Holistic Specifications for Robust Code

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based on prior work with James Noble (VU Wellington),
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Today

- Traditional Specifications do not adequately address Robustness
- Holistic Specifications — Summary and by Example
- Holistic Specification Semantics

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- Holistic Specifications — Summary and Examples
- Holistic Specification Semantics

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- designed for *closed* world
- pre- and post condition per function; *sufficient* conditions for some action/effect
- *explicit* about each individual function, and *implicit* about emergent behaviour

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Traditional Specs

- designed for *closed* world
- pre- and post condition per function; *sufficient* conditions for some action/effect
- *explicit* about each individual function, and *implicit* about emergent behaviour

Robustness considerations

- concerned with *open* world
- *necessary* conditions for some action/effect
- *explicit* about emergent behaviour

Today

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- **Holistic Specifications — Summary Examples**
- Holistic Specification Semantics

Holistic Assertions — summary

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e ::= this | x | e.fld | …

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e ::= this | x | e.fld | …

A ::= e>e | e=e | …

Holistic Assertions — summary

$$
\begin{array}{lll}
e & ::= & \text{this} \mid x \mid e.\text{fld} \mid \ldots \\
A & ::= & e > e \mid e = e \mid \ldots \\
 & & \mid A \rightarrow A \mid A \wedge A \mid \exists x.\, A \mid \ldots
\end{array}
$$

Holistic Assertions — summary

e ::= this | x | e.fld | …
A ::= e>e | e=e | …
| A → A | A ∧ A | ∃x. A | …
| **Access**(e,e’)

Holistic Assertions — summary

e ::= this | x | e.fld | …

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| **Changes**(e)

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| **Will**(A) | **Was**(A)

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| A **in** S

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| x.**Calls**(y,m,z1,..zn)

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| A **in** S

| x.**Calls**(y,m,z1,..zn)

| x **obeys** A

Holistic Assertions — summary

e ::= this | x | e.fld | …

A ::= e>e | e=e | …
| A → A | A ∧ A | ∃x. A | …

| **Access**(e,e’)	permission
| **Changes**(e)	authority
| **Will**(A) | **Was**(A)	time
| A **in** S	space
| x.**Calls**(y,m,z1,..zn)	control
| x **obeys** A	trust

Holistic Assertions — examples

- ERC20
- DAO
- DOM attenuation
- Bank & Account
- Escrow

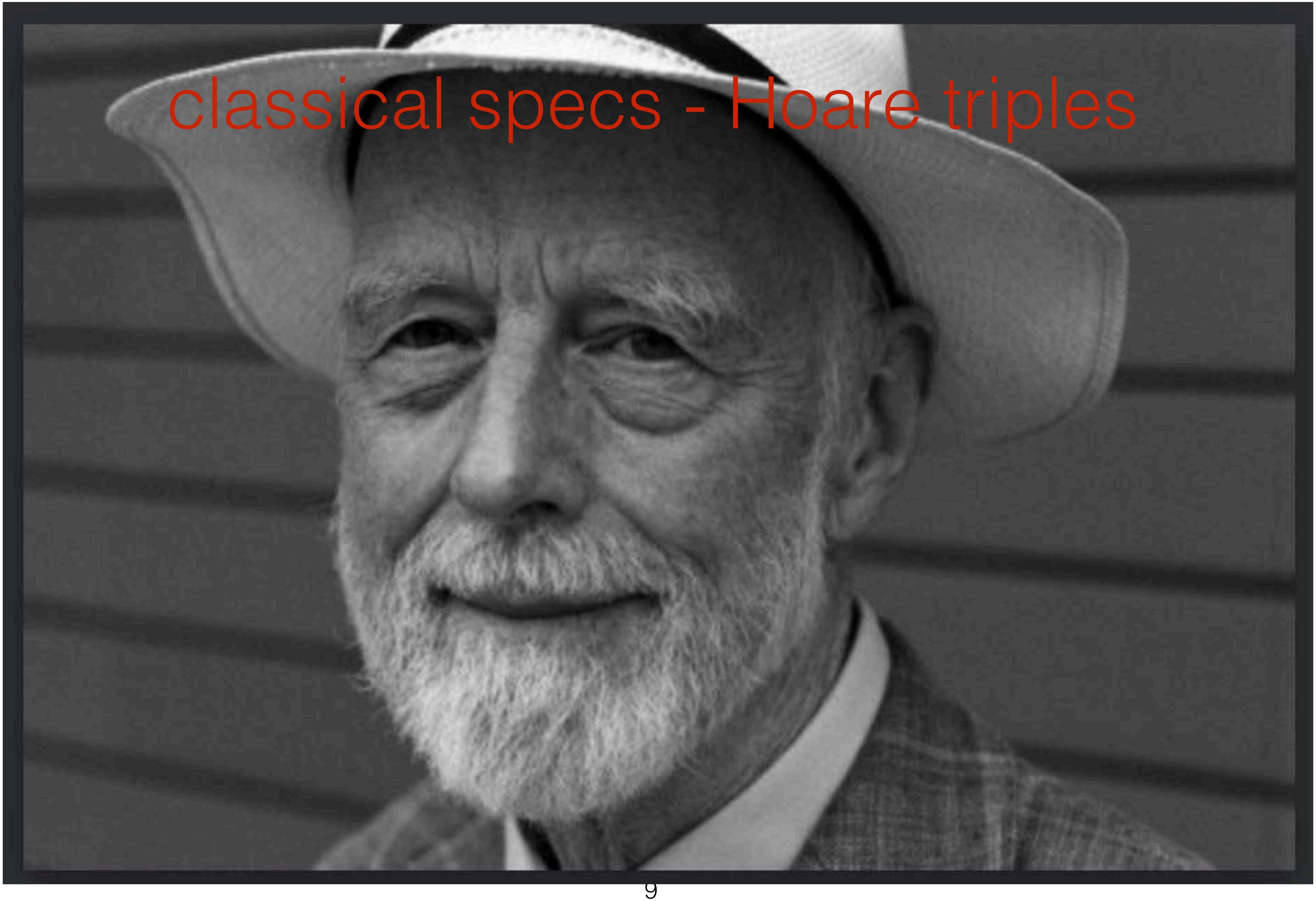
Example1: ERC20

a popular standard for initial coin offerings. (https://theethereum.wiki/w/index.php/ERC20_Token_Standard); allows clients to buy and transfer tokens, and to designate other clients to transfer on their behalf.

In particular, a client may call
- `transfer`: transfer some of her tokens to another clients,
- `approve`: authorise another client to transfer some of her tokens on her behalf.
- `transferFrom`: cause another client's tokens to be transferred

Moreover, ERC20 keeps for each client
- `balance` the number of tokens she owns

classical specs - Hoare triples



classical specs - Hoare triples

classical specs - Hoare triples

A

classical specs - Hoare triples

A { `x` **calls** `y.f(args)` }

classical specs - Hoare triples

A { `x` **calls** `y.f(args)` } **A'**

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A { `x` **calls** `y.f(args)` } **A**’

If **A** hods, and `x` calls `y.f(args)`, then, **A’** holds after the call

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precondition

postcondition

ERC20 classical spec - transfer

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For any ERC20 contract e, and different clients c1, c2.

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$$e{:}ERC20 \quad \wedge \quad this = c1 \neq c2 \quad \wedge \quad e.balance(c1) > m$$

$\{$ `e.transfer(c2,m)` $\}$

$$e.balance(c1) = e.balance(c1)_{pre} - m \quad \wedge \quad e.balance(c2) = e.balance(c2)_{pre} + m$$

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{ `e.transfer(c2,m)` }

$\text{e.balance(c1)} = \text{e.balance(c1)}_{\text{pre}} - \text{m} \land \text{e.balance(c2)} = \text{e.balance(c2)}_{\text{pre}} + \text{m}$

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effect

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$$\{\; \texttt{e.transfer(c2,m)} \;\}$$

$$e.balance(c1) = e.balance(c1)_{pre} - m \;\wedge\; e.balance(c2) = e.balance(c2)_{pre} + m$$

sufficient condition

effect

ERC20 classical spec - transfer - 2

What if c1’s balance not large enough?

ERC20 classical spec - transfer - 2

What if c1’s balance not large enough?

e:ERC20 $\wedge$ this = c $\wedge$ e,balance(c1) < m
{ `e.transfer(c2,m)` }
$\forall$ c. e,balance(c) = e,balance(c)$_{\text{pre}}$

ERC20 classic spec - authorised transfer

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For any ERC20 contract e, and different clients c1, c2, c3.

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For any ERC20 contract e, and different clients c1, c2, c3.

c1 is authorised to spend at least m on c2's behalf and

c2's balance is at least m

{ c1 calls `e.transferFrom(c2,c3,m)` }

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For any ERC20 contract e, and different clients c1, c2, c3.

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c2's balance decreases by m, and c3's balance increases by m.

ERC20 classic spec - authorised transfer

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c2’s balance is at least m

{ c1 calls `e.transferFrom(c2,c3,m)` }

c2’s balance decreases by m, and c3’s balance increases by m.

e:ERC20 ∧ this = c1≠c2≠c3≠c1 ∧
e.Authorized(c1,c2,m’) ∧ m’≧ m
e.balance(c1) ≧m
{ e.transferFrom(c2,c3,m) }
e.balance(c1) = e.balance(c1)$_{\text{pre}}$ -m ∧
e.balance(c2) = e.balance(c2)$_{\text{pre}}$ +m ∧
e.Authorized(c1,c2,m’-m)

ERC20 classic spec - authorised transfer - 2

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What if c1 is not authorised, or c1’’s authorisation is insufficient, or c2 ihas insufficient tokens?

ERC20 classic spec - authorised transfer - 2

What if c1 is not authorised, or c1’’s authorisation is insufficient, or c2 ihas insufficient tokens?

$$
\begin{array}{l}
\texttt{e}:\texttt{ERC20} \ \wedge \ \ \text{this} = c1 \neq c2 \neq c3 \neq c1 \ \wedge \\
(\ \neg \, \texttt{e.Authorized(c1,c2,m)} \\
\quad \vee \ \texttt{e.Authorized(c1,c2,m')} \ \wedge \ \ \texttt{m'<m} \\
\quad \vee \ \texttt{e.balance(c1)} < \texttt{m} \ \ ) \\
\qquad \{ \ \ \texttt{e.transferFrom(cl',m)} \ \ \} \\
\forall\, c. \ \ \texttt{e.balance(c)} = \texttt{e.balance(c)}_{\text{pre}} \ \ \wedge \\
\forall\, c,m. \, [\ \texttt{e.Authorized(c1,c2,m)} \longleftrightarrow \texttt{e.Authorized(c1,c2,m)} \,]
\end{array}
$$

