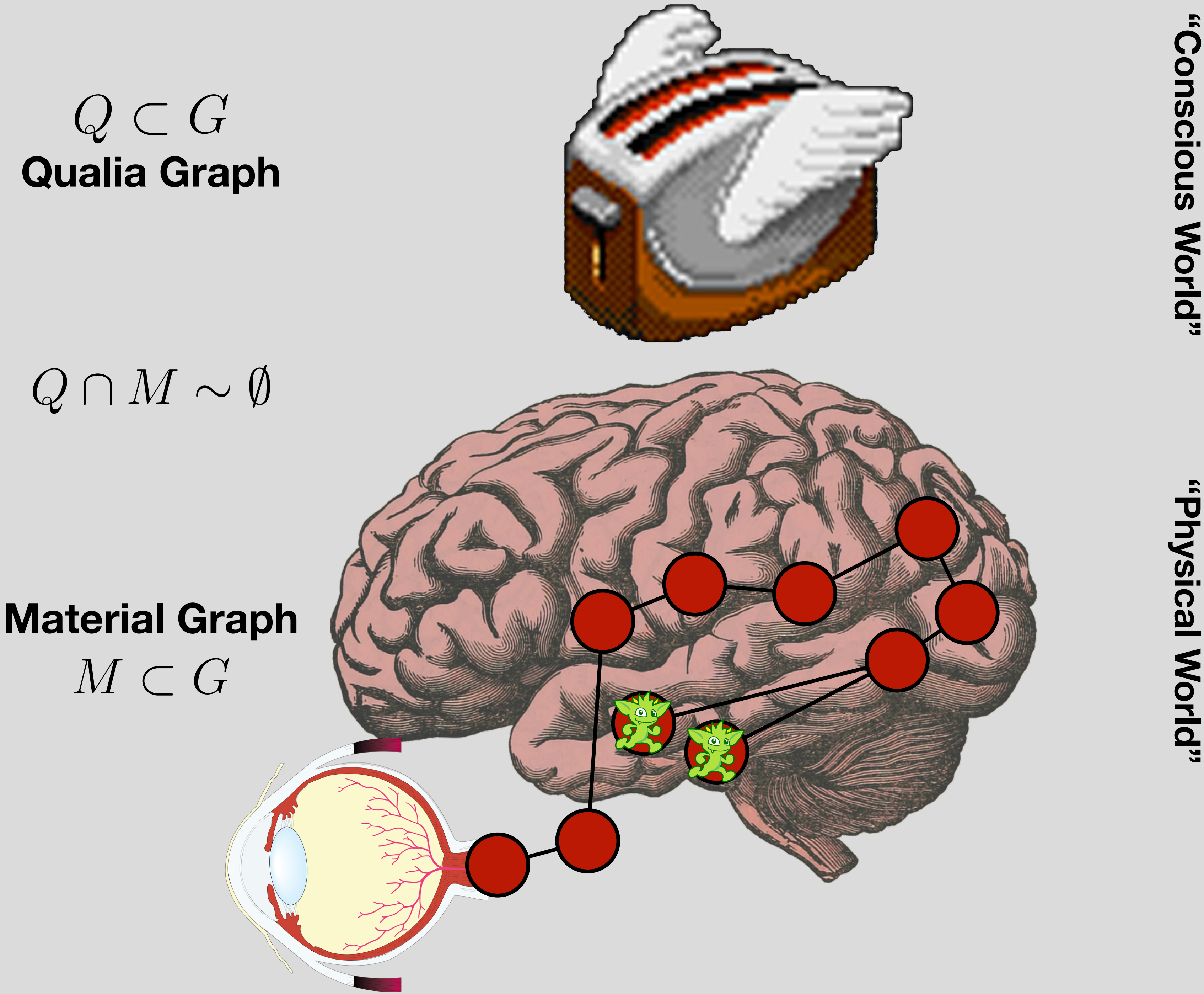

complex shapes
visual cortex — V2 through V4
occipital lobe


motion and holistic objects
visual cortex — V5 through V6
occipital lobe


"flying"
"toaster"
"grandmother cells"