ERC20 classic spec - authorising

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```
e:ERC20  ∧ this  = c1
     { e.approve(c2,m)  }
e.Authorized(c1,c2,m)
```

ERC20 classical spec

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$$e{:}ERC20 \quad \wedge \quad this = c1 \neq c2 \ \wedge \quad e.balance(c1) > m$$

{ `e.transfer(c2,m)` }

$$e.balance(c1) = e.balance(c1)_{pre} - m \ \wedge \ e.balance(c2) = e.balance(c2)_{pre} + m$$

ERC20 classical spec

$e{:}ERC20 \;\wedge\; this = c1 \neq c2 \;\wedge\; e.balance(c1) > m$

{ `e.transfer(c2,m)` }

$e.balance(c1) = e.balance(c1)_{pre} - m \;\wedge\; e.balance(c2) = e.balance(c2)_{pre} + m$

$e{:}ERC20 \;\wedge\; this = c1 \;\wedge\; e,balance(c1) < m$

{ `e.transfer(c2,m)` }

$\forall\, c.\; e,balance(c) = e,balance(c)_{pre}$

ERC20 classical spec

e:ERC20 ∧ this = c1≠c2 ∧ e.balance(c1) >m
{ `e.transfer(c2,m)` }
e.balance(c1) = e.balance(c1)$_{pre}$ -m ∧ e.balance(c2) = e.balance(c2)$_{pre}$ +m

e:ERC20 ∧ this = c1 ∧ e,balance(c1) < m
{ `e.transfer(c2,m)` }
∀ c. e,balance(c) = e,balance(c)$_{pre}$

e:ERC20 ∧ this = c1≠c2≠c3≠c1 ∧
e.Authorized(c1,c2,m’) ∧ m’≧ m
∧ e.balance(c1) ≧m
{ `e.transferFrom(c2,c3,m)` }
e.balance(c1) = e.balance(c1)$_{pre}$ -m ∧
e.balance(c2) = e.balance(c2)$_{pre}$ +m ∧ e.Authorized(c1,c2,m’-m)

ERC20 classical spec

e:ERC20 ∧ this = c1≠c2 ∧ e.balance(c1) >m

{ e.transfer(c2,m) }

e.balance(c1) = e.balance(c1)$_{\text{pre}}$ -m ∧ e.balance(c2) = e.balance(c2)$_{\text{pre}}$ +m

e:ERC20 ∧ this = c1 ∧ e,balance(c1) < m

{ e.transfer(c2,m) }

∀ c. e,balance(c) = e,balance(c)$_{\text{pre}}$

e:ERC20 ∧ this = c1≠c2≠c3≠c1 ∧

e.Authorized(c1,c2,m’) ∧ m’≧ m

∧ e.balance(c1) ≧m

{ e.transferFrom(c2,c3,m) }

e.balance(c1) = e.balance(c1)$_{\text{pre}}$ -m ∧

e.balance(c2) = e.balance(c2)$_{\text{pre}}$ +m ∧ e.Authorized(c1,c2,m’-m)

e:ERC20 ∧ this = c1≠c2≠c3≠c1 ∧

(¬ e.Authorized(c1,c2,m) ∨ e.Authorized(c1,c2,m’) ∧ m’<m

∨ e.balance(c1) < m)

{ e.transferFrom(c2,c3,m) }

∀ c. e.balance(c) = e.balance(c)$_{\text{pre}}$ ∧

∀ c,m. [e.Authorized(c1,c2,m)⟷e.Authorized(c1,c2,m)]

ERC20 classical spec

e:ERC20 ∧ this = c1≠c2 ∧ e.balance(c1) >m
{ e.transfer(c2,m) }
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e:ERC20 ∧ this = c1 ∧ e,balance(c1) < m
{ e.transfer(c2,m) }
∀ c. e,balance(c) = e,balance(c)$_{pre}$

e:ERC20 ∧ this = c1≠c2≠c3≠c1 ∧
e.Authorized(c1,c2,m’) ∧ m’≧ m
∧ e.balance(c1) ≧m
{ e.transferFrom(c2,c3,m) }
e.balance(c1) = e.balance(c1)$_{pre}$ -m ∧
e.balance(c2) = e.balance(c2)$_{pre}$ +m ∧ e.Authorized(c1,c2,m’-m)

e:ERC20 ∧ this = c1≠c2≠c3≠c1 ∧
(¬ e.Authorized(c1,c2,m) ∨ e.Authorized(c1,c2,m’) ∧ m’<m
∨ e.balance(c1) < m)
{ e.transferFrom(c2,c3,m) }
∀ c. e.balance(c) = e.balance(c)$_{pre}$ ∧
∀ c,m. [e.Authorized(c1,c2,m)⟷e.Authorized(c1,c2,m)]

e:ERC20 ∧ this = c1 { e.aprove(c2,m) } e.Authorized(c1,c2,m)

ERC20 classical spec

e:ERC20 ∧ this = c1≠c2 ∧ e.balance(c1) >m
{ `e.transfer(c2,m)` }
e.balance(c1) = e.balance(c1)$_{pre}$ -m ∧ e.balance(c2) = e.balance(c2)$_{pre}$ +m

e:ERC20 ∧ this = c1 ∧ e,balance(c1) < m
{ `e.transfer(c2,m)` }
∀ c. e,balance(c) = e,balance(c)$_{pre}$

e:ERC20 ∧ this = c1≠c2≠c3≠c1 ∧
e.Authorized(c1,c2,m') ∧ m'≧ m
∧ e.balance(c1) ≧m
{ `e.transferFrom(c2,c3,m)` }
e.balance(c1) = e.balance(c1)$_{pre}$ -m ∧
e.balance(c2) = e.balance(c2)$_{pre}$ +m ∧ e.Authorized(c1,c2,m'-m)

e:ERC20 ∧ this = c1≠c2≠c3≠c1 ∧
(¬ e.Authorized(c1,c2,m) ∨ e.Authorized(c1,c2,m') ∧ m'<m
∨ e.balance(c1) < m)
{ `e.transferFrom(c2,c3,m)` }
∀ c. e.balance(c) = e.balance(c)$_{pre}$ ∧
∀ c,m. [e.Authorized(c1,c2,m)⟷e.Authorized(c1,c2,m)]

e:ERC2

… { `e.balanceOf(c)` } ….

ERC20 classical spec

e:ERC20 ∧ this = c1≠c2 ∧ e.balance(c1) >m
{ e.transfer(c2,m) }
e.balance(c1) = e.balance(c1)$_{pre}$ -m ∧ e.balance(c2) = e.balance(c2)$_{pre}$ +m

e:ERC20 ∧ this = c1 ∧ e,balance(c1) < m
{ e.transfer(c2,m) }
∀ c. e,balance(c) = e,balance(c)$_{pre}$

e:ERC20 ∧ this = c1≠c2≠c3≠c1 ∧
e.Authorized(c1,c2,m’) ∧ m’≧ m
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e:ERC20 ∧ this = c1≠c2≠c3≠c1 ∧
(¬ e.Authorized(c1,c2,m) ∨ e.Authorized(c1,c2,m’) ∧ m’<m
∨ e.balance(c1) < m)
{ e.transferFrom(c2,c3,m) }
∀ c. e.balance(c) = e.balance(c)$_{pre}$ ∧
∀ c,m. [e.Authorized(c1,c2,m)⟷e.Authorized(c1,c2,m)]

… { e.totalSupply() } ….

… { e.balanceOf(c) } ….

ERC20 classical spec

e:ERC20 ∧ this = c1≠c2 ∧ e.balance(c1) >m
{ `e.transfer(c2,m)` }
e.balance(c1) = e.balance(c1)$_{pre}$ -m ∧ e.balance(c2) = e.balance(c2)$_{pre}$ +m

e:ERC20 ∧ this = c1 ∧ e,balance(c1) < m
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∀ c. e,balance(c) = e,balance(c)$_{pre}$

e:ERC20 ∧ this = c1≠c2≠c3≠c1 ∧
e.Authorized(c1,c2,m’) ∧ m’≧ m
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{ `e.transferFrom(c2,c3,m)` }
e.balance(c1) = e.balance(c1)$_{pre}$ -m ∧
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∨ e.balance(c1) < m)
{ `e.transferFrom(c2,c3,m)` }
∀ c. e.balance(c) = e.balance(c)$_{pre}$ ∧
∀ c,m. [e.Authorized(c1,c2,m)⟷e.Authorized(c1,c2,m)]

… { `e.totalSupply()` } ….

… { `e.allowanceOf(c2)` } ….

… { `e.balanceOf(c)` } ….

ERC20 classical spec

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{ e.transferFrom(c2,c3,m) }
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sufficient conditions
for change of balance

e:ERC20 ∧ this = c1≠c2≠c3≠c1 ∧
(¬ e.Authorized(c1,c2,m) ∨ e.Authorized(c1,c2,m’) ∧ m’<m
∨ e.balance(c1) < m)
{ e.transferFrom(c2,c3,m) }
∀ c. e.balance(c) = e.balance(c)$_{pre}$ ∧
∀ c,m. [e.Authorized(c1,c2,m)⟷e.Authorized(c1,c2,m)]

… { e.totalSupply() } ….

… { e.allowanceOf(c2) } ….

… { e.balanceOf(c) } ….

ERC20   classical spec

$e{:}ERC20 \;\land\; this = c1 \neq c2 \;\land\; e.balance(c1) > m$

{ `e.transfer(c2,m)` }

$e.balance(c1) = e.balance(c1)_{pre} - m \;\land\; e.balance(c2) = e.balance(c2)_{pre} + m$

$e{:}ERC20 \;\land\; this = c1 \;\land\; e,balance(c1) < m$

{ `e.transfer(c2,m)` }

$\forall c.\ e,balance(c) = e,balance(c)_{pre}$

$e{:}ERC20 \;\land\; this = c1 \neq c2 \neq c3 \neq c1 \;\land$

$e.Authorized(c1,c2,m') \;\land\; m' \geqq m$

$\land\; e.balance(c1) \geqq m$

{ `e.transferFrom(c2,c3,m)` }

$e.balance(c1) = e.balance(c1)_{pre} - m \;\land$

$e.balance(c2) = e.balance(c2)_{pre} + m \;\land\; e.Authorized(c1,c2,m'-m)$

$e{:}ERC20 \;\land\; this = c1 \neq c2 \neq c3 \neq c1 \;\land$

$(\;\neg\, e.Authorized(c1,c2,m) \;\lor\; e.Authorized(c1,c2,m') \;\land\; m' < m$

$\lor\; e.balance(c1) < m\;\;)$

{ `e.transferFrom(c2,c3,m)` }

$\forall c.\ e.balance(c) = e.balance(c)_{pre} \;\land$

$\forall c,m.\ [\; e.Authorized(c1,c2,m) \longleftrightarrow e.Authorized(c1,c2,m) \;]$

… { `e.totalSupply()` } ….

… { `e.allowanceOf(c2)` } ….

… { `e.balanceOf(c)` } ….

ERC20 classical spec

∧ e.balance(c1) >m
r(c2,m) }
ance(c2) = e.balance(c2)$_{pre}$ +m

RC20 ∧ this = c1 ∧ e,balance(c1) < m
{ e.transfer(c2,m) }
∀ c. e,balance(c) = e,balance(c)$_{pre}$

Is that robust?

e.A
∧ e.balance(c1) ≧m
{ e.transferFrom m) }
e.balance(c1) = e.bala pre -m ∧
e.balance(c2) = e.balanc re +m ∧ e.Authorized(c1,c2,m'-m)

e:ERC20 ∧ this = c1≠c2 1 ∧
(¬ e.Authorized(c1,c2 ∨ e.Authorized(c1,c2,m') ∧ m'<m
∨ e.balance(c1) < m)
{ e.transferFrom(c2, m) }
∀ c. e.balance(c) = e.balanc (c)$_{pre}$ ∧
∀ c,m. [e.Authorized(c1,c2,m → e.Authorized(c1,c2,m)]

… { e.totalSupply() } ….
… { e.allowanceOf(c2) } ….
… { e.balanceOf(c) } ….

ERC20 classical spec

∧ e.balance(c1) >m
r(c2,m) }
ance(c2) = e.balance(c2)$_{pre}$ +m

RC20 ∧ this = c1 ∧ e,balance(c1) < m
{ e.transf
∀ c. e,balance(c)

e.
∧ e.balance(c1) ≥m
{ e.transferFrom m) }
e.balance(c1) = e.bala $_{pre}$ -m ∧
e.balance(c2) = e.balanc $_{pre}$ +m ∧ e.Authorized(c1,c2, -m)

e:ERC20 ∧ this = c1≠c2 1 ∧
(¬ e.Authorized(c1,c2 ∨ e.Authorized(c1,c2,m’) ∧ m’<m
∨ e.balance(c1) < m)
{ e.transferFrom(c2, m) }
∀ c. e.balance(c) = e.balanc (c)$_{pre}$ ∧
∀ c,m. [e.Authorized(c1,c2,m) →e.Authorized(c1,c2,m)]

… { e.totalSupply() } ….
… { e.allowanceOf(c2) } ….
… { e.balanceOf(c) } ….

Is that robust?

a function that takes 0.5% from each account?

ERC20 classical spec

∧ e.balance(c1) >m
r(c2,m) }
ance(c2) = e.balance(c2)$_{pre}$ +m

RC20 ∧ this = c1 ∧ e,balance(c1) < m
{ e.transf
∀ c. e,balance(c)

e.:
∧ e.balance(c1) ≥m
{ e.transferFrom m) }
e.balance(c1) = e.bala $_{pre}$ -m ∧
e.balance(c2) = e.balanc re +m ∧ e.Authorized(c1,c2, -m)

e:ERC20 ∧ this = c1≠c2 1 ∧
(¬ e.Authorized(c1,c2 ∨ e.Authorized(c
∨ e.balance(c1) < m)
{ e.transferFrom(c2, m) }
∀c. e.balance(c) = e.balanc (c)$_{pre}$ ∧
∀c,m. [e.Authorized(c1,c2,m) → e.Authorized(c1,c2,m)]

… { e.totalSupply() } ….

… { e.allowanceOf(c2) } ….

… { e.balanceOf(c) } ….

Is that robust?

a function that takes 0.5% from each account?

can authority increase?

ERC20 classical spec

∧
r
ance

RC20 ∧ thi = c1 ∧ e,balance(c1) < m
{ .transf
∀ c. e,ba ance(c)

e.
∧ e.balance(c1) ≧m
{ e.transferFrom m) }
e.balance(c1) = e.bala $_{pre}$ -m ∧
e.balance(c2) = e.balanc $_{re}$ +m ∧ e.Autho ized(c1,c2, -m)

e:ERC20 ∧ this = c1≠c2 1 ∧
(¬ e.Authorized(c1,c2, ∨ e.Authorized(c
∨ e.balance(c1) < m)
{ e.transferFrom(c2, m) }
∀c. e.balance(c) = e.balanc (c)$_{pre}$ ∧
∀c,m. [e.Authorized(c1,c2,m) → e.Authori ed(c1,c2,m)]

… { e.totalSupply() } ….
… { e.allowanceOf(c2) } ….
… { e.balanceOf(c) } ….

Is that robust?

a “super-cleint,” authorised on all?

a function that takes 0.5% from each account?

can authority increase?

ERC20 classical spec

∧

r

ance

RC20 ∧ thi = c1 ∧ e,balance(c1) < m

{ .transf

∀ c. e,ba ance(c)

e.

∧ e.balance(c1) ≧m

{ e.transferFrom m) }

e.balance(c1) = e.bala $_{pre}$ -m ∧

e.balance(c2) = e.balanc re +m ∧ e.Autho ized(c1,c2, -m)

1 ∧

∨ e.Authorized(c

2, m) }

anc (c) $_{pre}$ ∧

c2,m, →e.Authori ed(c1,c2,m)]

.totalSupply() } ….

… { e.allowanceOf(c2) } ….

… { e.balanceOf(c) } ….

Is that robust?

a “super-cleint,”
authorised on all?

a function that
takes 0.5% from
each account?

can authority increase?

ERC20 classical spec

Is that robust?

a “super-cleint,” authorised on all?

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can authority increase?

∧

r

ance

RC20 ∧ thi = c1 ∧ e,balance(c1) < m

{ .transf

∀ c. e,ba ance(c)

e./

∧ e.balance(c1) ≥m

{ e.transferFrom m) }

e.balance(c1) = e.bala $_{pre}$ -m ∧

e.balance(c2) = e.balanc $_{re}$ +m ∧ e.Autho ized(c1,c2, -m)

I am worried about who/what can reduce my balance

zed(c

}

anc (c) $_{pre}$ ∧

c2,m) →e.Authori ed(c1,c2,m)]

.totalSupply() } ….

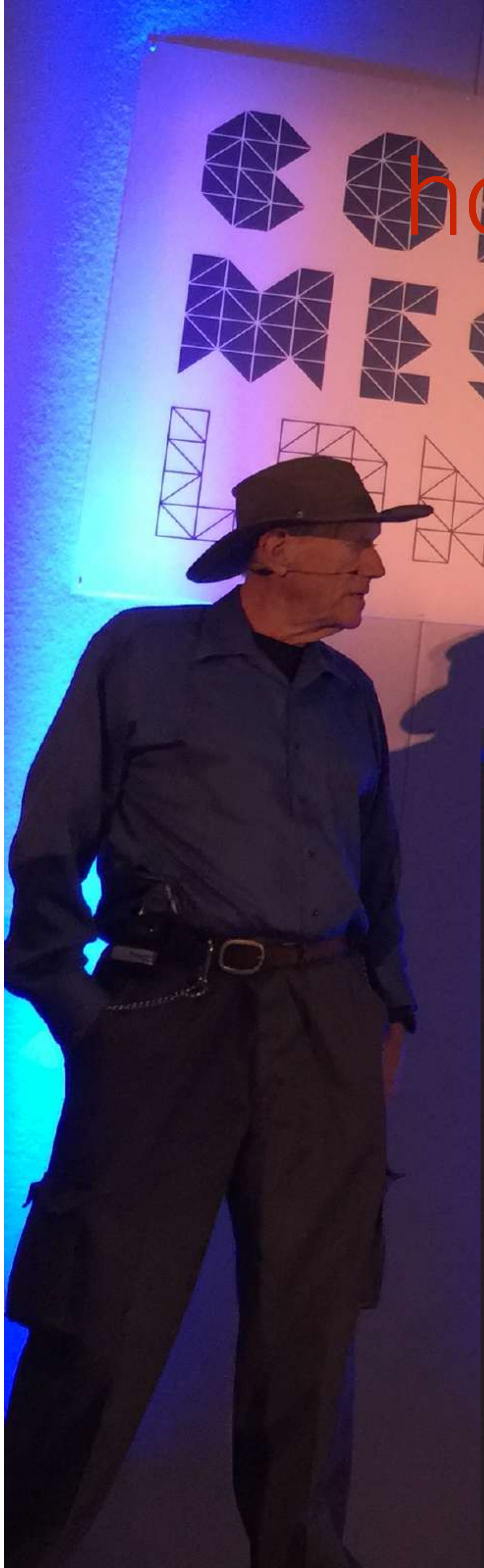
… { e.allowanceOf(c2) } ….

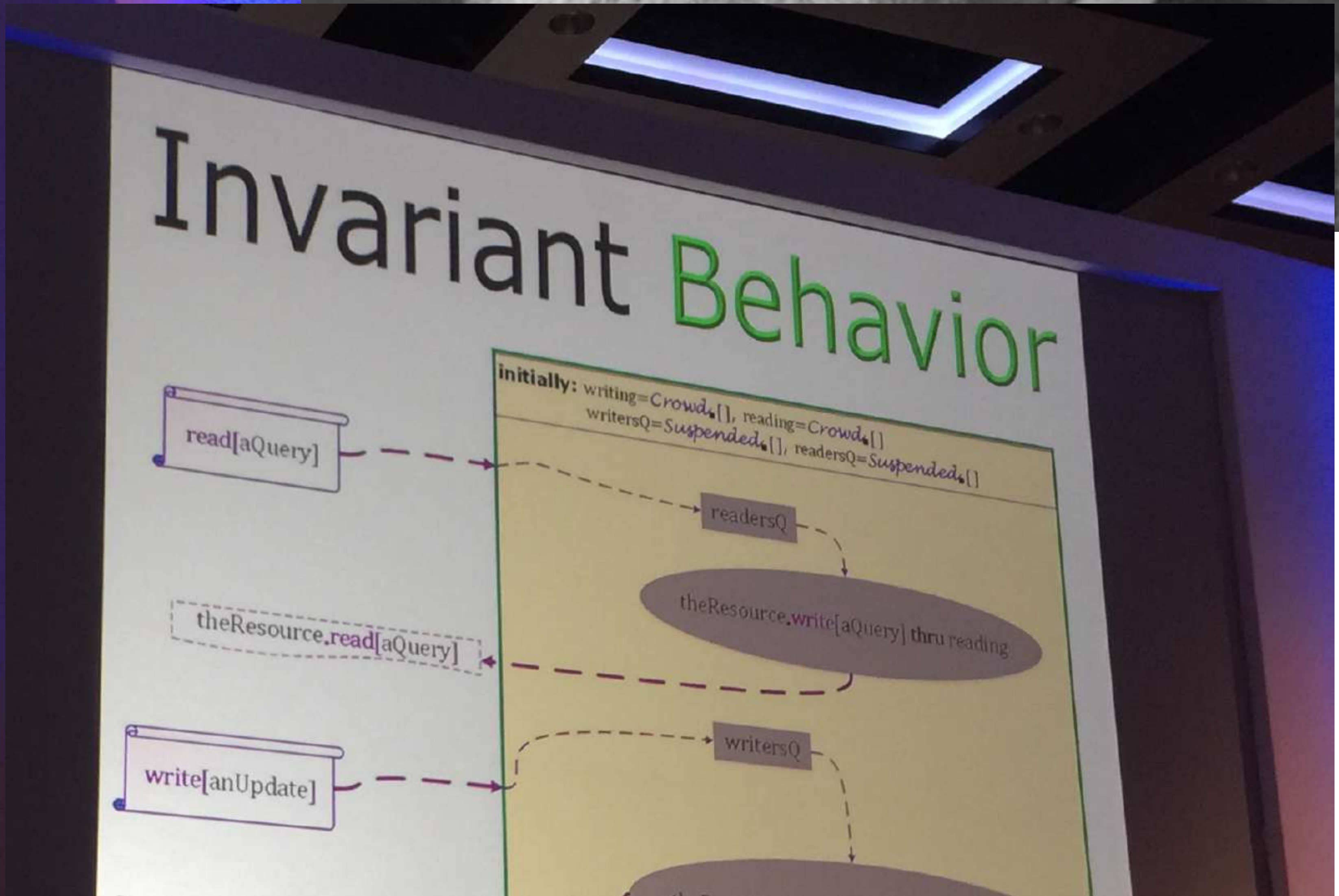
… { e.balanceOf(c) } ….

holistic specs - invariants

holistic specs - invariants

holistic specs - invariants





Invariant Behavior

initially: writing=Crowd•[], reading=Crowd•[]
writersQ=Suspended•[], readersQ=Suspended•[]

read[aQuery]

readersQ

theResource.write[aQuery] thru reading

theResource.read[aQuery]

writersQ

write[anUpdate]

holistic specs - invariants

- state

holistic specs - invariants ++

- state
- **time**
- **space**
- **control**
- **permission**
- **authority**
- **(when/where do they hold)**

holistic spec - reduce balance

holistic spec - reduce balance

∀ `e`:ERC20. ∀ `c1`: Client. ∀ m: Nat.

[`e.balance(c1) =` **Was**`(e.balance(c1))-m`

holistic spec - reduce balance

∀ `e`:ERC20. ∀ `c1`: Client. ∀ m: Nat.

[`e.balance(c1) =` **Was**(`e.balance(c1)-m`

⟶

holistic spec - reduce balance

∀ e:ERC20. ∀ c1: Client. ∀ m: Nat.

[e.balance(c1) = **Was**(e.balance(c1))-m

⟶

(∃c2,c3: Client.

Was (c1.**Calls**(e,transfer,c2,m)))

holistic spec - reduce balance

∀ e:ERC20. ∀ c1: Client. ∀ m: Nat.

[e.balance(c1) = **Was**(e.balance(c1)) - m

⟶

(∃c2,c3: Client.

Was (c1.**Calls**(e,transfer,c2,m)))

∨

Was (e.Authorized(c1,c2,m) ∧

c2.**Calls**(e,transferFrom,c1,c3,m)))   ]

holistic spec - reduce balance

∀ e:ERC20. ∀ c1: Client. ∀ m: Nat.
[e.balance(c1) = **Was**(e.balance(c1)) - m

⟶

(∃c2,c3: Client.
Was (c1.**Calls**(e,transfer,c2,m)))
∨
Was (e.Authorized(c1,c2,m) ∧
c2.**Calls**(e,transferFrom,c1,c3,m)))]

This says: A client's balance decreases *only* if that client, or somebody authorised by that client, made a payment.

holistic spec - reduce balance

∀ e:ERC20. ∀ c1: Client. ∀ m: Nat.
[e.balance(c1) = **Was**(e.balance(c1))-m

⟶

(∃c2,c3: Client.
Was (c1.**Calls**(e,transfer,c2,m)))
∨
Was (e.Authorized(c1,c2,m) ∧
c2.**Calls**(e,transferFrom,c1,c3,m)))]

effect

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holistic spec - reduce balance

∀ e:ERC20. ∀ c1: Client. ∀ m: Nat.

[e.balance(c1) = **Was**(e.balance(c1)) - m

⟶

(∃c2,c3: Client.

Was (c1.**Calls**(e,transfer,c2,m)))

∨

Was (e.Authorized(c1,c2,m) ∧
c2.**Calls**(e,transferFrom,c1,c3,m)))   ]

effect

necessary
condition

This says: A client's balance decreases *only* if that client, or somebody authorised by that client, made a payment.

holistic spec - authority

holistic spec - authority

`e.Authorized(c1,c2,m)` ≐

`c2` is authorised by `c1` for `m` iff

holistic spec - authority

`e.`Authorized(`c1,c2`,`m`) ≐

Was(`c1`.**Calls**(`e,approve,`c2,`m`))

`c2` is authorised by `c1` for `m` iff

in previous step `c1` informed `e` that it authorised `c2` for `m`

holistic spec - authority

$$e.\mathrm{Authorized}(c1,c2,m) \stackrel{\cdot}{\equiv}$$

$$\textbf{Was}(\,c1.\textbf{Calls}(e,\mathtt{approve},c2,m)\,)$$

$$\vee$$

$$\textbf{Was}(\,e.\mathrm{Authorized}(c1,c2,m+m') \wedge c2.\textbf{Calls}(e,\mathtt{transferFrom},c1,\_,m')\,)$$

c2 is authorised by c1 for m iff

in previous step c1 informed e that it authorised c2 for m

or

in previous step c2 was authorised for m+m’ and spent m’ for c1

holistic spec - authority

$$e.\text{Authorized}(c1,c2,m) \stackrel{\cdot}{\equiv}$$

$$\textbf{Was}(\ c1.\textbf{Calls}(e,\text{approve},c2,m)\ )$$

$$\vee$$

$$\textbf{Was}(\ e.\text{Authorized}(c1,c2,m+m')\ \wedge c2.\textbf{Calls}(e,\text{transferFrom},c1,\_,m')\ )$$

$$\vee$$

$$\textbf{Was}(\ e.\text{Authorized}(c1,c2,m)\ \wedge \neg\, c2.\textbf{Calls}(e,\text{transferFrom},c1,\_,\_)\ )$$

c2 is authorised by c1 for m iff

in previous step c1 informed e that it authorised c2 for m

or

in previous step c2 was authorised for m+m’ and spent m’ for c1

or

in previous step c2 was authorised for m and did not spend c1

holistic spec - authority

effect

$$\boxed{\texttt{e.Authorized(c1,c2,m)}} \doteq$$

$$\textbf{Was}(\ \texttt{c1.}\textbf{Calls}(\texttt{e,approve,c2,m})\ )$$

$$\vee$$

$$\textbf{Was}(\ \texttt{e.Authorized(c1,c2,m+m')}\ \wedge\ \texttt{c2.}\textbf{Calls}(\texttt{e,transferFrom,c1,\_,m'})\ )$$

$$\vee$$

$$\textbf{Was}(\ \texttt{e.Authorized(c1,c2,m)}\ \wedge\ \neg\ \texttt{c2.}\textbf{Calls}(\texttt{e,transferFrom,c1,\_,\_})\ )$$

c2 is authorised by c1 for m iff

in previous step c1 informed e that it authorised c2 for m

or

in previous step c2 was authorised for m+m’ and spent m’ for c1

or

in previous step c2 was authorised for m and did not spend c1

holistic spec - authority

effect

e.Authorized(c1,c2,m) ≐

Was(c1.**Calls**(e,approve,c2,m))

∨

Was(e.Authorized(c1,c2,m+m') ∧ c2.**Calls**(e,transferFrom,c1,_,m'))

∨

Was(e.Authorized(c1,c2,m) ∧ ¬ c2.**Calls**(e,transferFrom,c1,_,_))

necessary
conditions

c2 is authorised by c1 for m iff

in previous step c1 informed e that it authorised c2 for m

or

in previous step c2 was authorised for m+m' and spent m' for c1

or

in previous step c2 was authorised for m and did not spend c1

classical vs holistic

classical vs holistic

$$e{:}\mathrm{ERC20} \wedge e.\mathrm{balance}(cl) > m \wedge e.\mathrm{balance}(cl') = m' \wedge cl \neq cl'$$
$$\{\ \texttt{e.transfer}(cl', m) \wedge \mathrm{Caller} = cl \}$$
$$e.\mathrm{balance}(cl) = e.\mathrm{balance}(cl)_{pre} - m \wedge e.\mathrm{balance}(cl')_{pre} = m' + m$$

$$e{:}\mathrm{ERC20} \wedge e.\mathrm{balance}(cl) > m \wedge e.\mathrm{balance}(cl') = m' \wedge cl \neq cl'$$
$$\wedge \mathrm{Authorized}(e, cl, cl'')$$
$$\{\ \texttt{e.transferFrom}(cl', m) \wedge \mathrm{Caller} = cl'' \}$$
$$e.\mathrm{balance}(cl) = e.\mathrm{balance}(cl)_{pre} - m \wedge e.\mathrm{balance}(cl')_{pre} = m' + m$$

$$e{:}\mathrm{ERC20} \wedge e.\mathrm{balance}(cl) > m \wedge e.\mathrm{balance}(cl') = m'$$
$$\{\ \texttt{e.allow}(cl') \wedge \mathrm{Caller} = cl \ \}$$
$$\mathrm{Authorized}(e, cl, cl'')$$

Classical

- per function; :*sufficient* conditions for some action/effect
- *explicit* about individual function, and *implicit* about emergent behaviour

classical vs holistic

$e{:}ERC20 \wedge\ e.balance(cl) > m\ \wedge\ e.balance(cl') = m'\ \wedge cl \neq cl'$

$\{\ \texttt{e.transfer}(cl',m)\ \wedge Caller{=}cl\}$

$e.balance(cl) = e.balance(cl)_{pre} - m\ \wedge\ e.balance(cl')_{pre} = m'+m$

$e{:}ERC20 \wedge\ e.balance(cl) > m\ \wedge\ e.balance(cl') = m'\ \wedge cl \neq cl'$

$\wedge\ \ Authorized\,(e, cl, cl'')$

$\{\ \texttt{e.transferFrom}(cl',m)\ \wedge Caller{=}cl''\}$

$e.balance(cl) = e.balance(cl)_{pre} - m\ \wedge\ e.balance(cl')_{pre} = m'+m$

$e{:}ERC20 \wedge\ e.balance(cl) > m\ \wedge\ e.balance(cl') = m'$

$\{\ \texttt{e.allow}(cl')\ \wedge Caller{=}cl\ \}$

$Authorized\,(e, cl, cl'')$

… … another 7 specs … ….

Classical

- per function; :*sufficient* conditions for some action/effect
- *explicit* about individual function, and *implicit* about emergent behaviour

classical vs holistic

e:ERC20 ∧ e.balance(cl) >m ∧ e.balance(cl’) = m’ ∧ cl≠cl’
{ `e.transfer`(cl’,m) ∧ Caller=cl}
e.balance(cl) = e.balance(cl)$_{pre}$ -m ∧ e.balance(cl’)$_{pre}$ = m’+m

e:ERC20 ∧ e.balance(cl) >m ∧ e.balance(cl’) = m’ ∧ cl≠cl’
∧ Authorized(e, cl, cl’’)
{ `e.transferFrom`(cl’,m) ∧ Caller=cl’’}
e.balance(cl) = e.balance(cl)$_{pre}$ -m ∧ e.balance(cl’)$_{pre}$ = m’+m

e:ERC20 ∧ e.balance(cl) >m ∧ e.balance(cl’) = m’
{ `e.allow`(cl’) ∧ Caller=cl }
Authorized(e, cl, cl’’)

… … another 7 specs … ….

Classical

- per function; :*sufficient* conditions for some action/effect
- *explicit* about individual function, and *implicit* about emergent behaviour

Holistic

- *necessary* conditions for some action/effect
- *explicit* about emergent behaviour

∀ e:ERC20. ∀ cl: Client.
[e.balance(cl) = **Was**(e.balance(cl)) - m)
→
(∃cl’,cl’’: Client.
Was (cl.**Calls**(`e.transfer`(cl’,m)))
∨
Was (Authorized(e,cl, cl’’) ∧ cl’’.**Calls**(`e.transferFrom`(cl,cl’,m)))]

Authorized(cl, cl’) ≐ ∃m: Nat. **Was***(cl.**Calls**(`e.approve`(cl’,m)))

classical vs holistic

$e{:}ERC20 \wedge e.balance(cl) > m \wedge e.balance(cl') = m' \wedge cl \neq cl'$

$\{\ \texttt{e.transfer}(cl', m) \wedge Caller = cl \}$

$e.balance(cl) = e.balance(cl)_{pre} - m \wedge e.balance(cl')_{pre} = m' + m$

$e{:}ERC20 \wedge e.balance(cl) > m \wedge e.balance(cl') = m' \wedge cl \neq cl'$

$\wedge\ Authorized(e, cl, cl'')$

$\{\ \texttt{e.transferFrom}(cl', m) \wedge Caller = cl'' \}$

$e.balance(cl) = e.balance(cl)_{pre} - m \wedge e.balance(cl')_{pre} = m' + m$

$e{:}ERC20 \wedge e.balance(cl) > m \wedge e.balance(cl') = m'$

$\{\ \texttt{e.allow}(cl') \wedge Caller = cl \ \}$

$Authorized(e, cl, cl'')$

… … another 7 specs … ….

Classical

- per function; :*sufficient* conditions for some action/ effect
- *explicit* about individual function, and *implicit* about emergent behaviour

Holistic

- *necessary* conditions for some action/effect
- *explicit* about emergent behaviour

$\forall\ e{:}ERC20.\ \forall\ cl{:}\ Client.$

$[\ e.balance(cl) = \textbf{Was}(e.balance(cl)) - m\ )$

$\rightarrow$

$(\ \exists cl', cl''{:}\ Client.$

$\textbf{Was}(\ cl.\textbf{Calls}(\texttt{e.transfer}(cl', m))\ )$

$\vee$

$\textbf{Was}(\ Authorized(e, cl, cl'') \wedge cl''.\textbf{Calls}(\texttt{e.transferFrom}(cl, cl', m))\ )\ ]$

$Authorized(cl, cl') \doteq \exists m{:}\ Nat.\ \textbf{Was*}(\ cl.\textbf{Calls}(\texttt{e.approve}(cl', m))\ )$

Example2: DAO simplified

DAO, a “hub that disperses funds”; (https://www.ethereum.org/dao).
… clients may contribute and retrieve funds :

- `payIn(m)` pays into DAO m on behalf of client
- `repay()` withdraws all moneys from DAO

Vulnerability: Through a buggy version of `repay()`, a client could re-enter the call and deplete all funds of the DAO.

classical spec

Assuming DAO keeps a directory of contributions, and require:

R1: directory is compatible with the amount of ether kept in the DAO, and

R2: that withdraw reduces the ether by that amount.

classical spec

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R1: directory is compatible with the amount of ether kept in the DAO, and