inferior temporal gyrus
temporal lobe



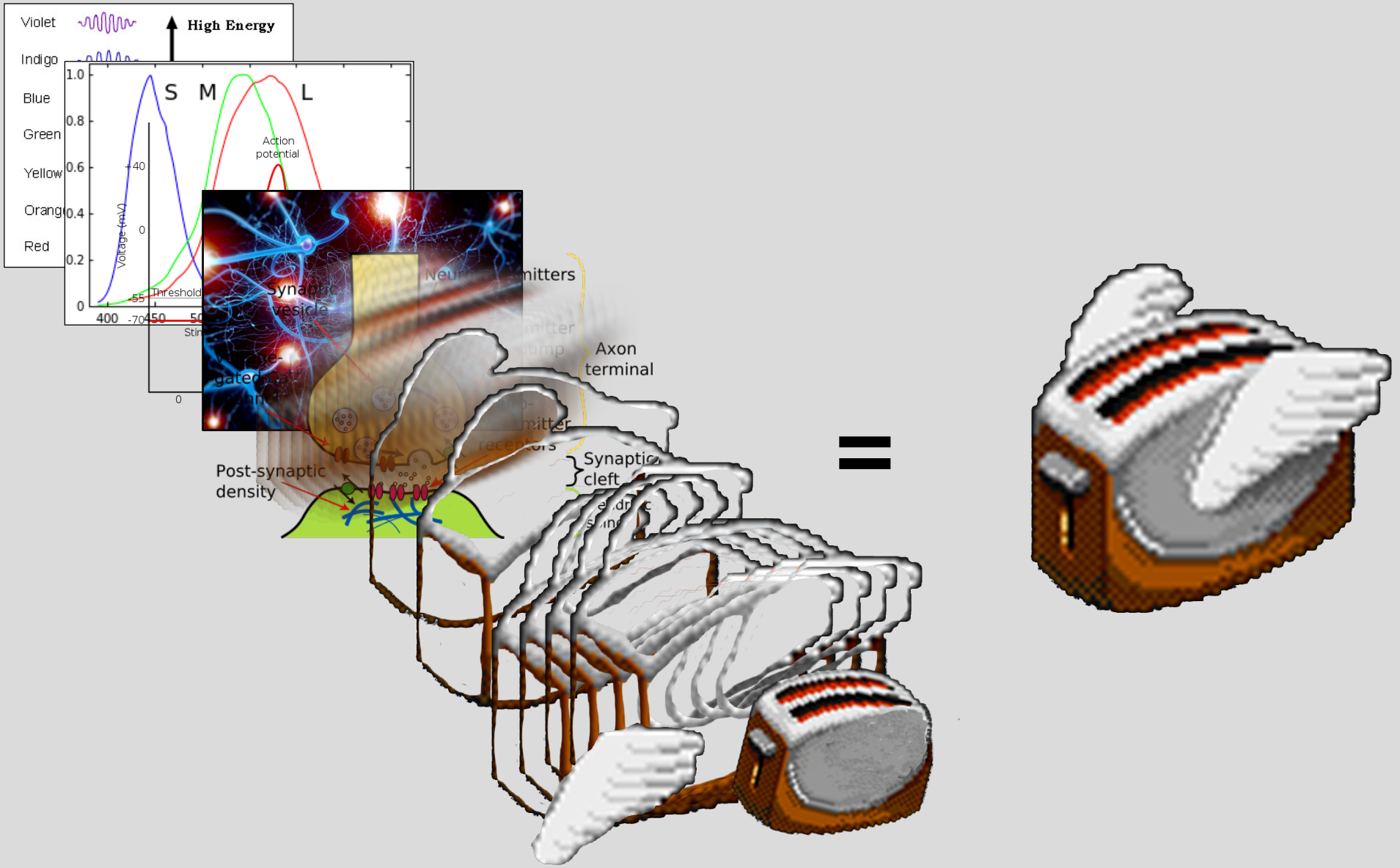
“Everything is a graph.”



$Q \subset G$
Qualia Graph
$Q \cap M \sim \emptyset$
Material Graph
$M \subset G$
"Conscious World"
"Physical World"