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R1: $\forall d{:}DAO.\quad d.ether = \sum_{\texttt{cl} \in dom(\texttt{d.directory})} \texttt{d.directory(cl)}$

classical spec

Assuming DAO keeps a directory of contributions, and require:

R1: directory is compatible with the amount of ether kept in the DAO, and

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R1: $\forall d{:}DAO. \quad d.ether = \sum_{\mathtt{cl} \in dom(\mathtt{d.directory})} \mathtt{d.directory(cl)}$

R2: $d{:}DAO \ \wedge \ n{:}Nat \ \wedge \ d.directory(cl)=n>0 \ \wedge \ this=cl$

$\{$ `d.repay()` $\}$

$d.directory(cl)=0 \ \wedge d.\mathbf{Calls}(cl,send,\mathtt{n})$

classical spec

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{ `d.repay()` }

$d.directory(cl)=0 \ \wedge d.\mathbf{Calls}(cl,send,n)$

$d{:}DAO \ \wedge \ n{:}Nat \ \wedge \ d.directory(cl)=0 \ \wedge \ this=cl$

{ `d.repay()` }

“nothing changes”

classical spec

Assuming DAO keeps a directory of contributions, and require:

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R1: $\forall d{:}DAO.\quad d.ether = \sum_{\mathtt{cl} \in dom(\mathtt{d.directory})} \mathtt{d.directory(cl)}$

R2: $d{:}DAO \ \wedge\ n{:}Nat \ \wedge\ d.directory(cl)=n>0 \ \wedge\ this=cl$

$\{\ \mathtt{d.repay()}\ \}$

$d.directory(cl)=0 \ \wedge\ d.\mathbf{Calls}(cl,send,n)$

$d{:}DAO \ \wedge\ n{:}Nat \ \wedge\ d.directory(cl)=0 \ \wedge\ this=cl$

$\{\ \mathtt{d.repay()}\ \}$

“nothing changes”

This spec avoids the vulnerability, 😅

classical spec

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$\{\ $ `d.repay()` $\ \}$

$d.directory(cl)=0 \ \wedge d.\mathbf{Calls}(cl,send,\mathtt{n})$

$d{:}DAO \ \wedge\ n{:}Nat \ \wedge\ d.directory(cl)=0 \ \wedge\ this=cl$

$\{\ $ `d.repay()` $\ \}$

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This spec avoids the vulnerability, 😅

provided the attack goes through the function repay. 😢

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R1: directory is compatible with the amount of ether kept in the DAO, and

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R1: $\forall d{:}DAO.\quad d.ether = \sum_{\mathtt{cl} \in dom(\mathtt{d.directory})} \mathtt{d.directory(cl)}$

R2: $d{:}DAO \ \wedge\ n{:}Nat \ \wedge\ d.directory(cl)=n>0 \ \wedge\ this=cl$

$\{\ \mathtt{d.repay()}\ \}$

$d.directory(cl)=0 \ \wedge\ d.\mathbf{Calls}(cl,send,\mathtt{n})$

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To avoid the vulnerability in general, we need to inspect the specification of *all* the functions in the DAO.

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R2: $d{:}DAO \;\wedge\; n{:}Nat \;\wedge\; d.directory(cl){=}n{>}0 \;\wedge\; this{=}cl$

{ `d.repay()` }

$d.directory(cl){=}0 \;\wedge\; d.$**Calls**$(cl,send,n)$

$d{:}DAO \;\wedge\; n{:}Nat \;\wedge\; d.directory(cl){=}0 \;\wedge\; this{=}cl$

{ `d.repay()` }

“nothing changes”

This spec avoids the vulnerability, 😅

provided the attack goes through the function repay. 😢

To avoid the vulnerability in general, we need to inspect the specification of *all* the functions in the DAO. DAO - interface has *nineteen* functions. 🥵

holistic

holistic

∀ cl:External. **∀**d:DAO. **∀**.n:Nat.
[cl.**Calls**(`d.repay()`) ∧ d.Balance(cl) = n
→
d.ether≧n ∧ **Will**(d.**Calls**(cl.send(n))]

holistic

$$
\begin{array}{l}
\forall\ \mathrm{cl{:}External}.\ \forall \mathrm{d{:}DAO}.\ \forall.\mathrm{n{:}Nat}. \\
[\ \ \mathrm{cl}.\textbf{Calls}(\texttt{d.repay()}\ )\ \wedge\ \mathrm{d.Balance(cl)} = \mathrm{n} \\
\quad \rightarrow \\
\quad \mathrm{d.ether} \geqq \texttt{n} \wedge\ \textbf{Will}(\mathrm{d}.\textbf{Calls}(\mathrm{cl.send}(\texttt{n}\ ))\ \ ]
\end{array}
$$

This specification avoids the vulnerability, regardless of which function introduces it:
The DAO will always be able to repay all its customers.

holistic

$$
\begin{aligned}
&\forall\ \text{cl:External. } \forall\text{d:DAO. } \forall\text{.n:Nat.}\\
&[\ \ \text{cl.}\mathbf{Calls}(\texttt{d.repay()}\ )\ \wedge\ \text{d.Balance(cl)} = \text{n}\\
&\quad \rightarrow\\
&\quad \text{d.ether}\geqq\texttt{n}\ \wedge\ \mathbf{Will}(\text{d.}\mathbf{Calls}(\text{cl.send(}\texttt{n}\text{))}\ \ ]
\end{aligned}
$$

This specification avoids the vulnerability, regardless of which function introduces it:
The DAO will always be able to repay all its customers.

$\text{d.Balance(cl)} \equiv$

holistic

$$\begin{array}{l} \forall\ cl{:}External.\ \forall d{:}DAO.\ \forall.n{:}Nat. \\ [\ \ cl.\mathbf{Calls}(\texttt{d.repay()}\ )\ \wedge\ d.Balance(cl) = n \\ \quad \rightarrow \\ \quad d.ether \geqq \texttt{n}\ \wedge\ \mathbf{Will}(d.\mathbf{Calls}(cl.send(\texttt{n}\ ))\ \ ] \end{array}$$

This specification avoids the vulnerability, regardless of which function introduces it:
The DAO will always be able to repay all its customers.

$$d.Balance(cl) \equiv \quad 0 \qquad \text{if}\ \ cl.\mathbf{Calls}(d,initialize()\ )$$

holistic

∀ cl:External. **∀**d:DAO. **∀**.n:Nat.
[cl.**Calls**(`d.repay()`) ∧ d.Balance(cl) = n
→
d.ether≥`n` ∧ **Will**(d.**Calls**(cl.send(`n`))]

This specification avoids the vulnerability, regardless of which function introduces it:
The DAO will always be able to repay all its customers.

d.Balance(cl) ≡ 0 if cl.**Calls**(d,initialize())
m+m' if **Was**(d.Balance(cl),m) ∧ cl.**Calls**(d.payIn(m'))

holistic

$$
\begin{array}{l}
\forall\ cl{:}External.\ \forall d{:}DAO.\ \forall .n{:}Nat. \\
[\ \ cl.\mathbf{Calls}(\texttt{d.repay()}\ )\ \wedge\ d.Balance(cl) = n \\
\quad \rightarrow \\
\quad d.ether \geqq \texttt{n}\ \wedge\ \mathbf{Will}(d.\mathbf{Calls}(cl.send(\texttt{n}\ ))\ \ ]
\end{array}
$$

This specification avoids the vulnerability, regardless of which function introduces it:
The DAO will always be able to repay all its customers.

$$
d.Balance(cl) \equiv
\begin{array}{ll}
0 & \text{if}\ \ cl.\mathbf{Calls}(d,initialize()\ ) \\
m+m' & \text{if}\ \ \mathbf{Was}(d.Balance(cl),m)\ \ \wedge\ cl.\mathbf{Calls}(d.payIn(m')\ \ ) \\
0 & \text{if}\ \ \mathbf{Was}(cl.\mathbf{Calls}(d.repayIn()\ \ )
\end{array}
$$

holistic

$$\forall\ cl{:}External.\ \forall d{:}DAO.\ \forall.n{:}Nat.$$

$$[\ \ cl.\mathbf{Calls}(\texttt{d.repay()}\ )\ \wedge\ d.Balance(cl) = n$$

$$\rightarrow$$

$$d.ether \geqq \texttt{n} \wedge\ \mathbf{Will}(d.\mathbf{Calls}(cl.send(\texttt{n}\ ))\ \ ]$$

This specification avoids the vulnerability, regardless of which function introduces it:
The DAO will always be able to repay all its customers.

$$d.Balance(cl) \equiv \begin{cases} 0 & \text{if } cl.\mathbf{Calls}(d,initialize()\ ) \\ m+m' & \text{if } \mathbf{Was}(d.Balance(cl),m)\ \wedge\ cl.\mathbf{Calls}(d.payIn(m')\ \ ) \\ 0 & \text{if } \mathbf{Was}(cl.\mathbf{Calls}(d.repayIn()\ \ ) \\ \mathbf{Was}(d.Balance(cl)) & \text{otherwise} \end{cases}$$

classical vs holistic

$\forall d{:}DAO.\quad d.ether = \sum_{\texttt{cl} \in dom(\texttt{d.directory})} \texttt{d.directory(cl)}$

$d{:}DAO \ \wedge\ n{:}Nat \ \wedge\ d.directory(cl) = n > 0 \wedge\ \texttt{this} = cl$
{ `d.repay()` }
$d.directory(cl) = 0 \ \wedge d.Calls(cl.send(\texttt{n}))$

$d{:}DAO \ \wedge\ n{:}Nat \ \wedge\ d.directory(cl) = 0 \ \wedge\ this = cl$
{ `d.repay()` }
“nothing changes”

classical vs holistic

$$\forall d{:}DAO.\quad d.ether = \sum_{\texttt{cl} \,\in\, dom(\texttt{d.directory})} \texttt{d.directory(cl)}$$

$d{:}DAO \;\wedge\; n{:}Nat \;\wedge\; d.directory(cl)=n>0 \;\wedge\; \texttt{this}=cl$

{ `d.repay()` }

$d.directory(cl)=0 \;\wedge\; d.Calls(cl.send(\texttt{n}))$

$d{:}DAO \;\wedge\; n{:}Nat \;\wedge\; d.directory(cl)=0 \;\wedge\; this=cl$

{ `d.repay()` }

"nothing changes"

Classical

- per function; *sufficient* conditions for some action/effect
- *explicit* about individual function, and *implicit* about emergent behaviour

classical vs holistic

$\forall$d:DAO.   d.ether = $\sum_{\texttt{cl} \in \text{dom}(\texttt{d.directory})}$ `d.directory(cl)`

d:DAO ∧ n:Nat ∧ d.directory(cl)=n>0 ∧ `this`=cl
{ `d.repay()` }
d.directory(cl)=0 ∧ d.Calls(cl.send(n))

d:DAO ∧ n:Nat ∧ d.directory(cl)=0 ∧ this=cl
{ `d.repay()` }
“nothing changes”

… … specs for another 19 functions ….

Classical

- per function; *sufficient* conditions for some action/effect
- *explicit* about individual function, and *implicit* about emergent behaviour

classical vs holistic

$\forall$d:DAO. d.ether = $\sum_{\texttt{cl} \in \mathrm{dom}(\texttt{d.directory})}$ `d.directory(cl)`

d:DAO ∧ n:Nat ∧ d.directory(cl)=n>0 ∧ `this`=cl
{ `d.repay()` }
d.directory(cl)=0 ∧ d.Calls(cl.send(`n`))

d:DAO ∧ n:Nat ∧ d.directory(cl)=0 ∧ this=cl
{ `d.repay()` }
“nothing changes”

… … specs for another 19 functions ….

Classical

- per function; *sufficient* conditions for some action/effect
- *explicit* about individual function, and *implicit* about emergent behaviour

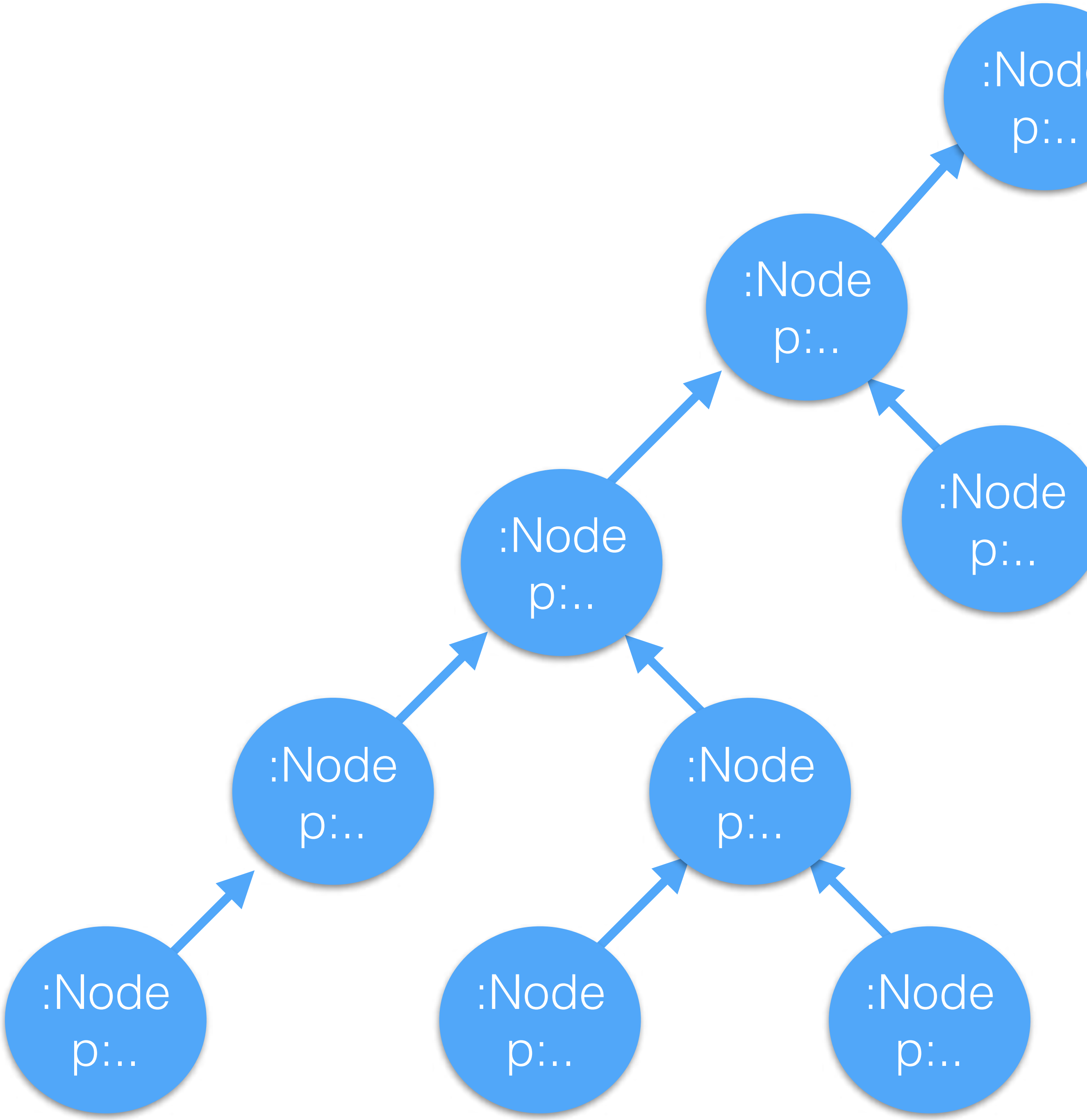
Holistic

- *necessary* conditions for some action/effect
- *explicit* about emergent behaviour

∀ cl:External. ∀d:DAO. ∀.n:Nat.
[cl.**Calls**(`d.repay()`) ∧ d.Balance(cl) = n
→
d.ether≥`n` ∧ **Will**(d.**Calls**(cl.send(`n`))]

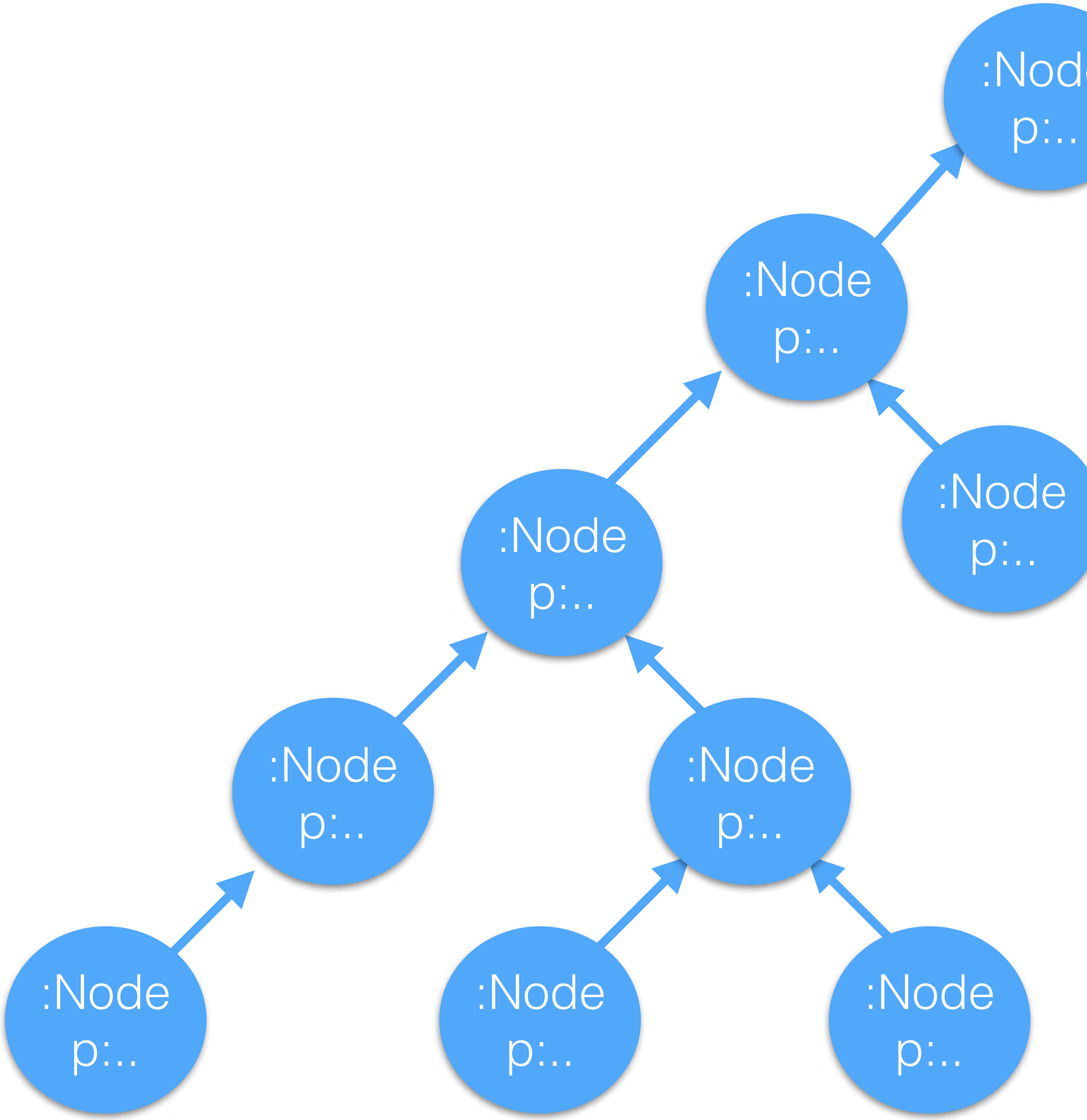
d.Balance(cl) ≡	m	if cl.**Calls**(d,initialize,m)
	m+m’	if **Was**(d.Balance(cl),m) ∧ **Was**(cl.**Calls**(d.payIn(m’))
	0	if **Was**(cl.**Calls**(d.repayIn())

Example 3: DOM attenuation



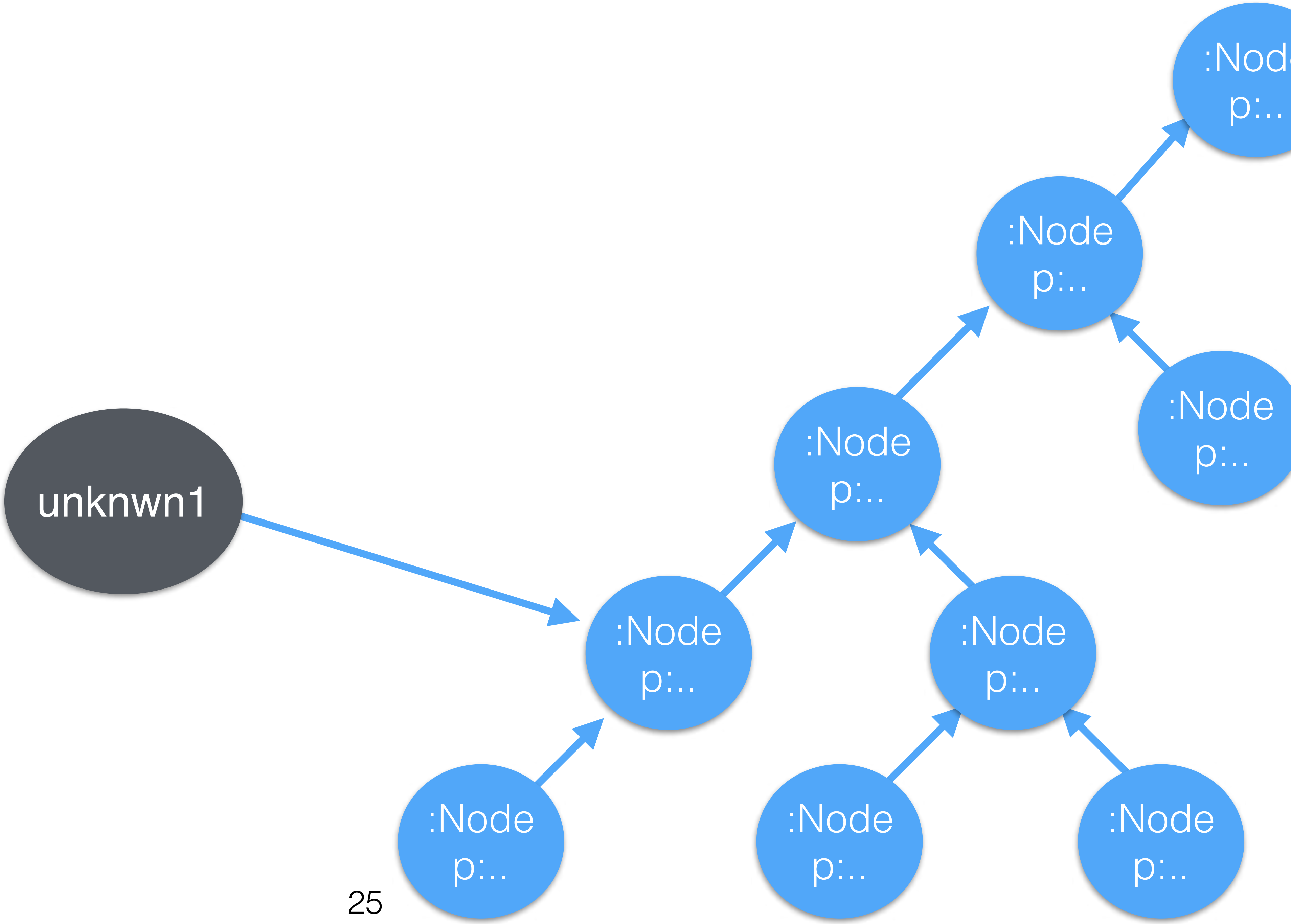
Example 3: DOM attenuation

Access to any `Node` gives access to ***complete*** tree



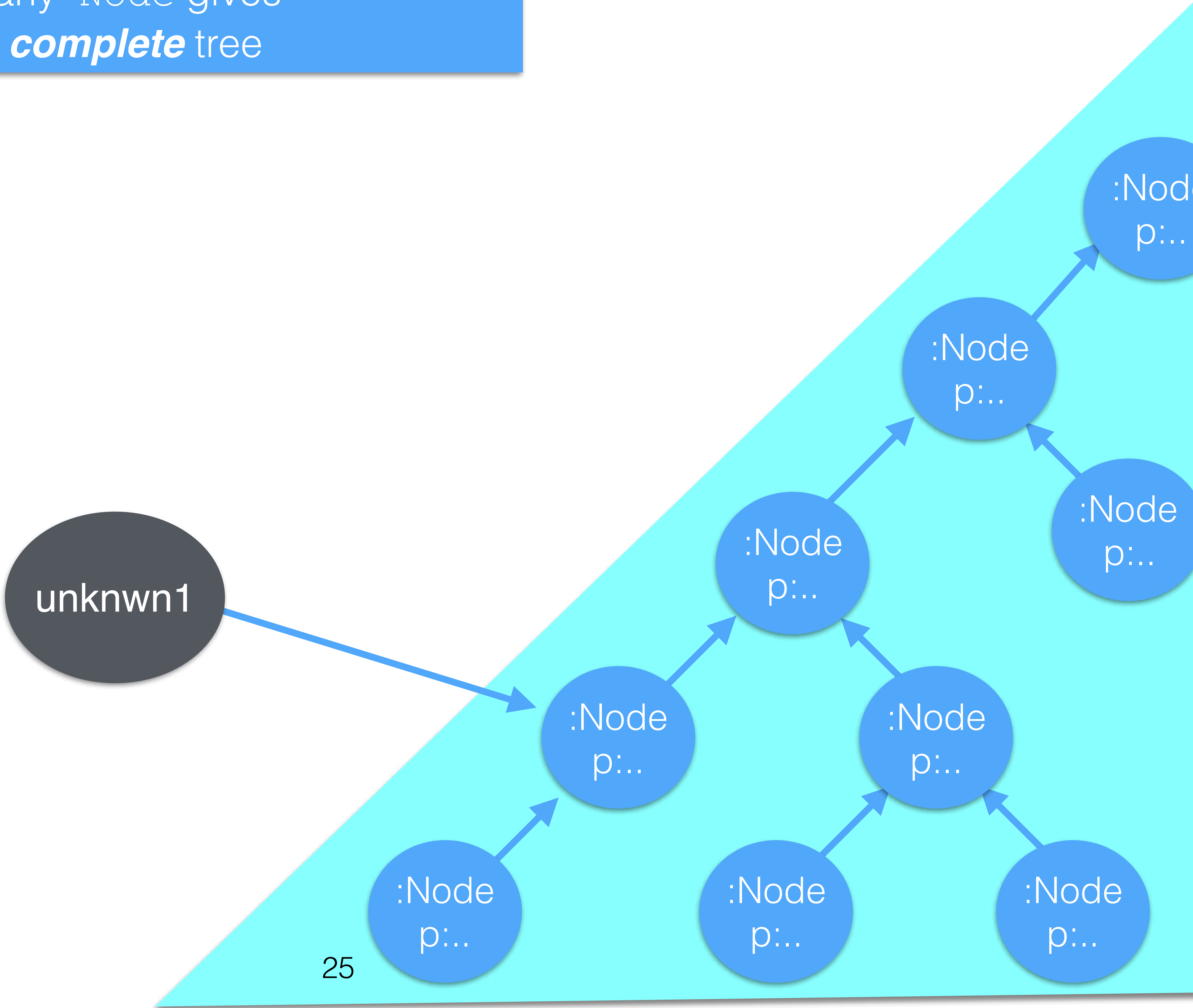
Example 3: DOM attenuation

Access to any `Node` gives access to ***complete*** tree



Example 3: DOM attenuation

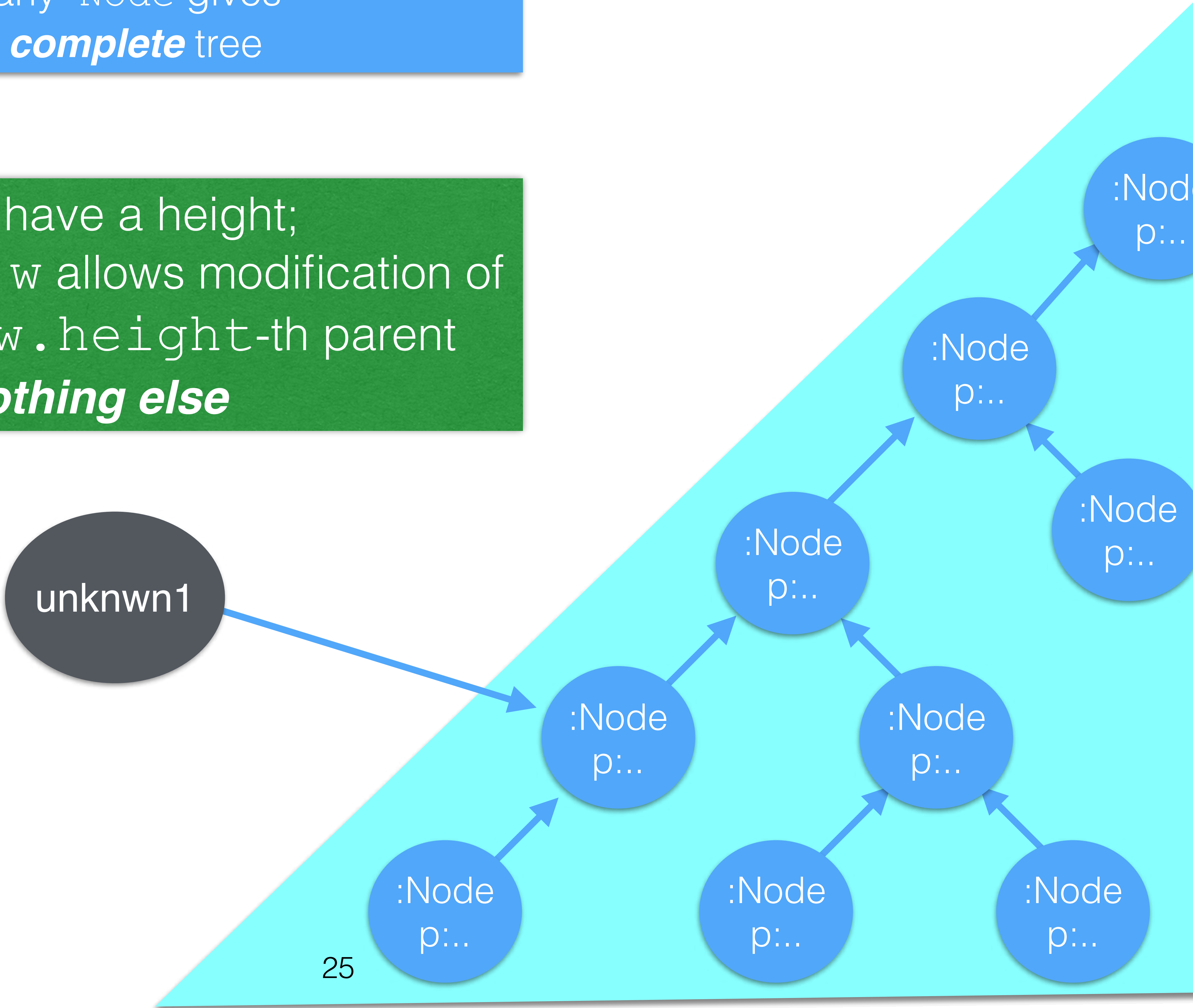
Access to any `Node` gives access to ***complete*** tree



Example 3: DOM attenuation

Access to any `Node` gives access to ***complete*** tree

Wrappers have a height;
Access to Wrapper `w` allows modification of `Node`s under the `w.height`-th parent
and nothing else



Example 3: DOM attenuation

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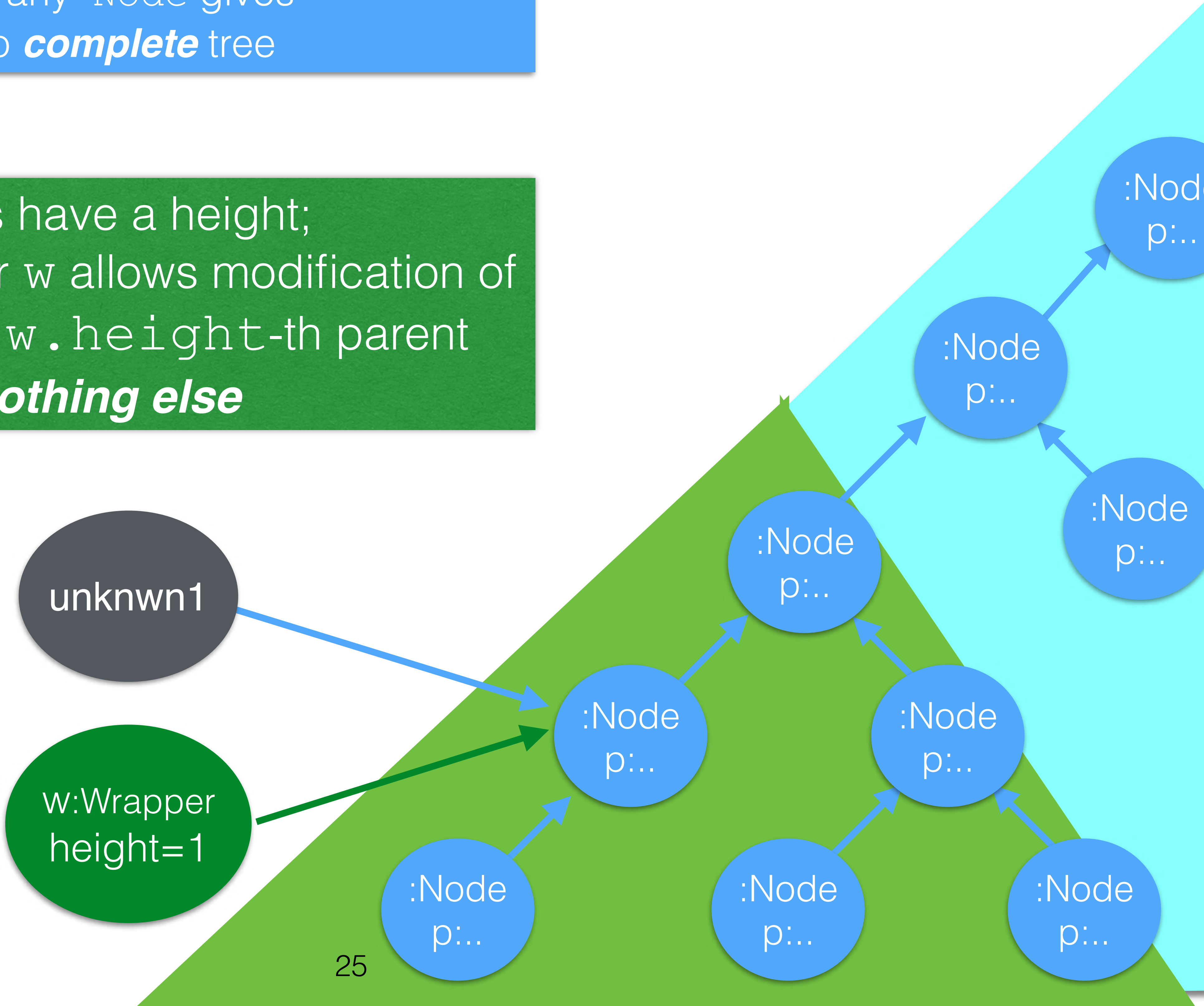

Example 3: DOM attenuation

Access to any `Node` gives
access to ***complete*** tree

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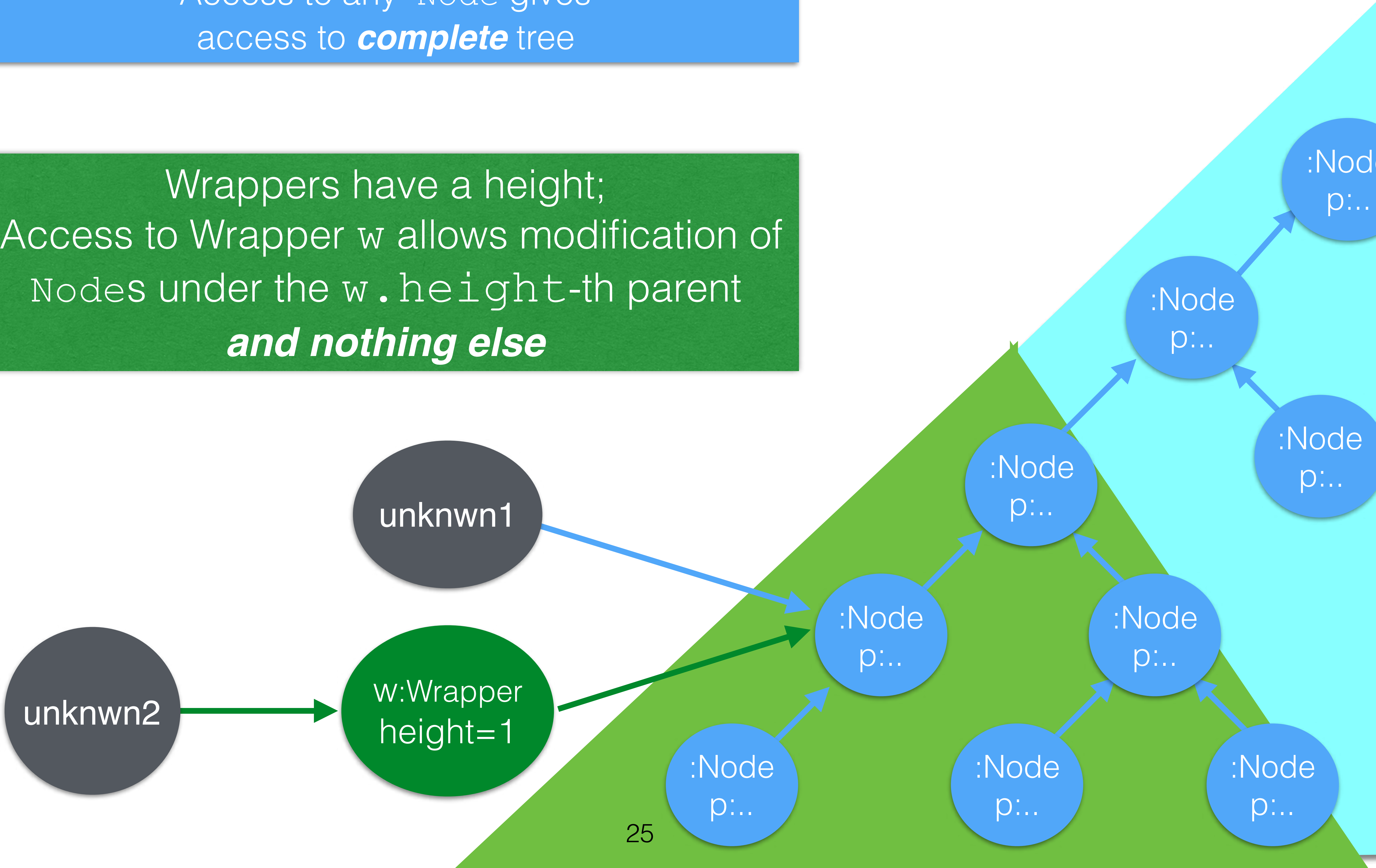
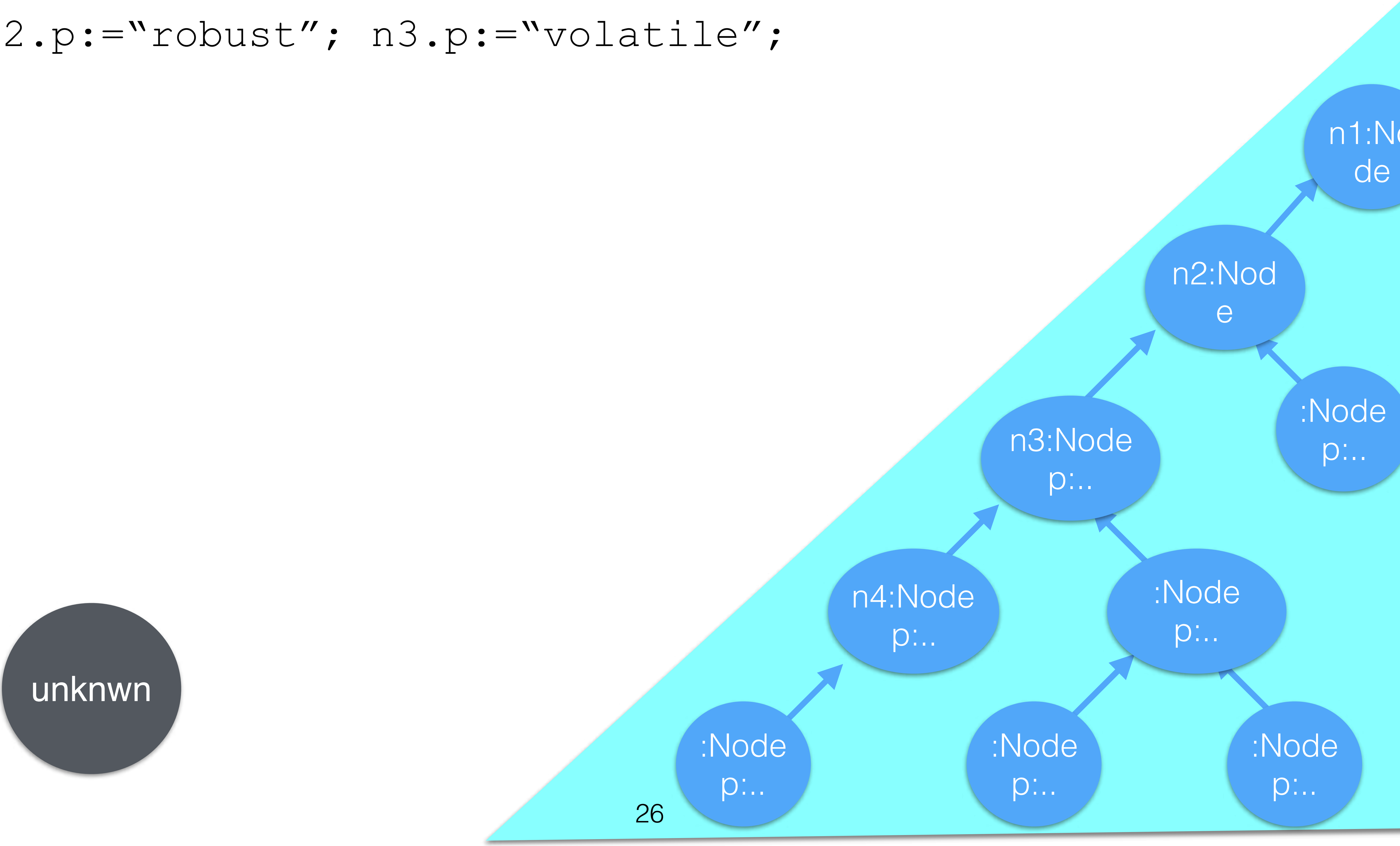


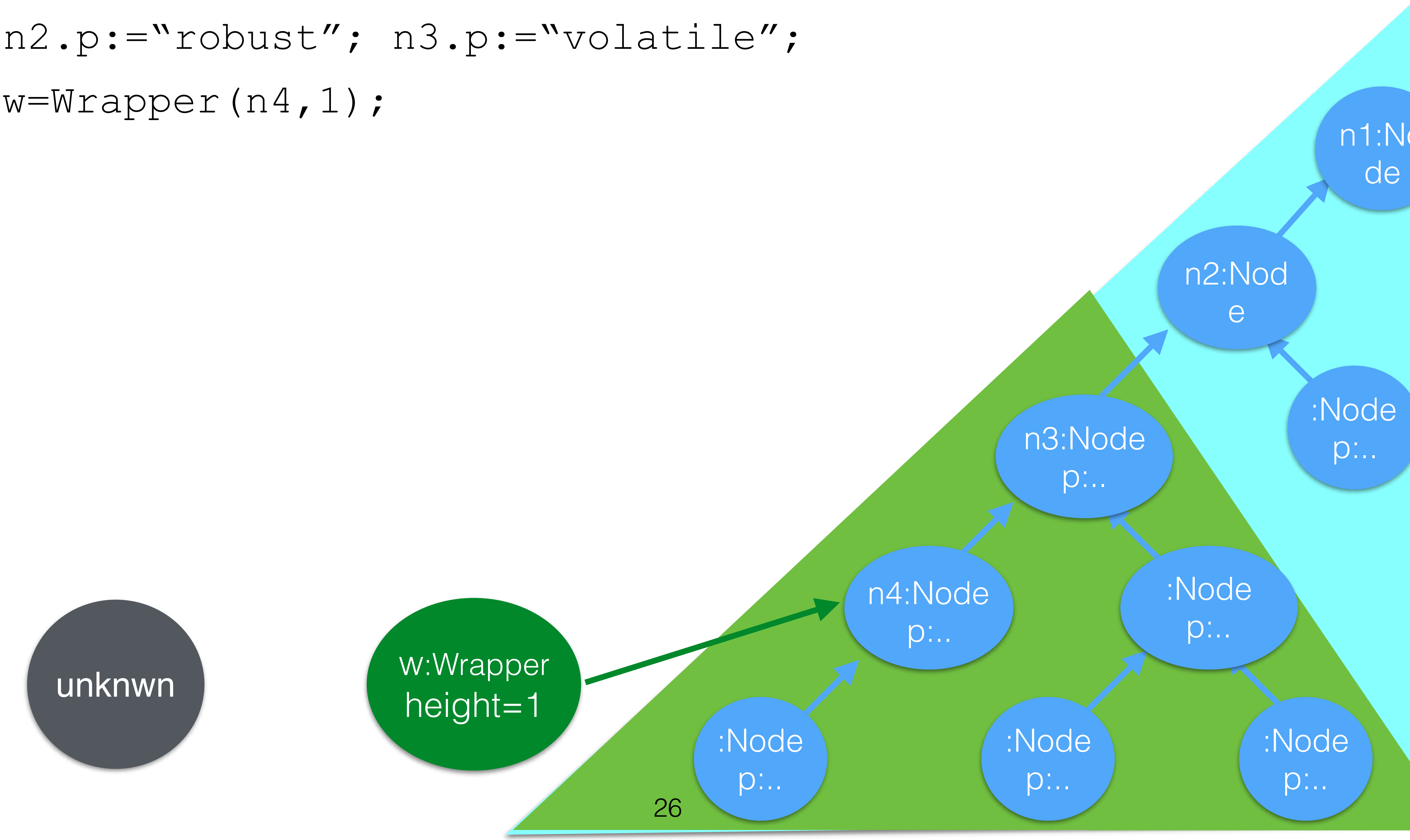
DOM attenuation