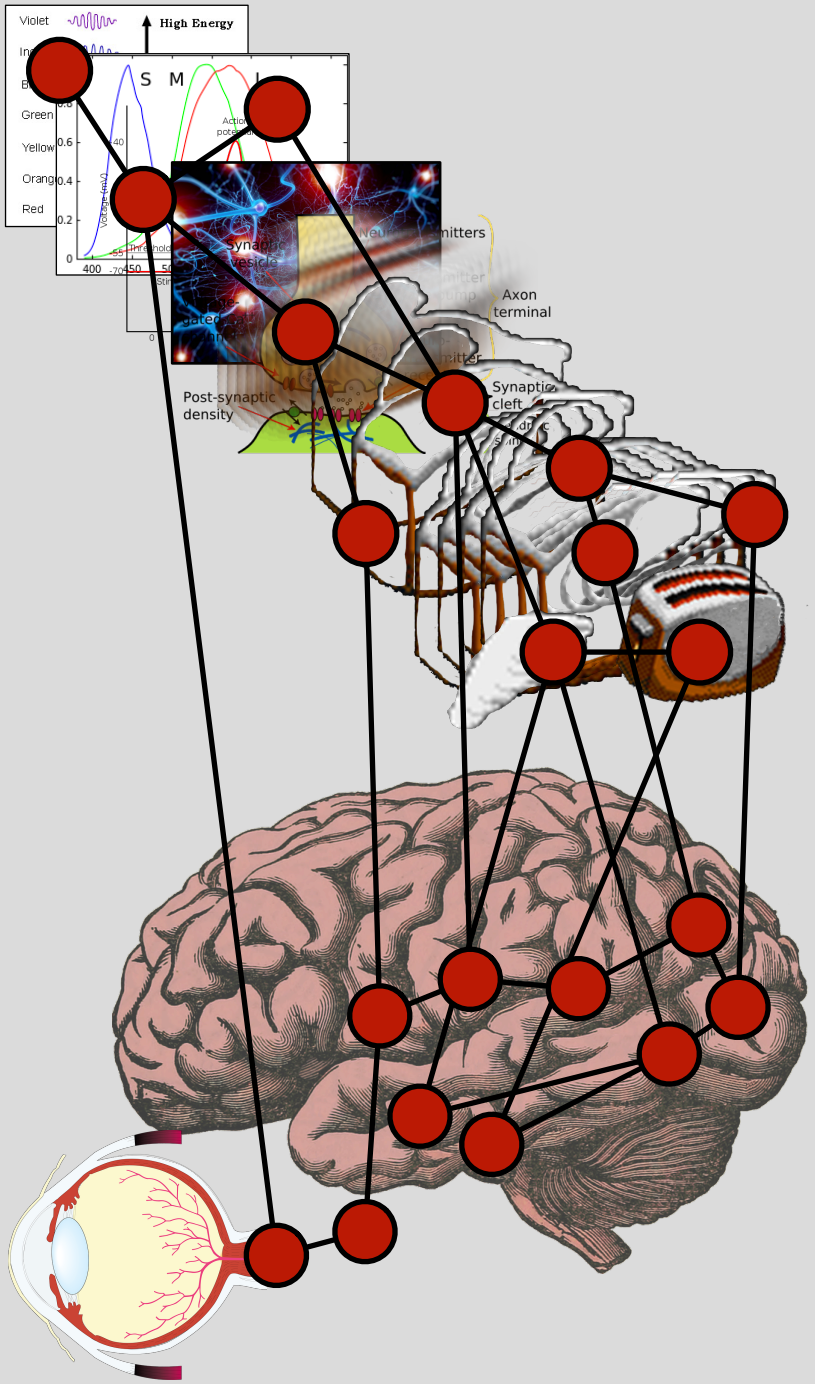
Open Problem #2

How does the universal graph encode the qualia of thought as vertices and edges?



The process is the conscious experience…

$$G \longleftrightarrow T \longleftrightarrow \Psi$$

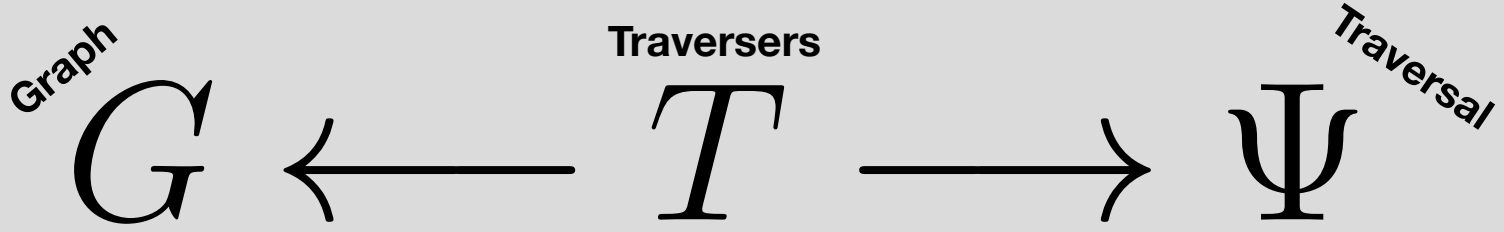


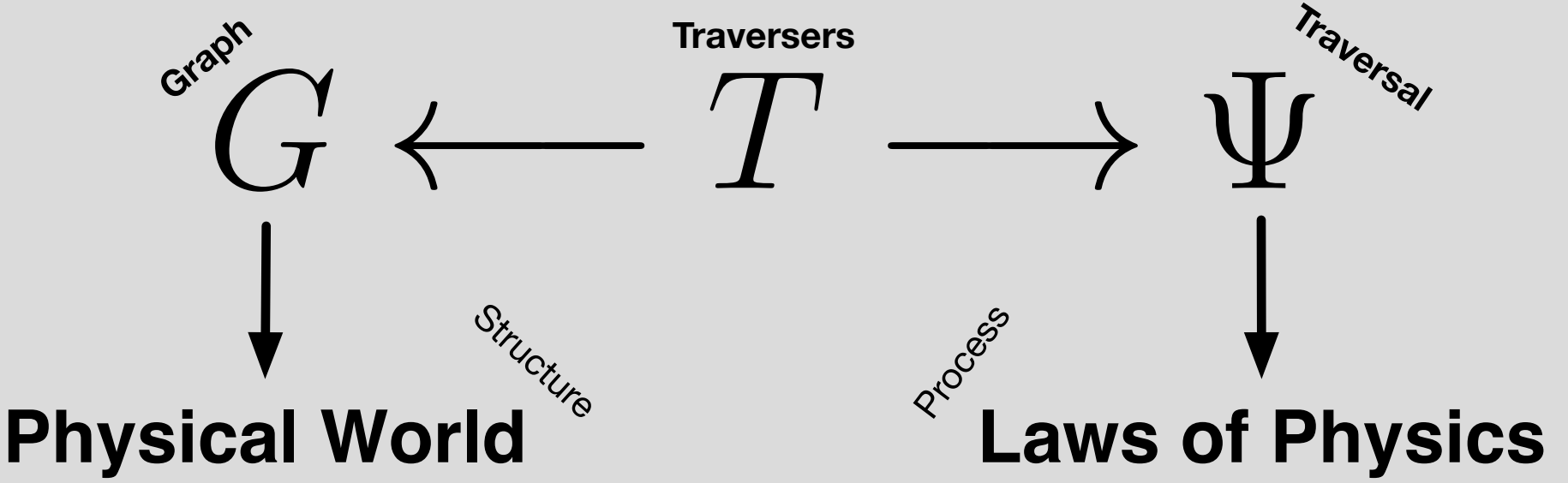
"Everything is a graph."