```
function mm(unknwn){
  n1:=Node(…); n2:=Node(n1,…);n3:=Node(n2,…);n4:=Node(n3,…);
  n2.p:=“robust”; n3.p:=“volatile”;
```



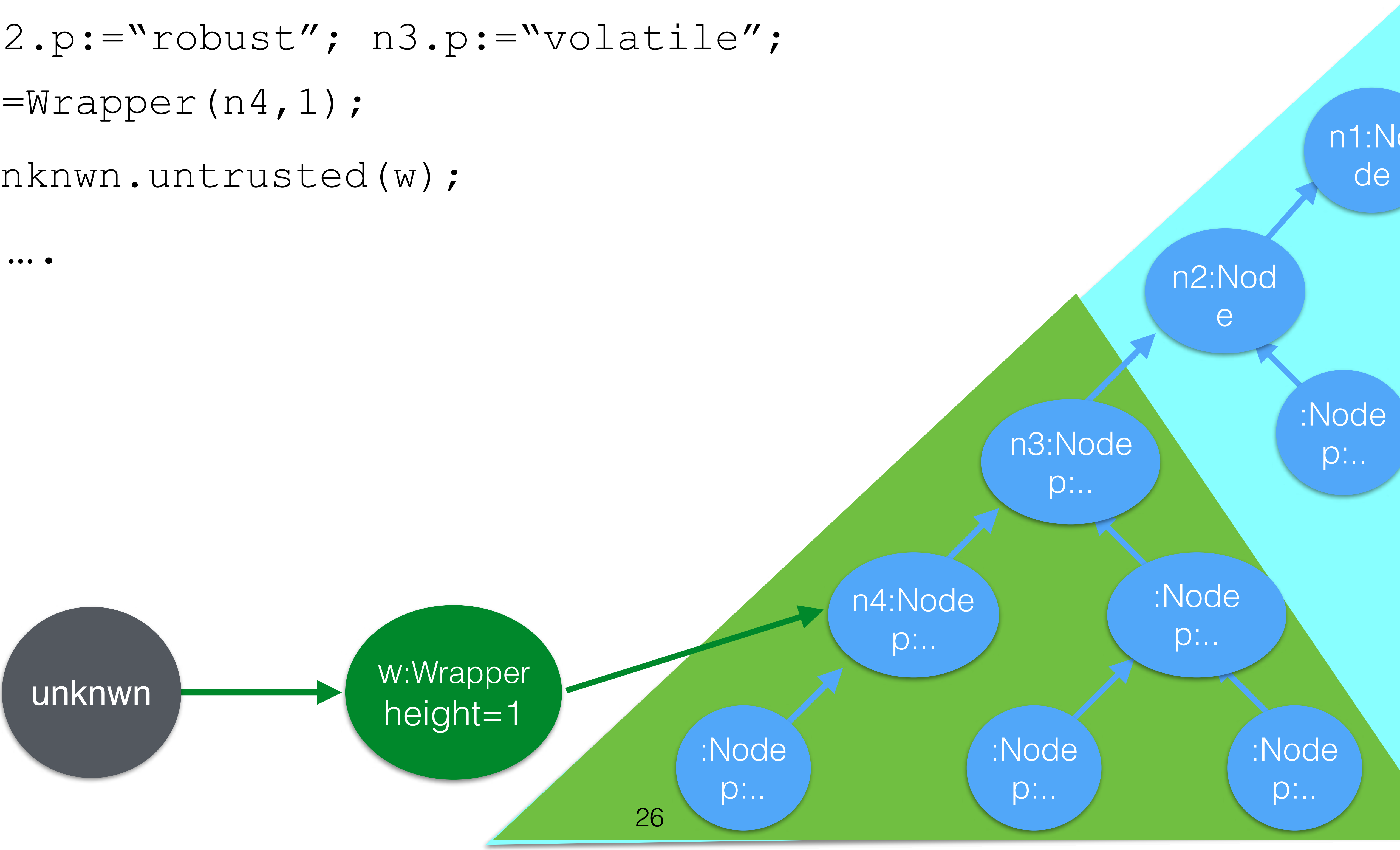
DOM attenuation

```
function mm(unknwn){
  n1:=Node(…); n2:=Node(n1,…);n3:=Node(n2,…);n4:=Node(n3,…);
  n2.p:=“robust”; n3.p:=“volatile”;
  w=Wrapper(n4,1);
```



DOM attenuation

```
function mm(unknwn){
  n1:=Node(…); n2:=Node(n1,…);n3:=Node(n2,…);n4:=Node(n3,…);
  n2.p:=“robust”; n3.p:=“volatile”;
  w=Wrapper(n4,1);
  unknwn.untrusted(w);
   ….
```



DOM attenuation

```
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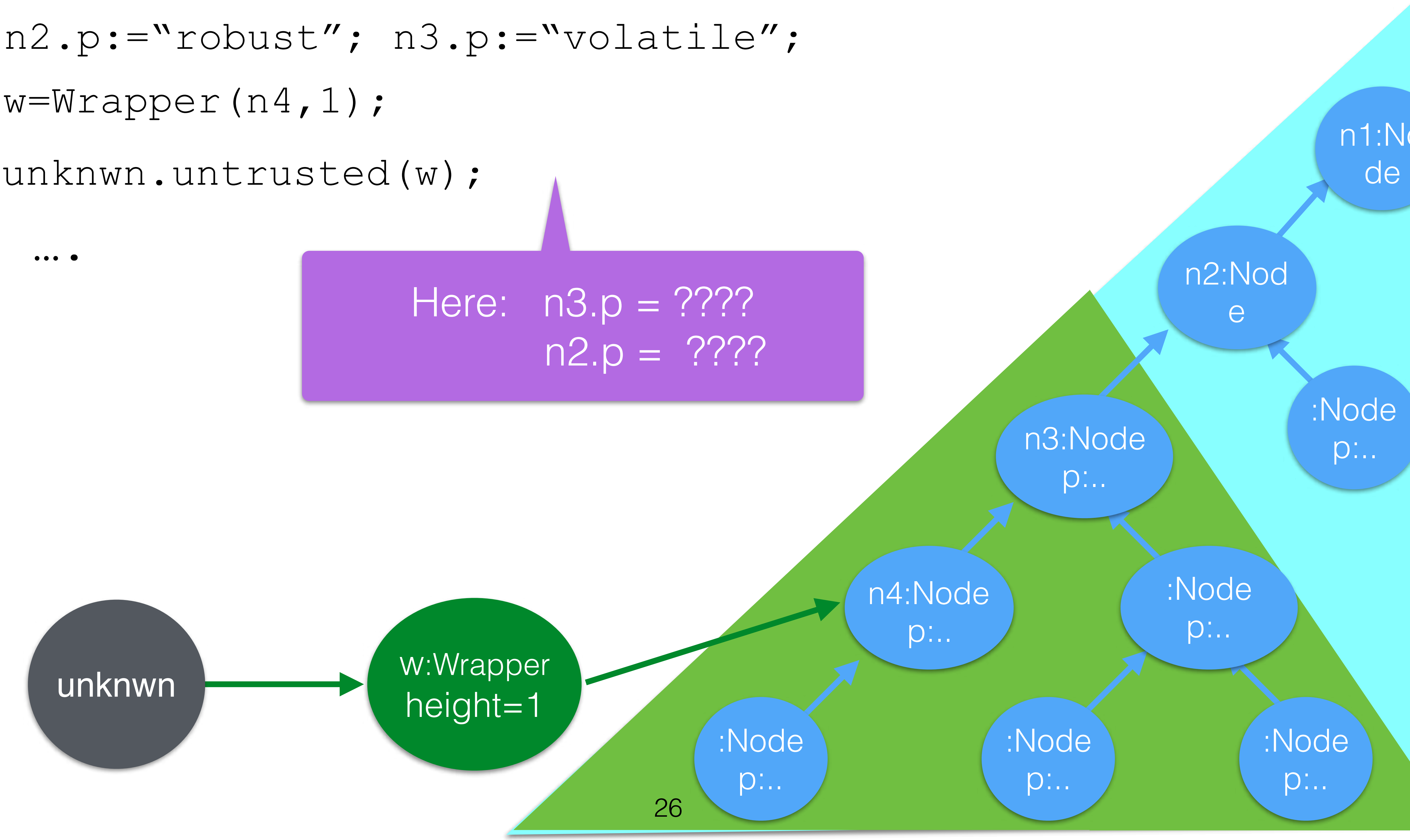
  n1:=Node(…); n2:=Node(n1,…);n3:=Node(n2,…);n4:=Node(n3,…);
  n2.p:=“robust”; n3.p:=“volatile”;
  w=Wrapper(n4,1);
  unknwn.untrusted(w);
   ….
```

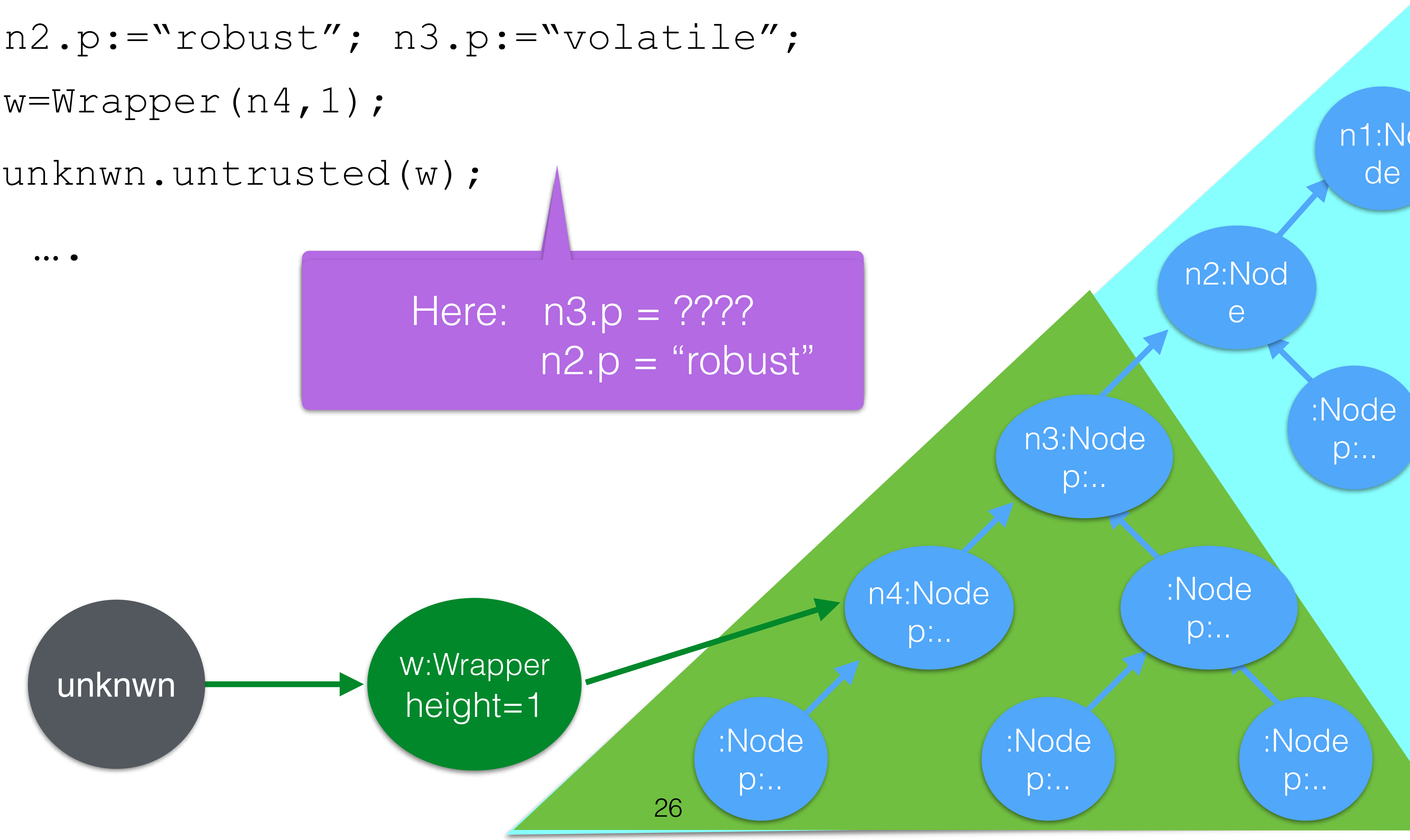
Here: n3.p = ????
n2.p = ????



DOM attenuation