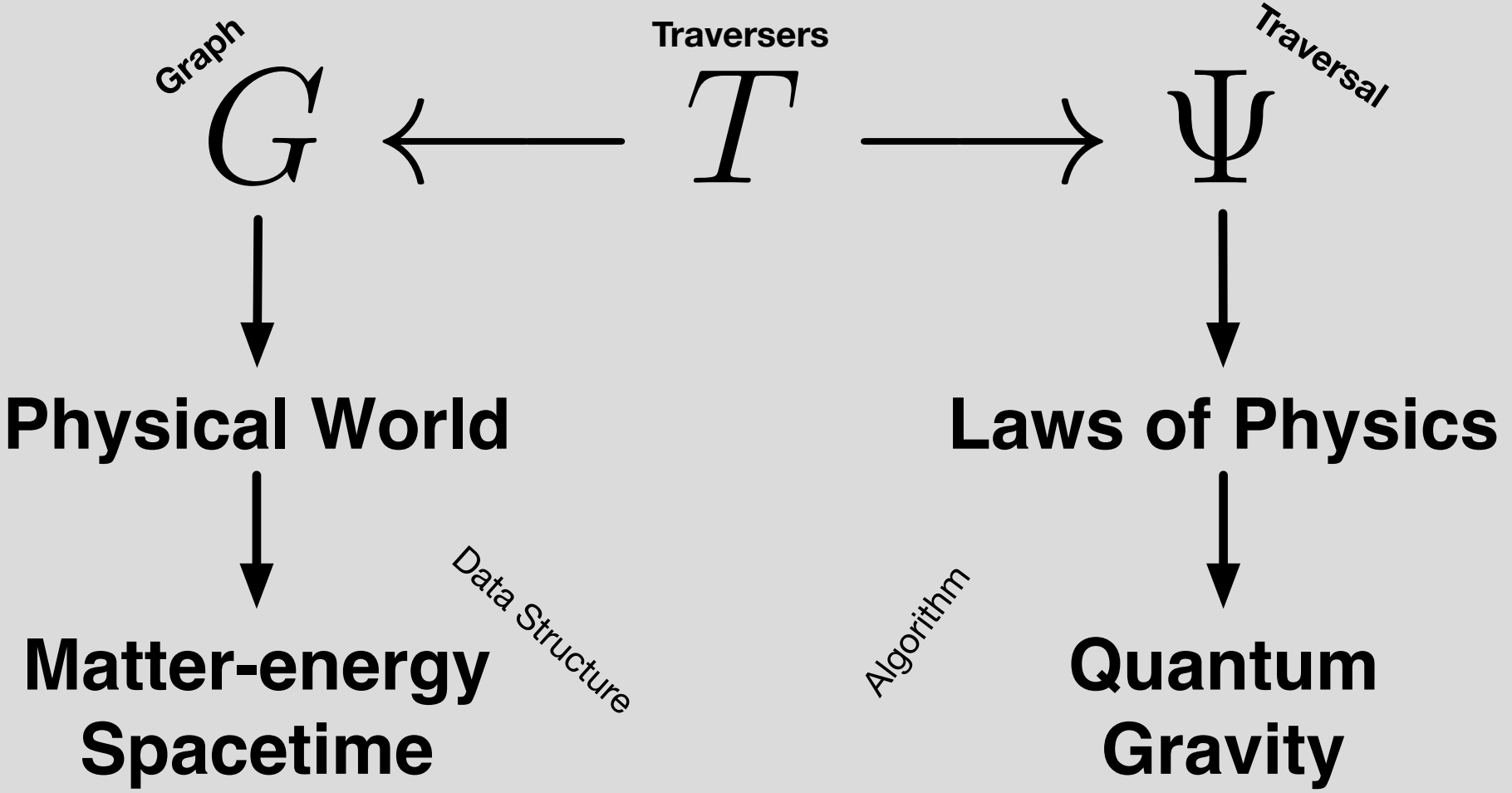
$$G = (V, E)$$

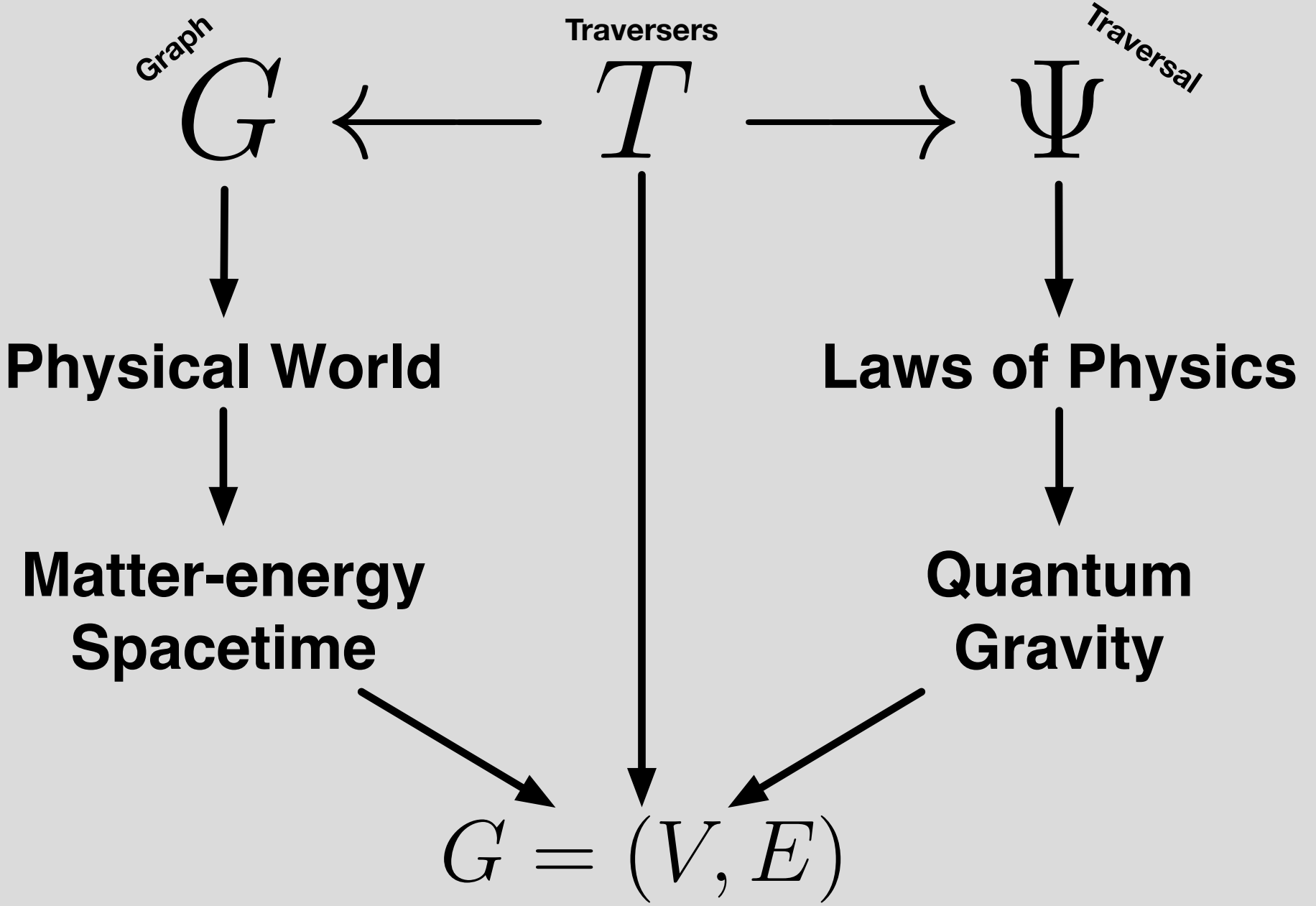
...but process has a structural, graph encoding.

Creativity:
Altering the Structure of Process

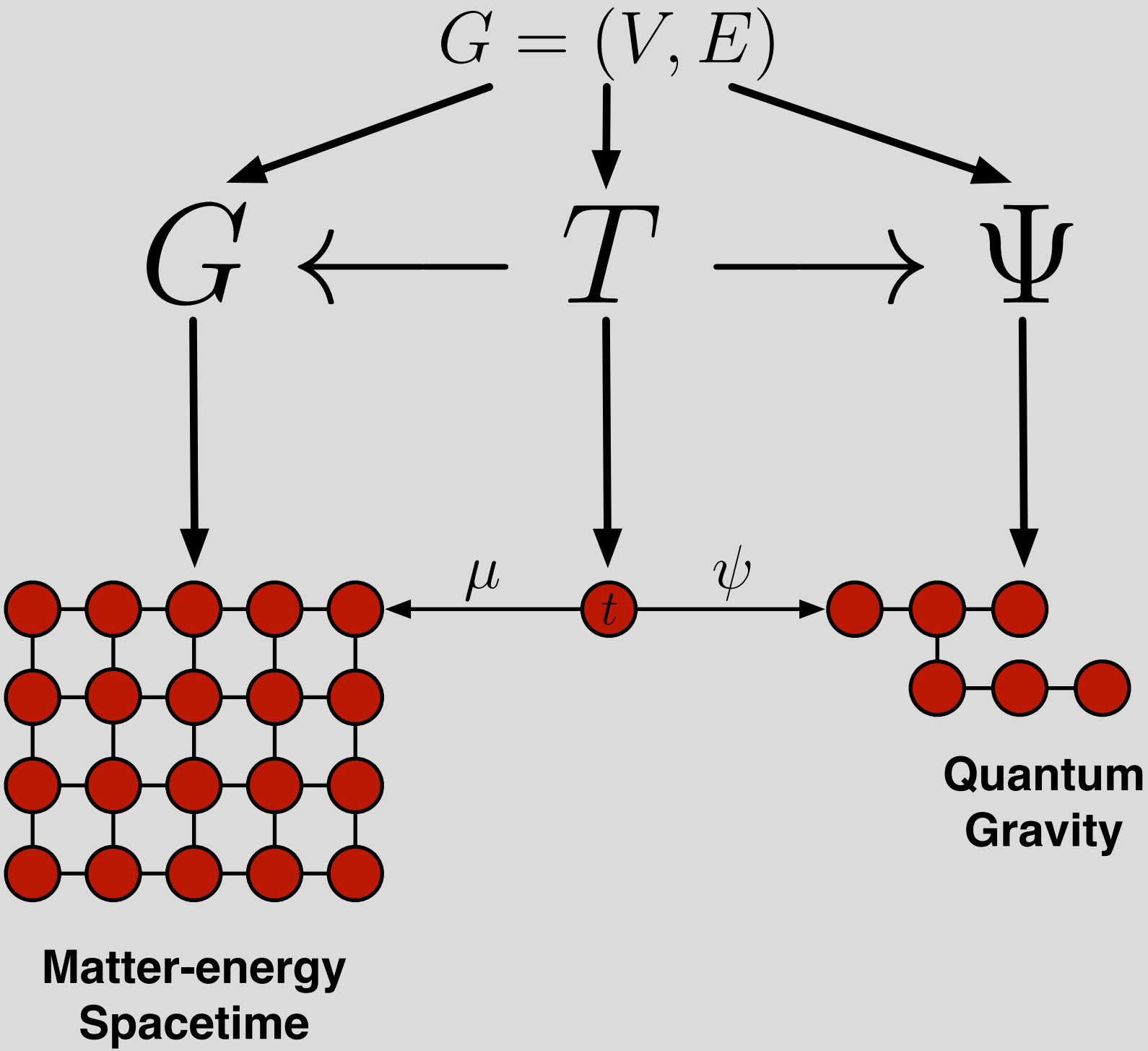

Graph
Traversers
Traversal
$G \longleftarrow T \longrightarrow \Psi$


Graph
Traversers
Traversal
G
T
Ψ
Structure
Process
Physical World
Laws of Physics