```
function mm(unknwn){
  n1:=Node(…); n2:=Node(n1,…);n3:=Node(n2,…);n4:=Node(n3,…);
  n2.p:=“robust”; n3.p:=“volatile”;
  w=Wrapper(n4,1);
  unknwn.untrusted(w);
   ….
```

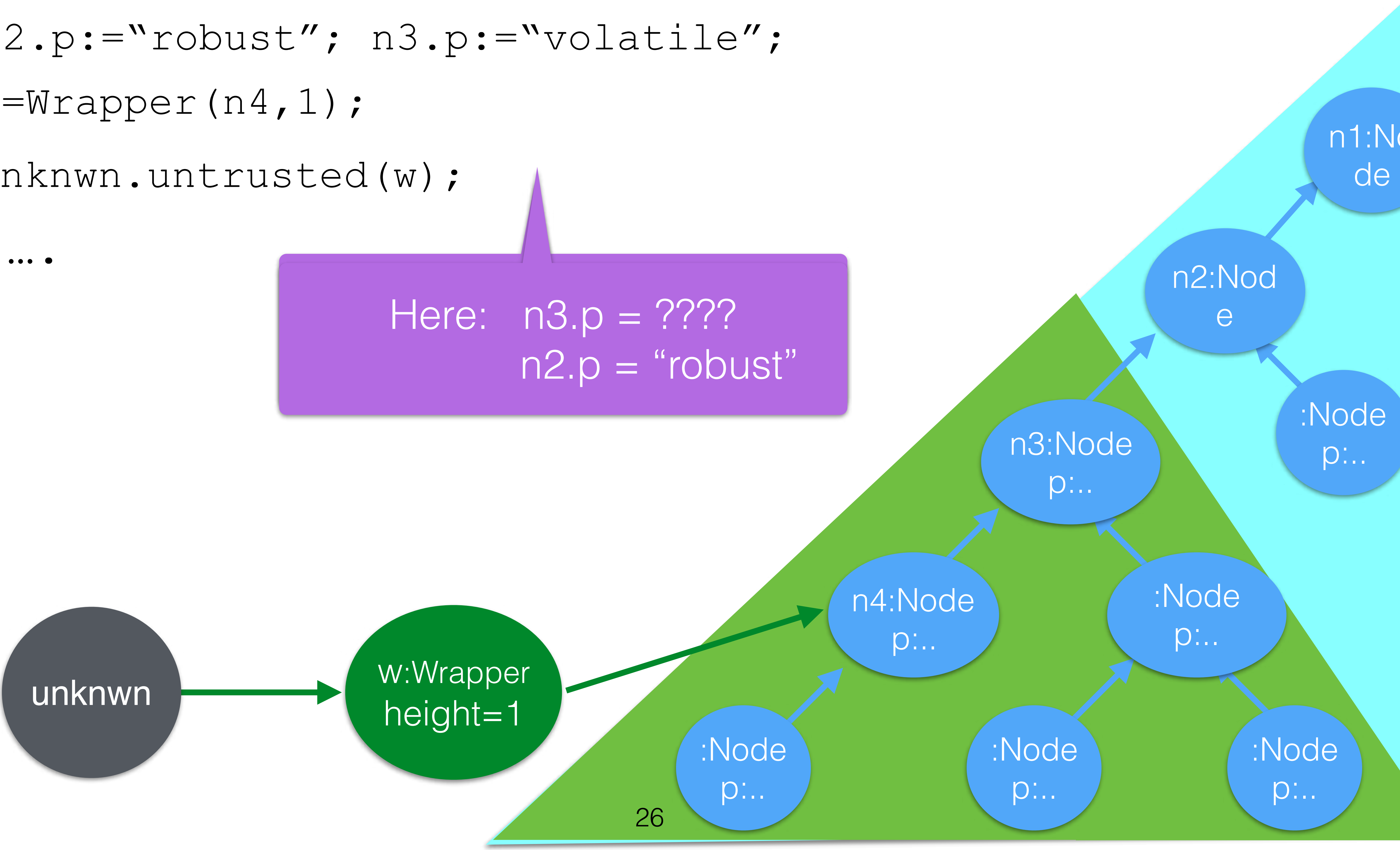
Here: n3.p = ????
n2.p = “robust”



DOM attenuation

```
function mm(unknwn){
  n1:=Node(…); n2:=Node(n1,…);n3:=Node(n2,…);n4:=Node(n3,…);
  n2.p:=“robust”; n3.p:=“volatile”;
  w=Wrapper(n4,1);
  unknwn.untrusted(w);
   ….
```

Here: n3.p = ????
n2.p = “robust”

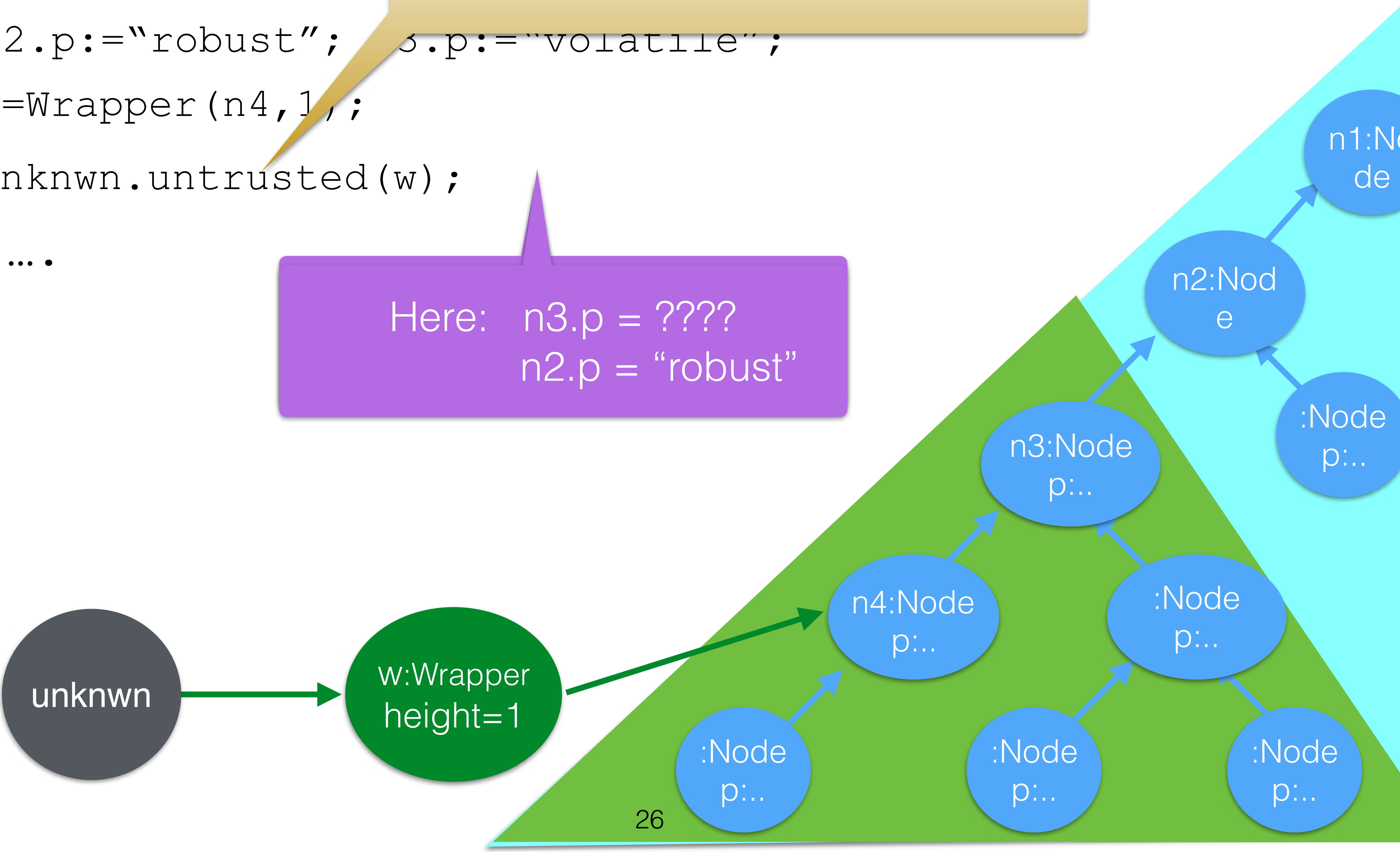


DOM attenuation

```
function mm(unknwn)
  n1:=Node(…); n2:=                                :=Node(n3,…);
  n2.p:=“robust”;  3.p:=“volatile”;
  w=Wrapper(n4,1);
  unknwn.untrusted(w);
   ….
```

open world

Here: n3.p = ????
       n2.p = “robust”



DOM attenuation