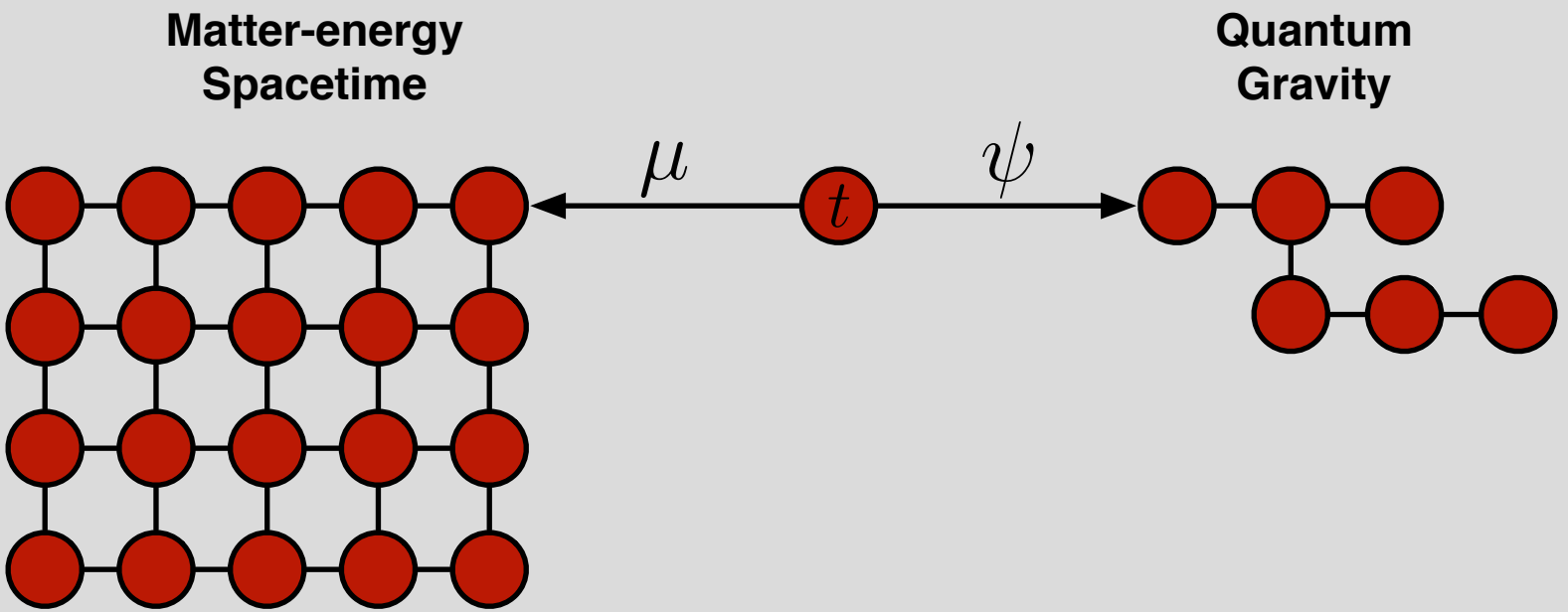

Graph
Traversers
Traversal
G
T
Ψ
Physical World
Laws of Physics
Data Structure
Algorithm
Matter-energy
Spacetime
Quantum
Gravity



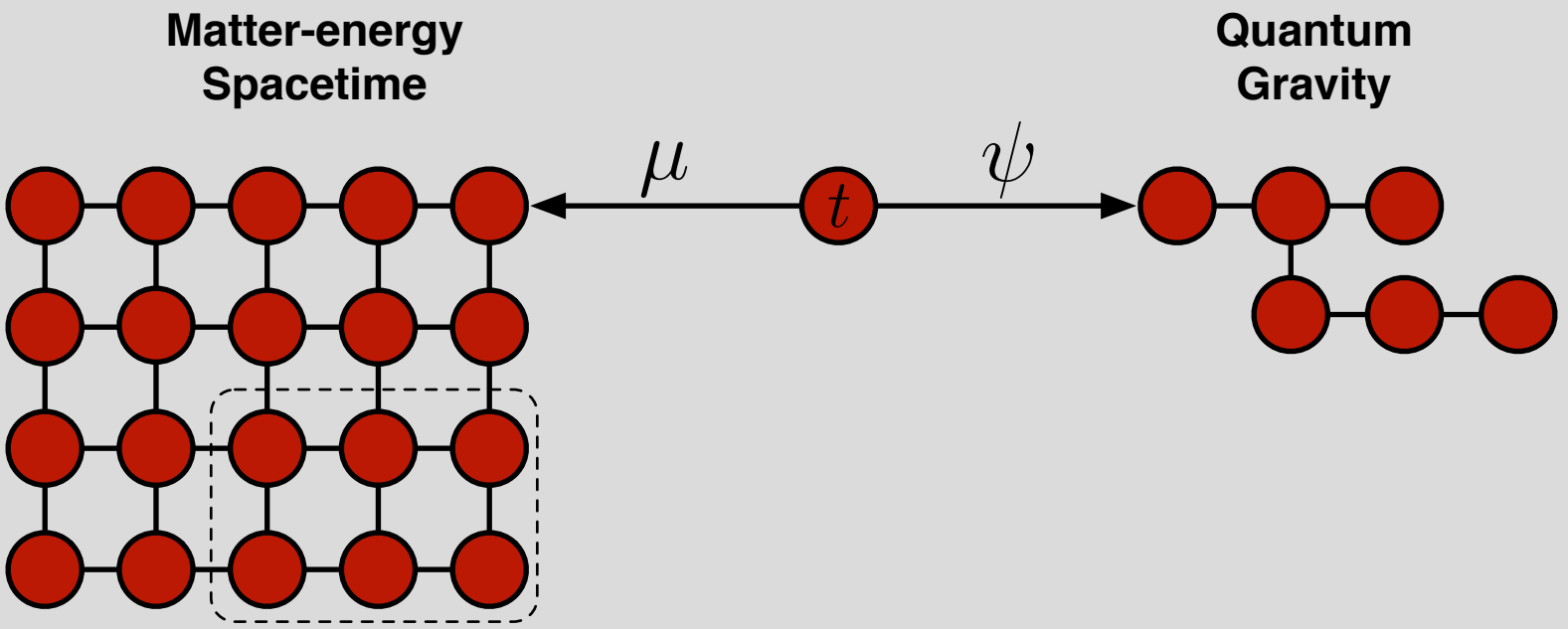
“Everything is a graph.”


$G = (V, E)$
G
T
Ψ
μ
t
ψ
Matter-energy
Spacetime
Quantum
Gravity

$$G \longleftarrow T \longrightarrow \Psi$$



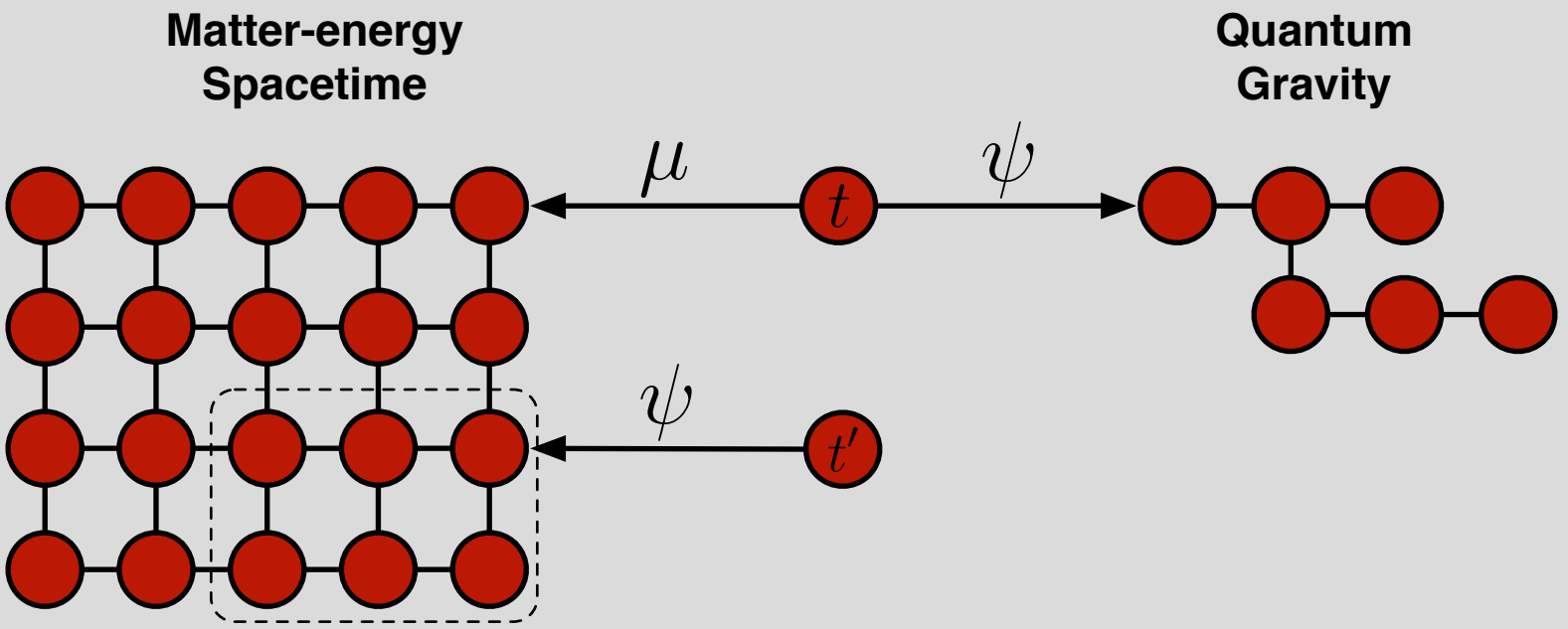
$$G \longleftarrow T \longrightarrow \Psi$$



Laws of Physics
Manipulation
Technology

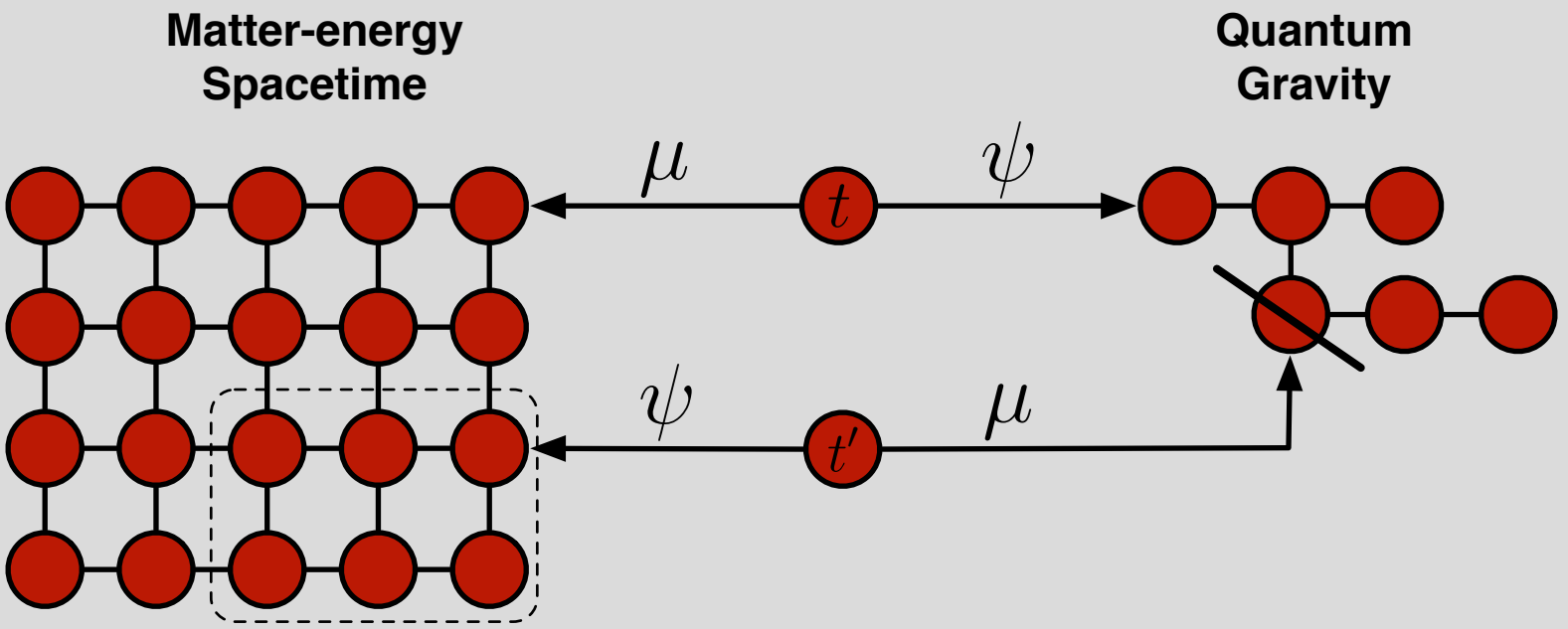
$$\Psi'$$

$$G \longleftarrow T \longrightarrow \Psi$$



$$\Psi' \longleftarrow T'$$

$$G \longleftarrow T \longrightarrow \Psi$$

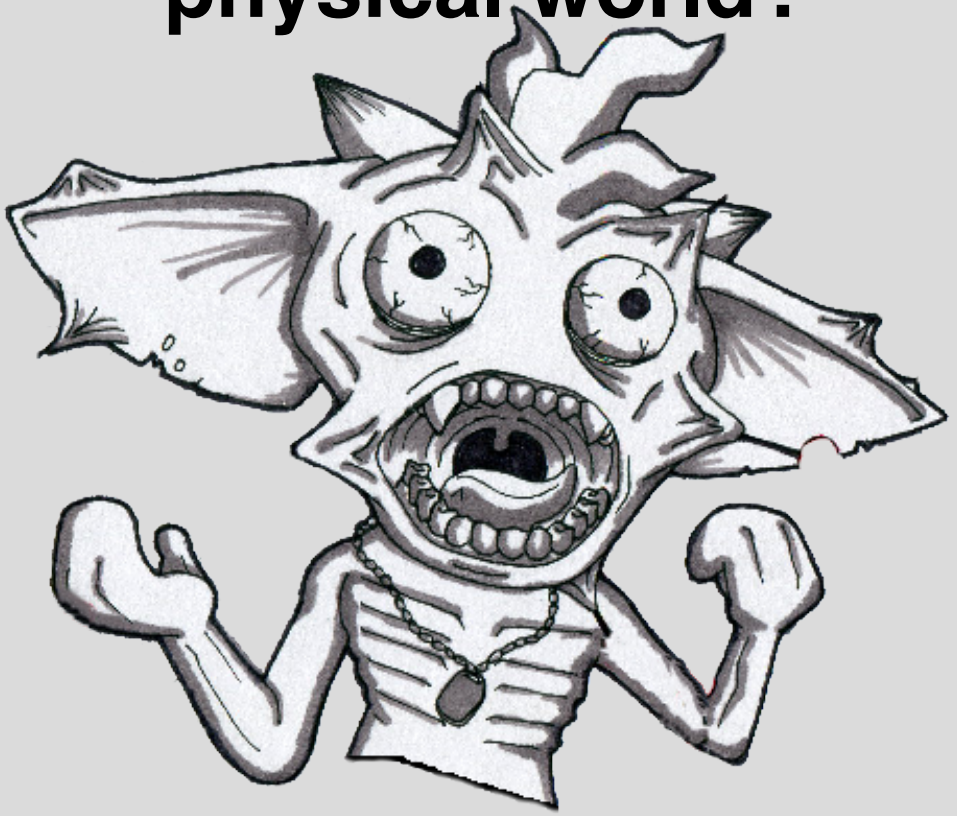


$$\Psi' \longleftarrow T' \longrightarrow G'$$

“Everything is a graph.”

Open Problem #3

If process is as malleable as structure, then how does one get a reference to the "laws of physics" in order to alter the evolution of the physical world?



DATASTAX

Apache TinkerPop

Thank you.

2018-2019 Sabbatical

Coming in 2020

“A Graph Computing Book”