```
function mm(unknwn){
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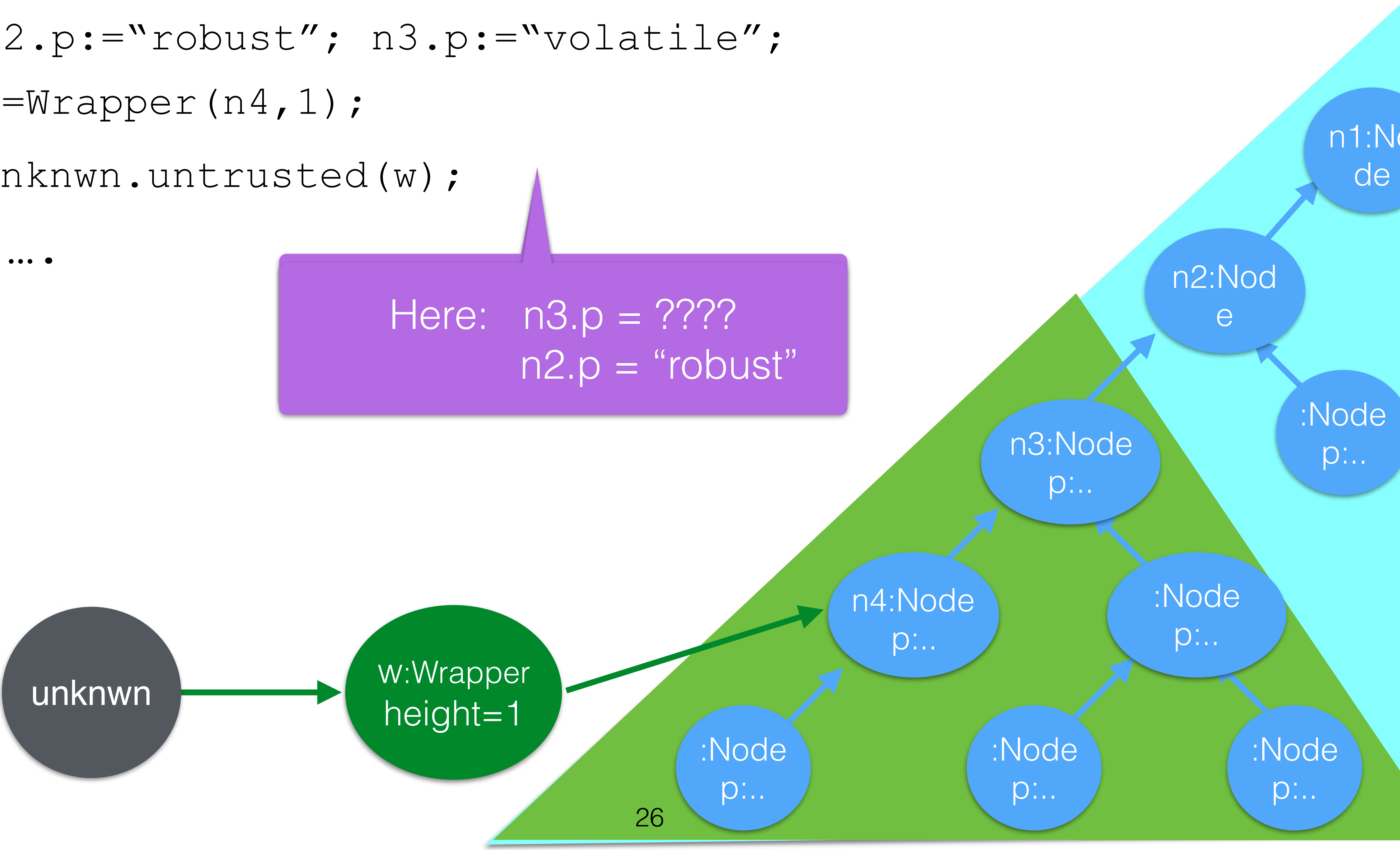
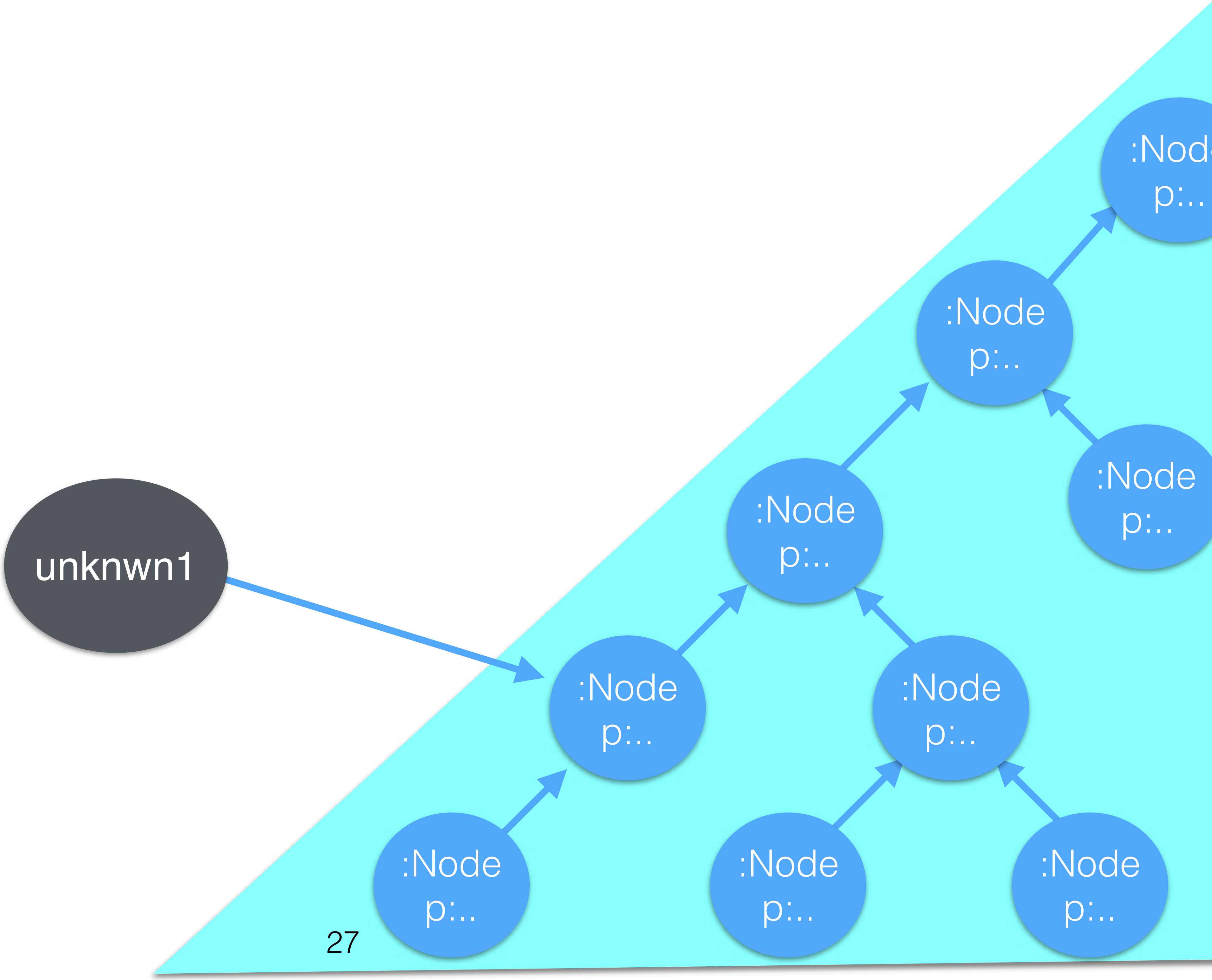
  n2.p:=“robust”; n3.p:=“volatile”;
  w=Wrapper(n4,1);
  unknwn.untrusted(w);
   ….
```

Here: n3.p = ????
n2.p = “robust”



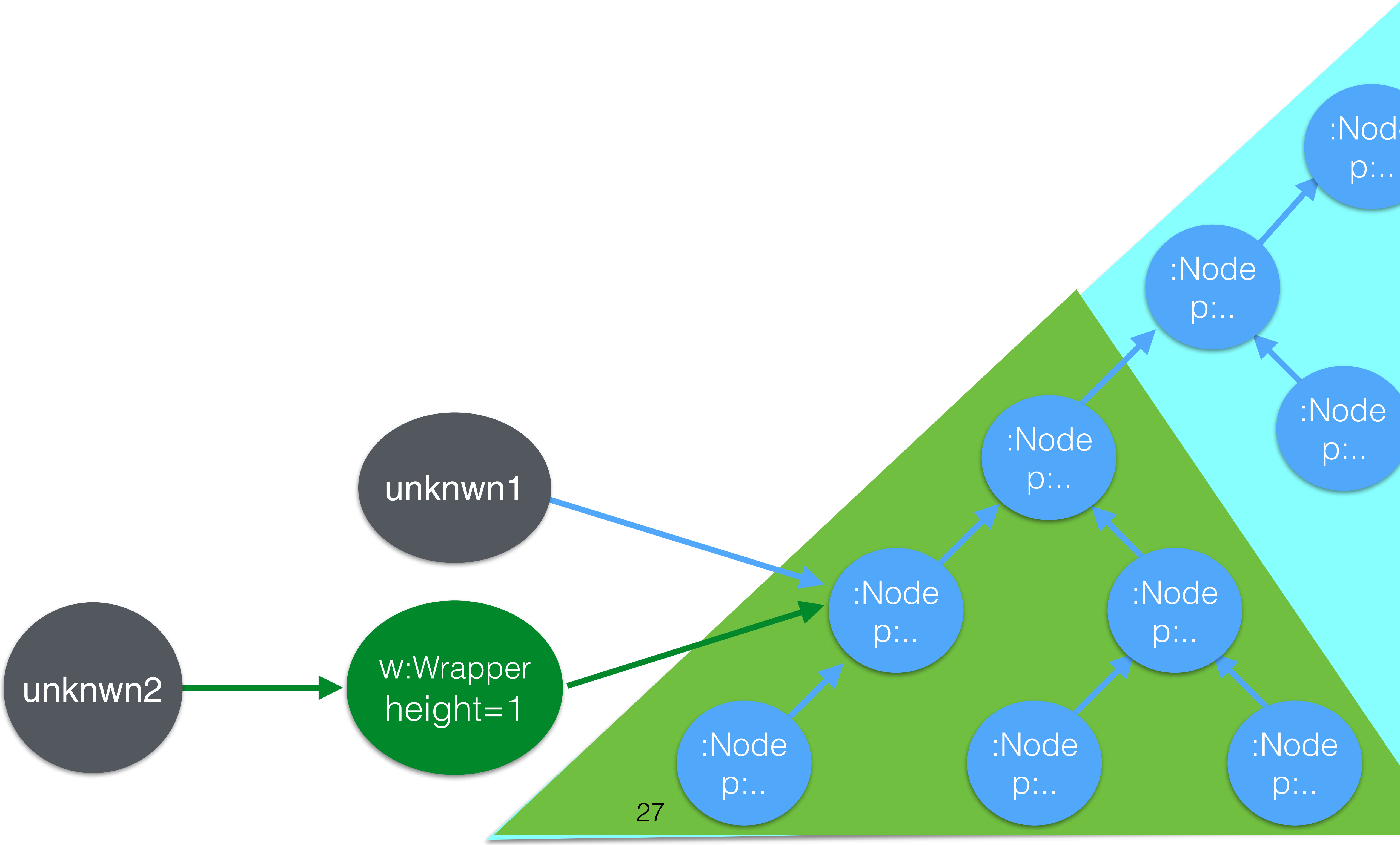
classical

Access to Wrapper `w` allows modification of `Node`s under the `w.height`-th parent and nothing else



classical

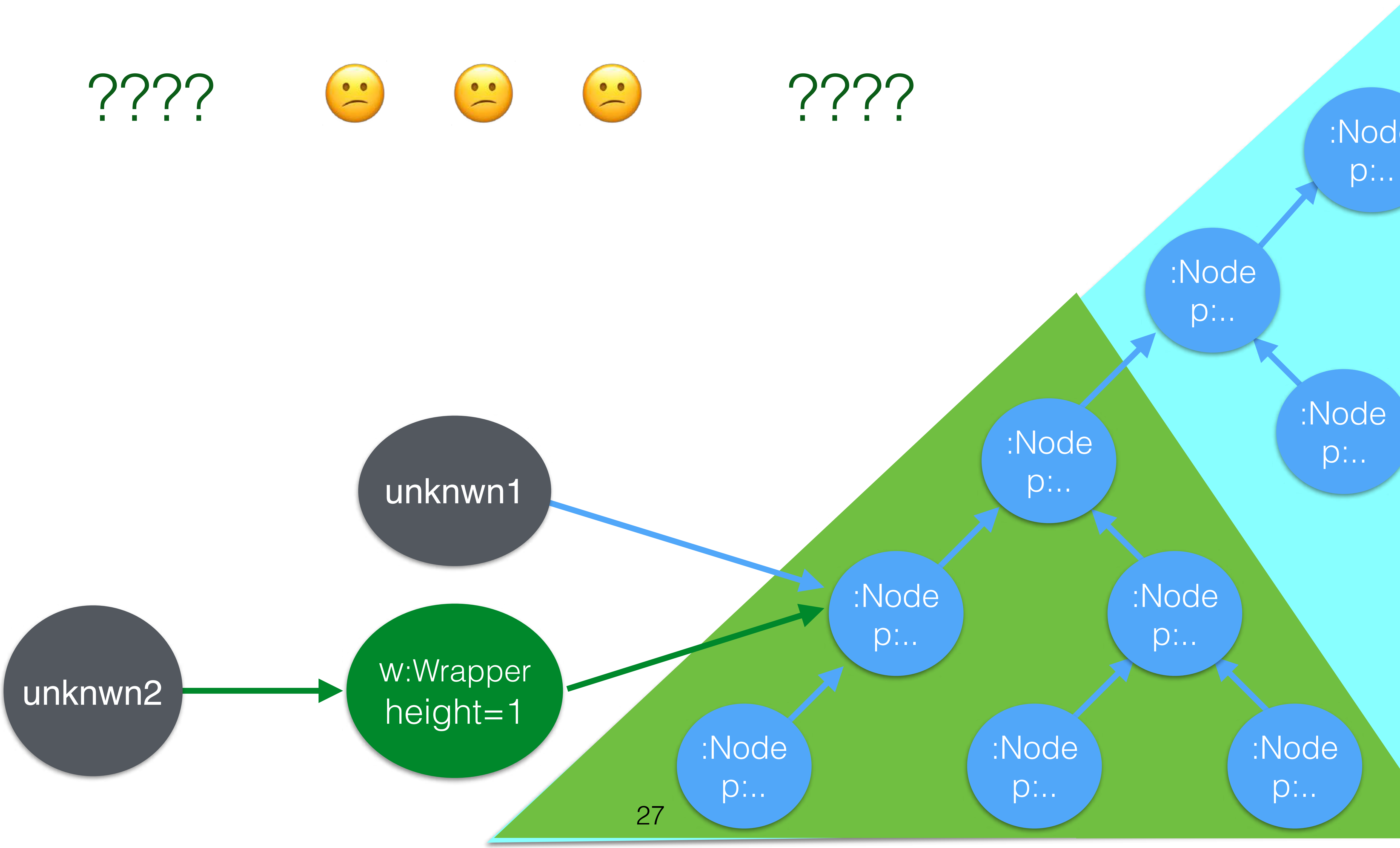
Access to Wrapper `w` allows modification of `Node`s under the `w.height`-th parent and nothing else



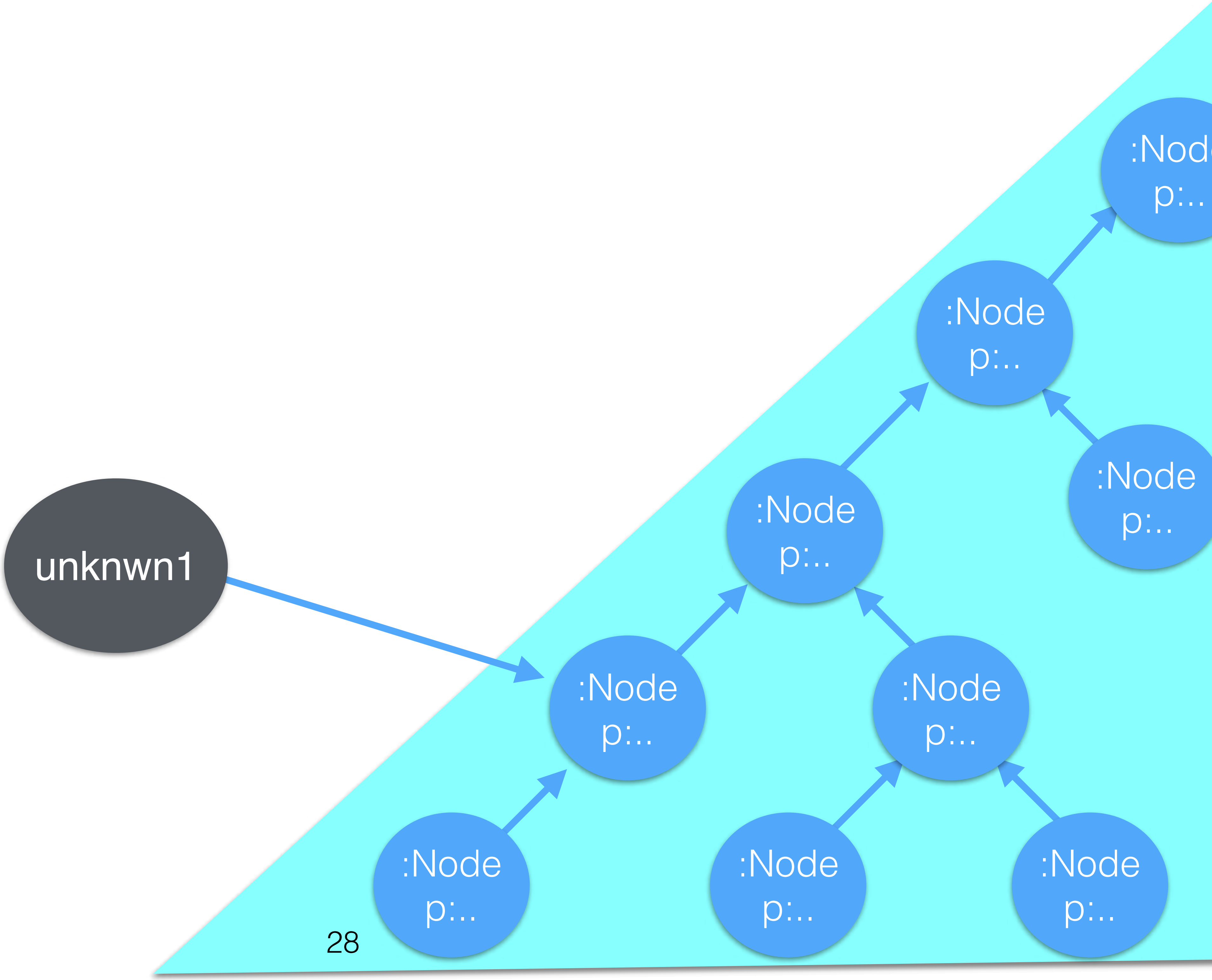
classical

Access to Wrapper `w` allows modification of `Node`s under the `w.height`-th parent and nothing else

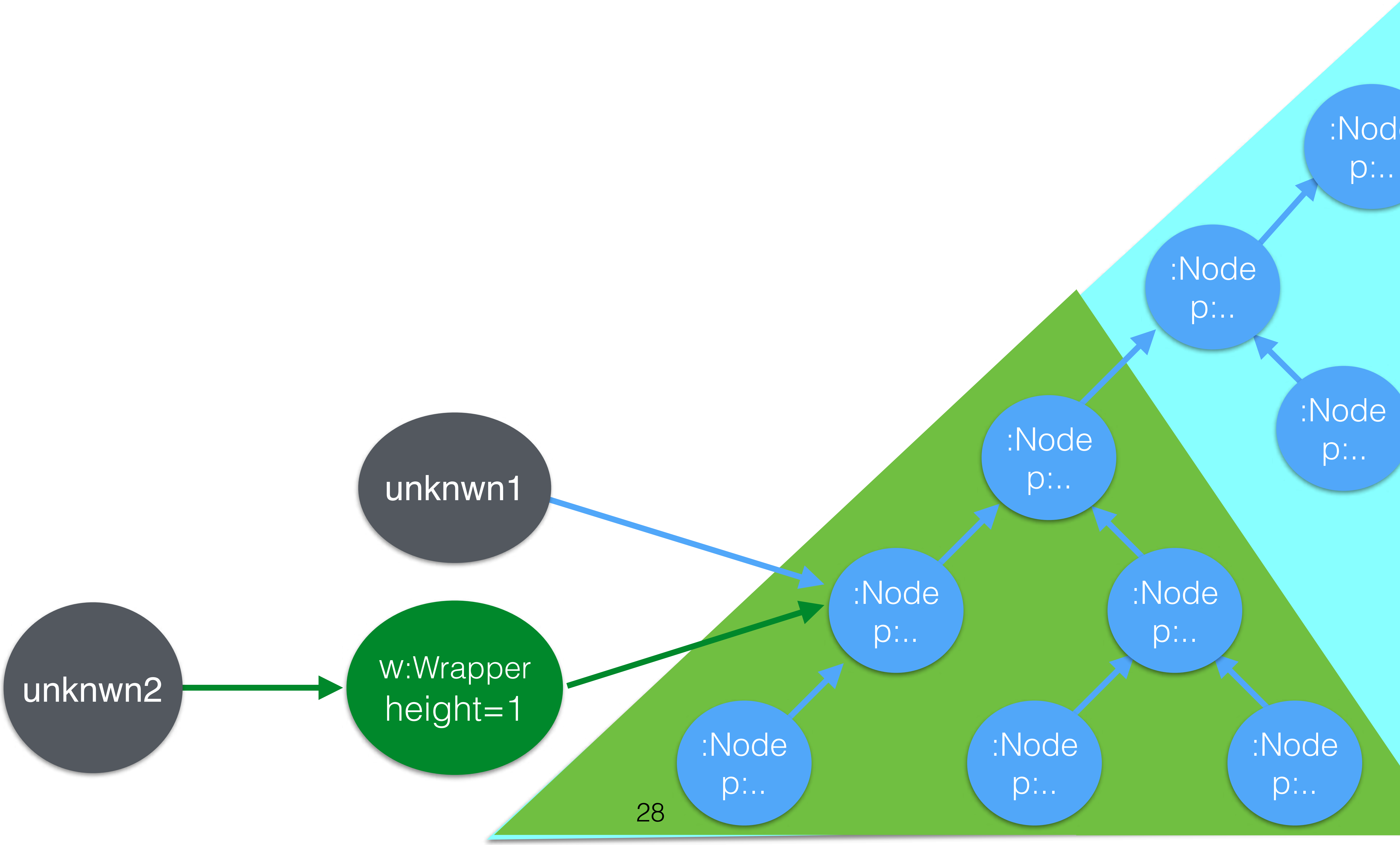
???? 😕 😕 😕 ????



holistic


unknwn1
:Node
p:..
:Node
p:..
:Node
p:..
:Node
p:..
:Node
p:..
:Node
p:..
:Node
p:..
:Node
p:..
:Node
p:..

holistic


:Nod
p:..
:Node
p:..
:Node
p:..
:Node
p:..
unknwn1
:Node
p:..
:Node
p:..
unknwn2
w:Wrapper
height=1
:Node
p:..
:Node
p:..
:Node
p:..

holistic

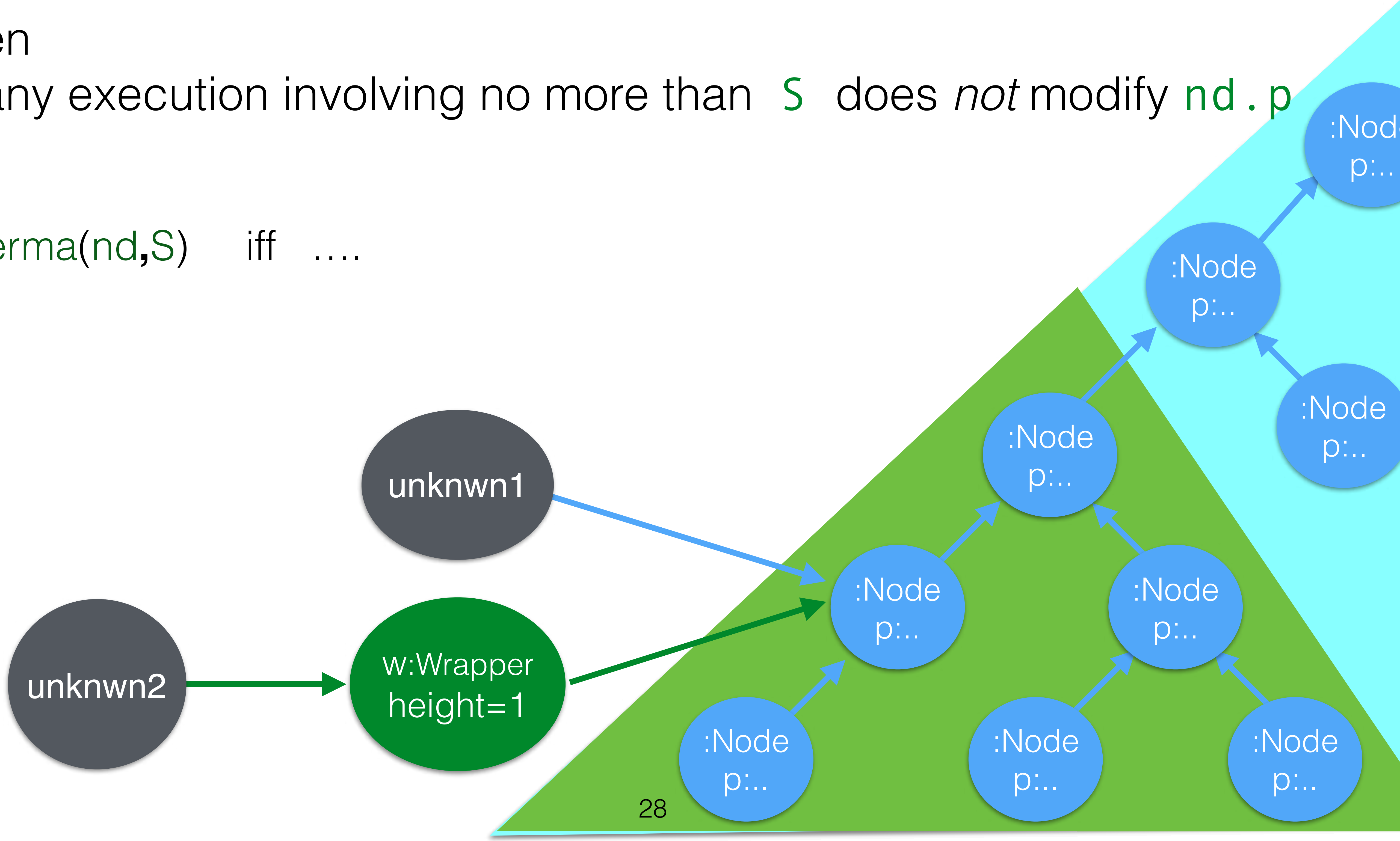
If

a node `nd` is external to a set `S`

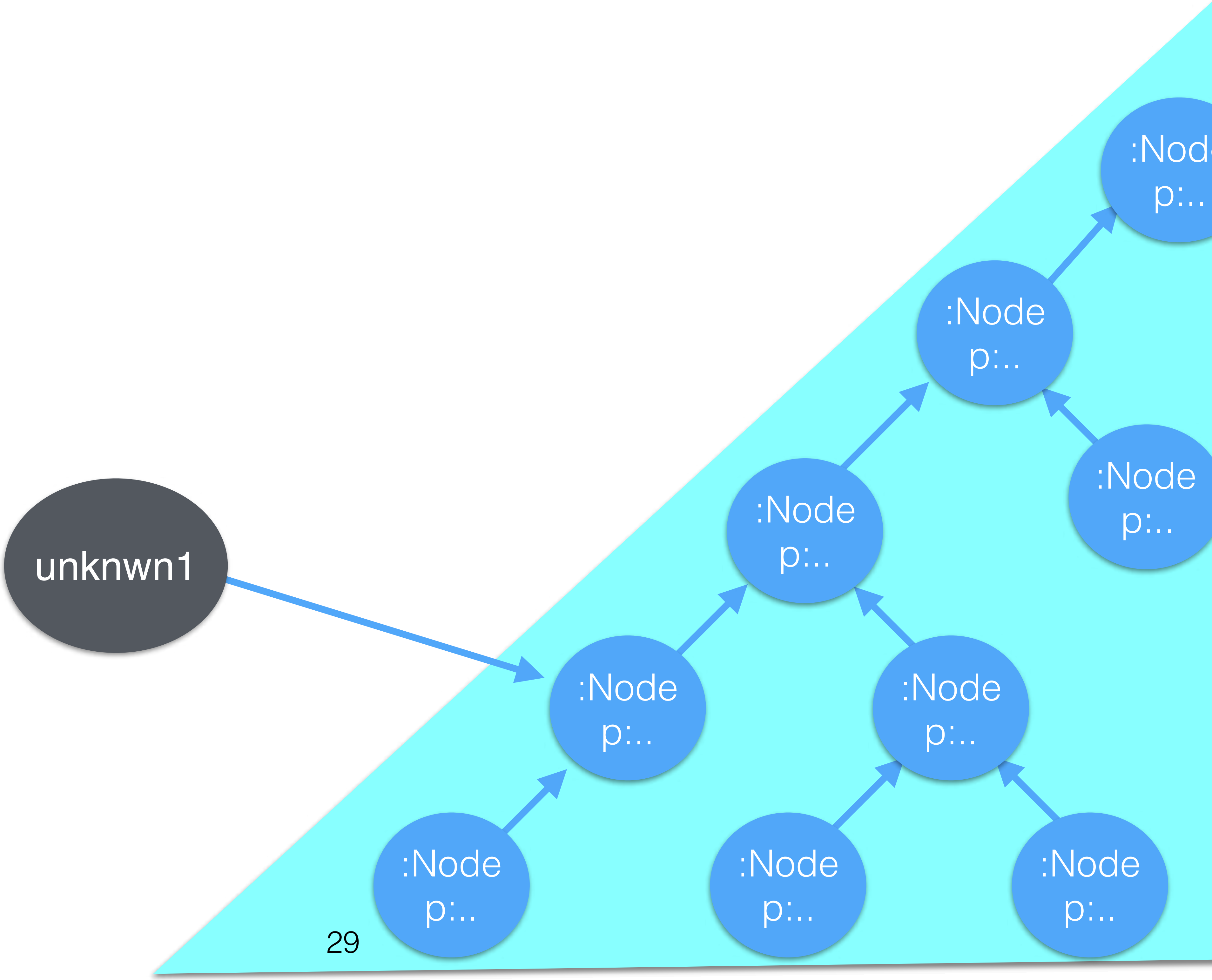
then

any execution involving no more than `S` does *not* modify `nd.p`

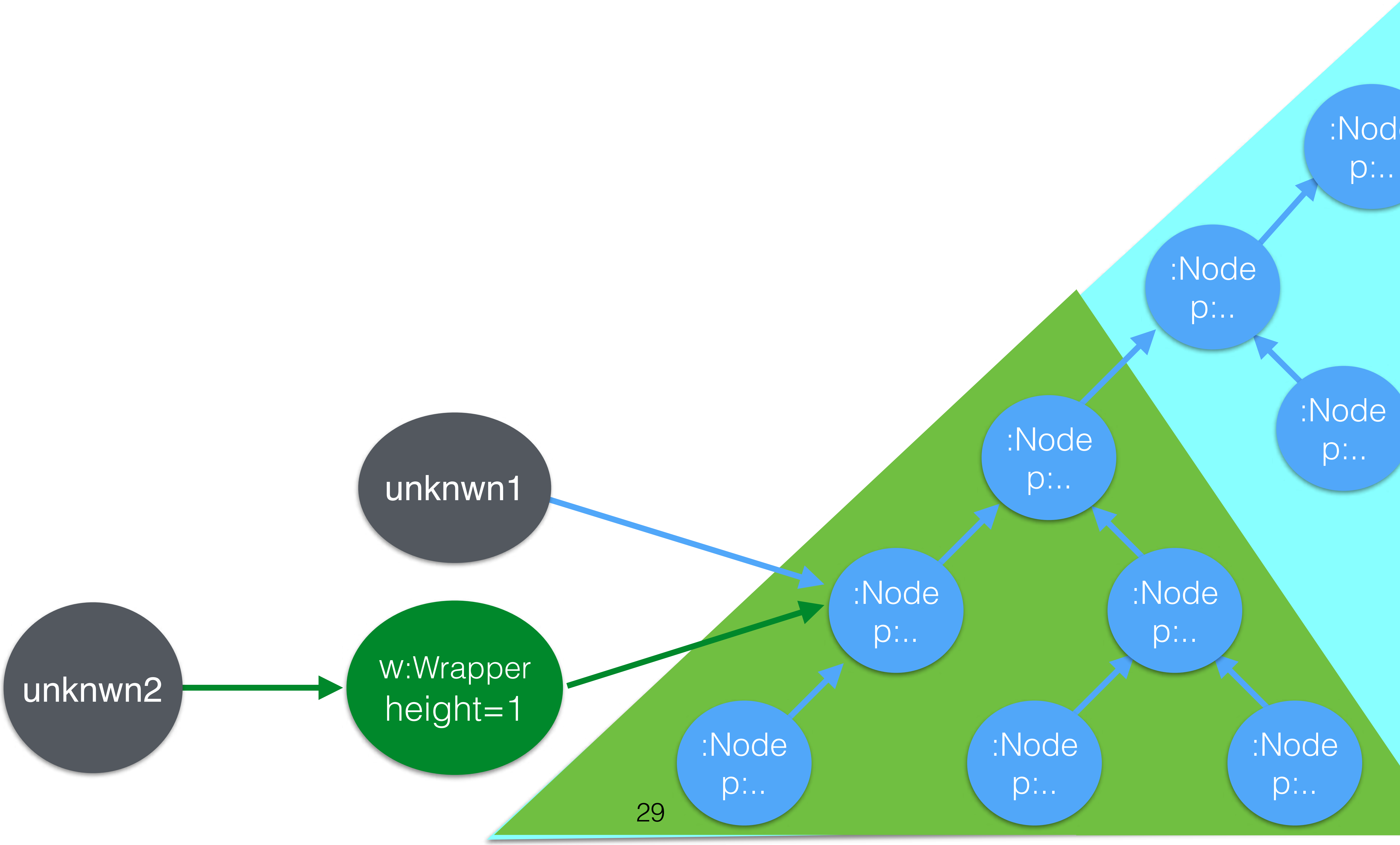
Exterma(nd**,**S) iff ….



holistic


unknwn1
:Node p:..
:Node p:..
:Node p:..
:Node p:..
:Node p:..
:Node p:..
:Node p:..
:Node p:..
:Node p:..

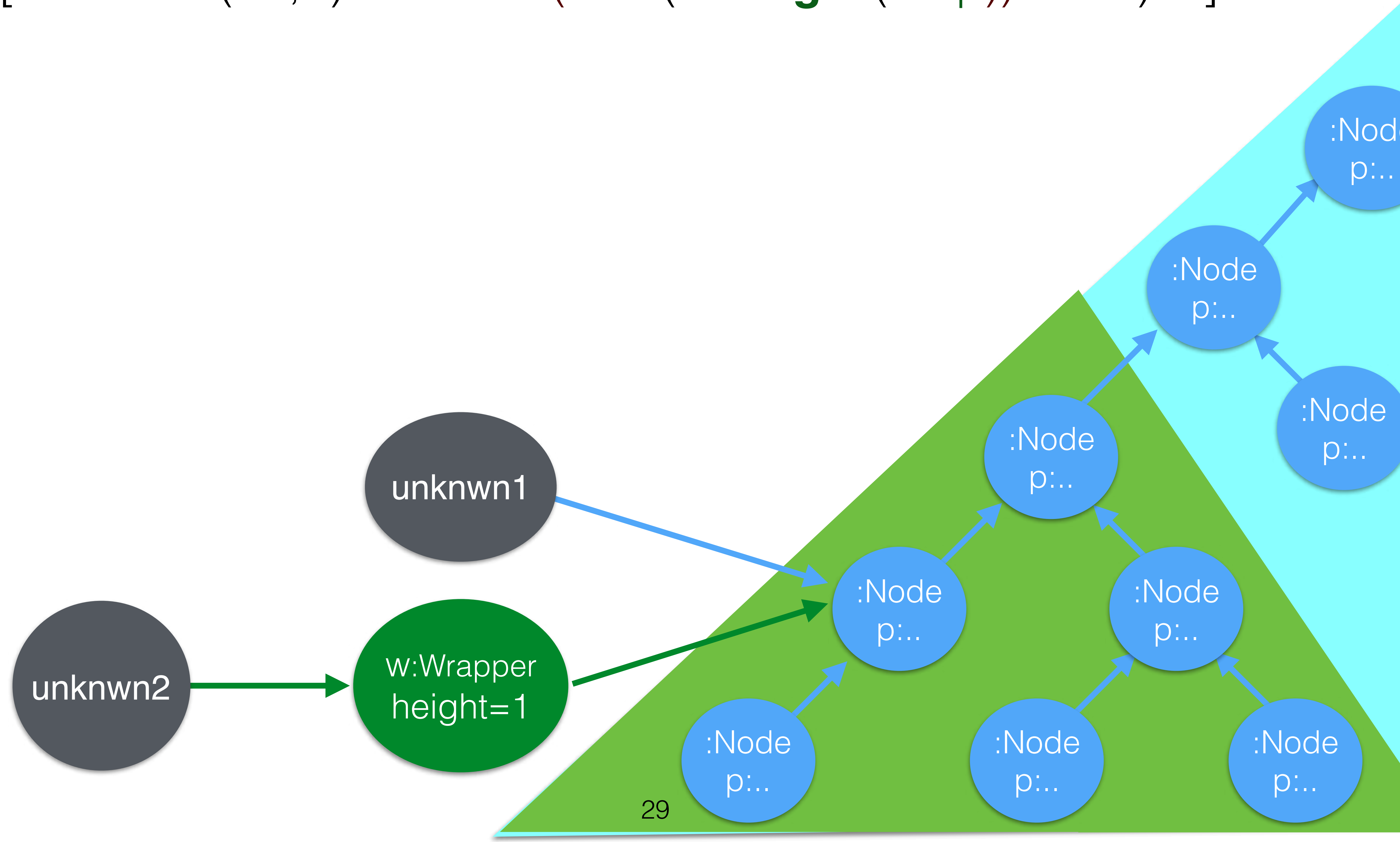
holistic


:Nod
p:..
:Node
p:..
:Node
p:..
:Node
p:..
unknwn1
:Node
p:..
:Node
p:..
unknwn2
w:Wrapper
height=1
:Node
p:..
:Node
p:..
:Node
p:..

holistic

∀S:Set. ∀nd:Node.

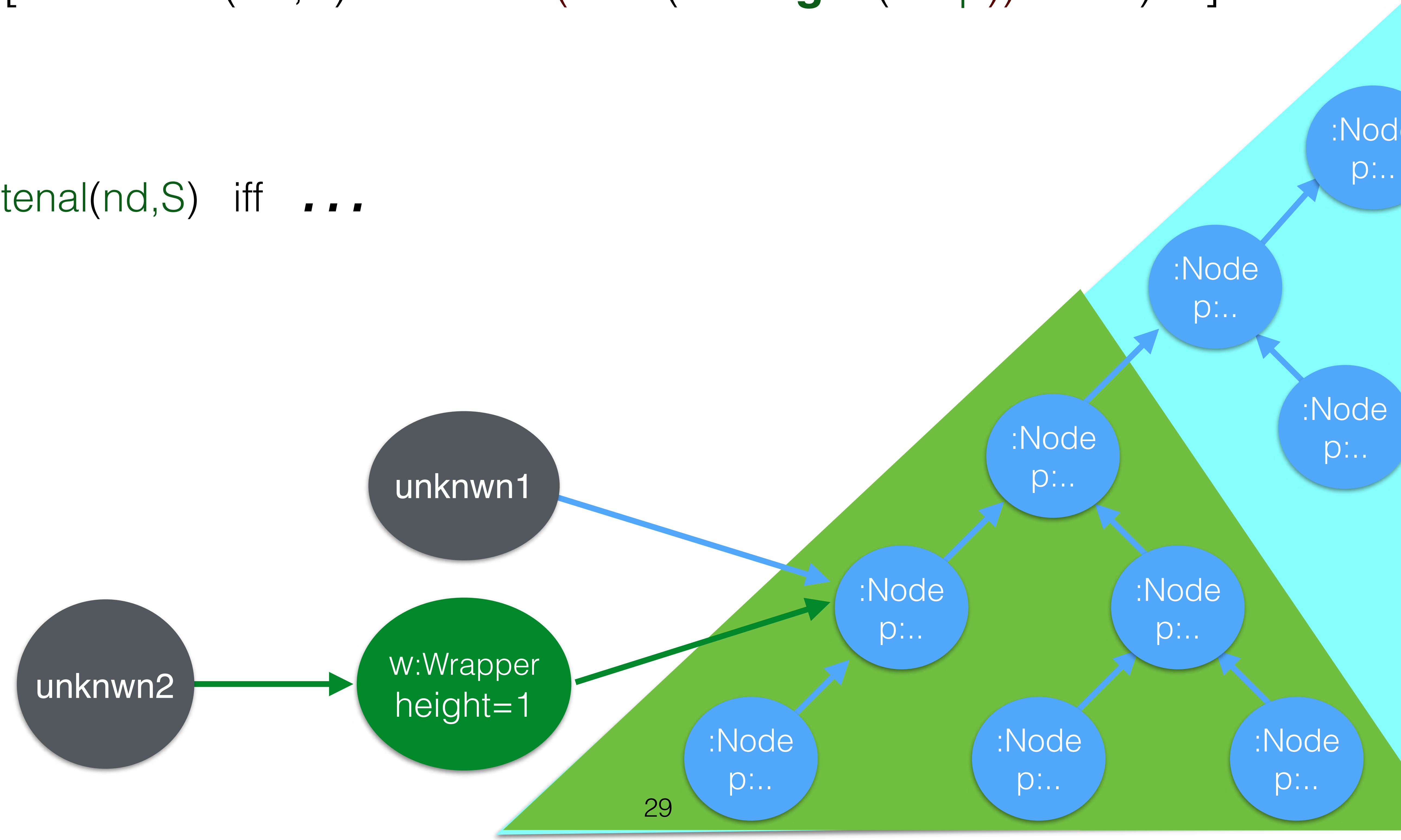
[Extenal(nd,S) → ¬ (**Will**(**Changes**(nd.p)) **in** S)]



holistic

∀S:Set. ∀nd:Node.
[Extenal(nd,S) → ¬ (**Will**(**Changes**(nd.p)) **in** S)]

Extenal(nd,S) iff **. . .**



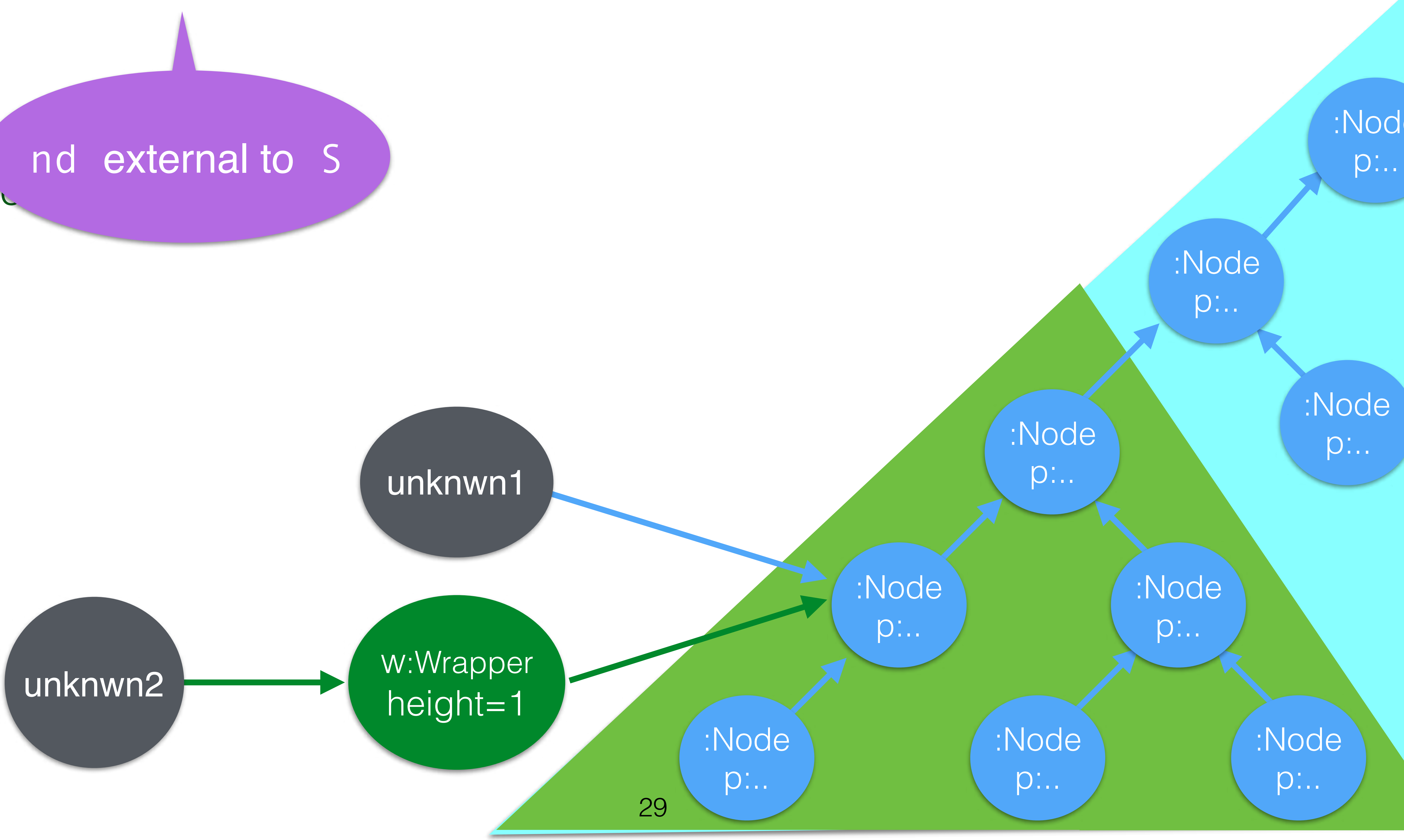
holistic

$\forall$S:Set. $\forall$nd:Node.

[Extenal(nd,S) → ¬ (**Will**(**Changes**(nd.p)) **in** S)]

nd external to S

Ext



holistic

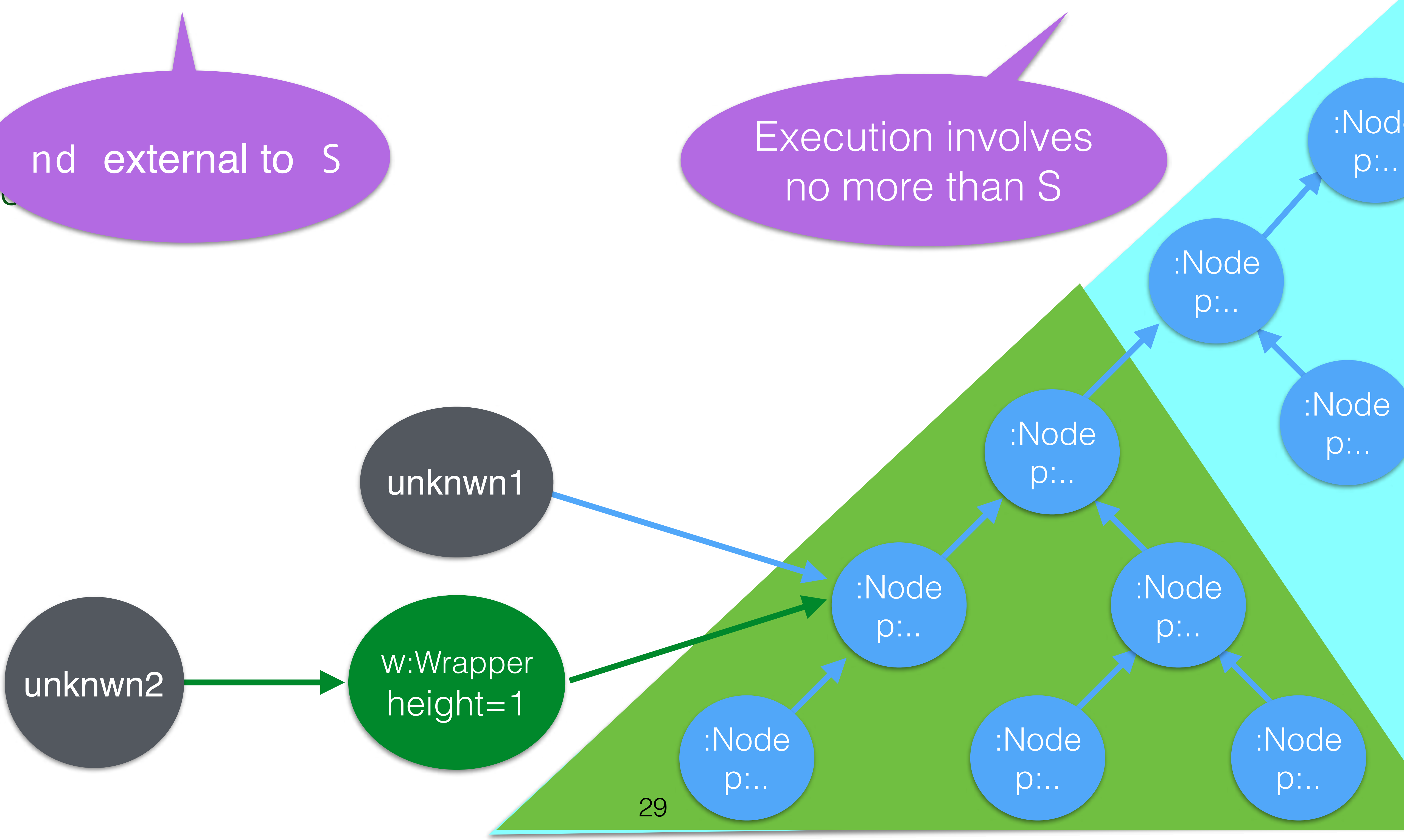
∀S:Set. ∀nd:Node.

[Extenal(nd,S) → ¬ (**Will**(**Changes**(nd.p)) **in** S)]

nd external to S

Execution involves no more than S

Ext



holistic

∀S:Set. ∀nd:Node.

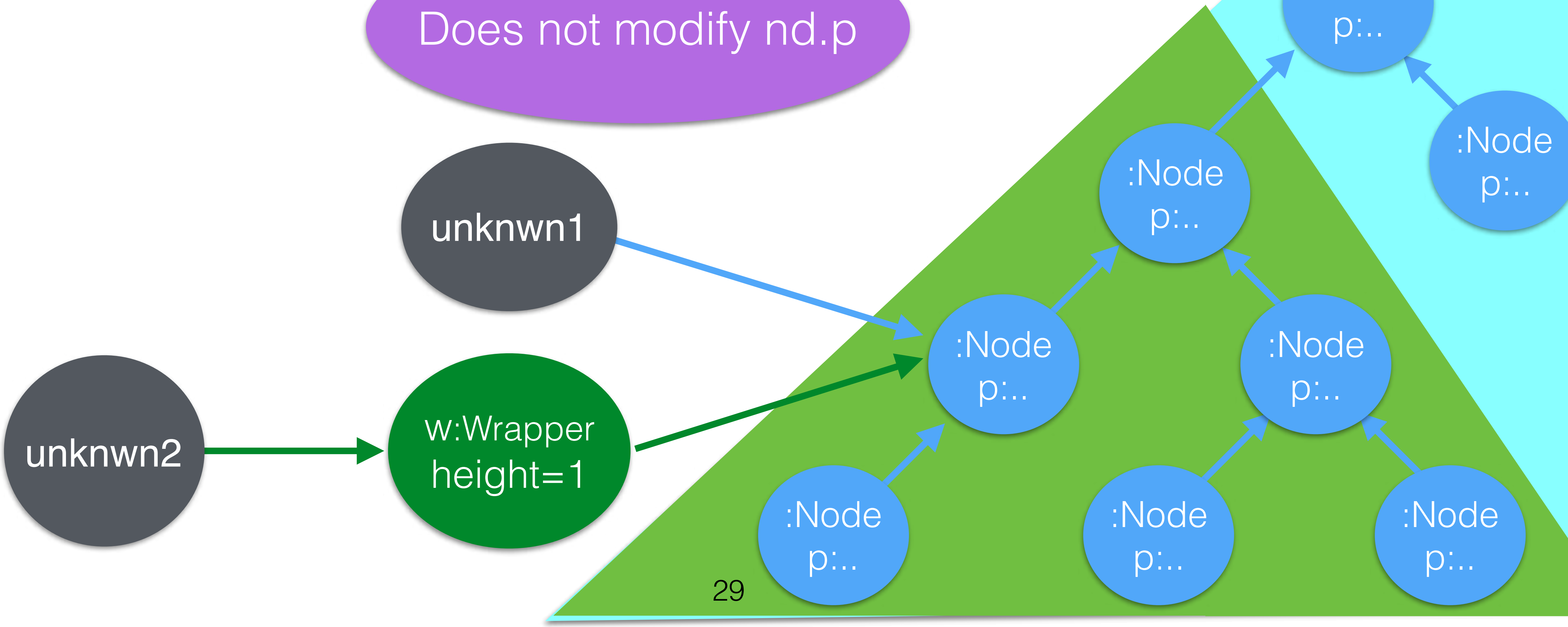
[Extenal(nd,S) → ¬ (**Will**(**Changes**(nd.p)) **in** S)]

nd external to S

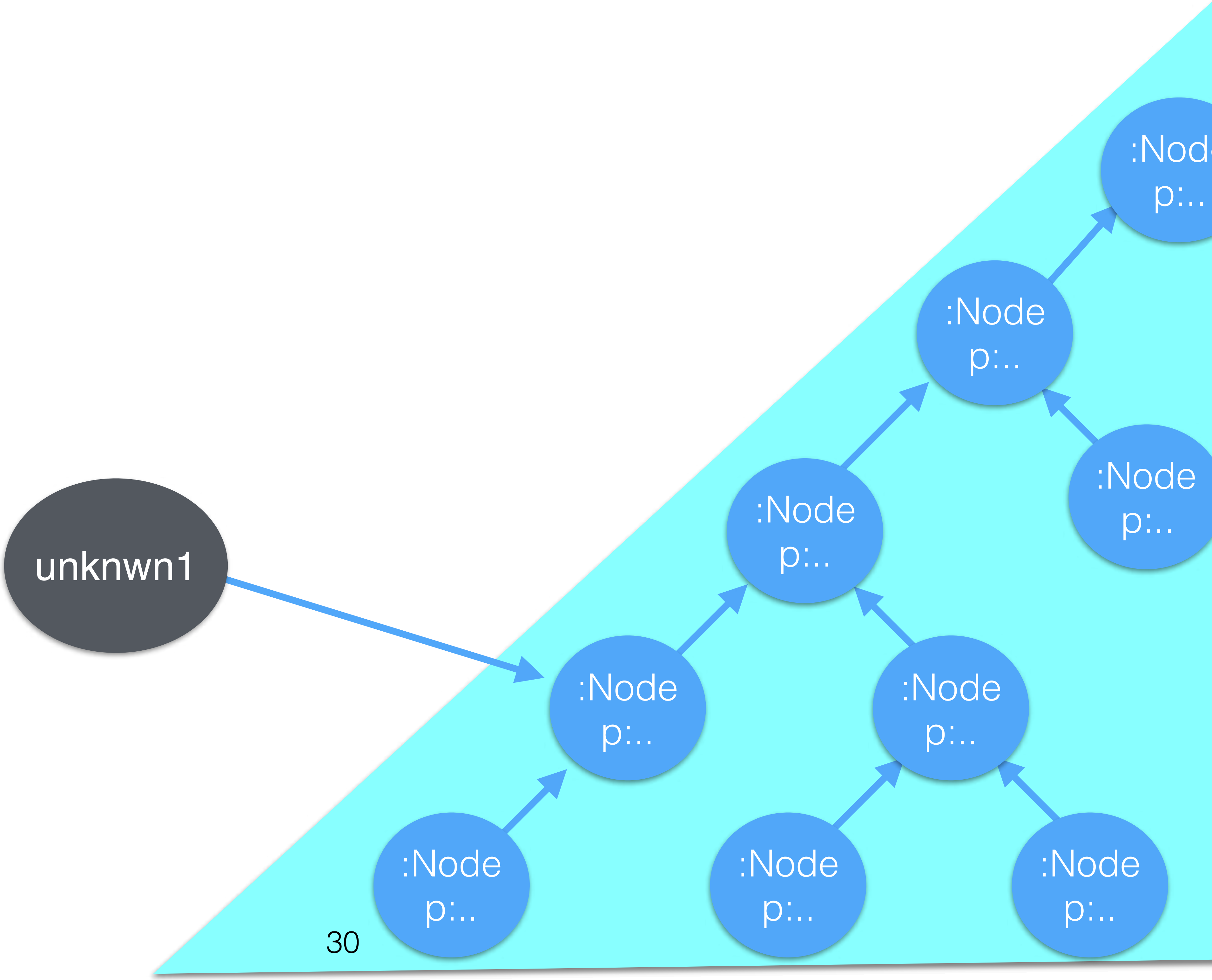
Execution involves no more than S

Ext

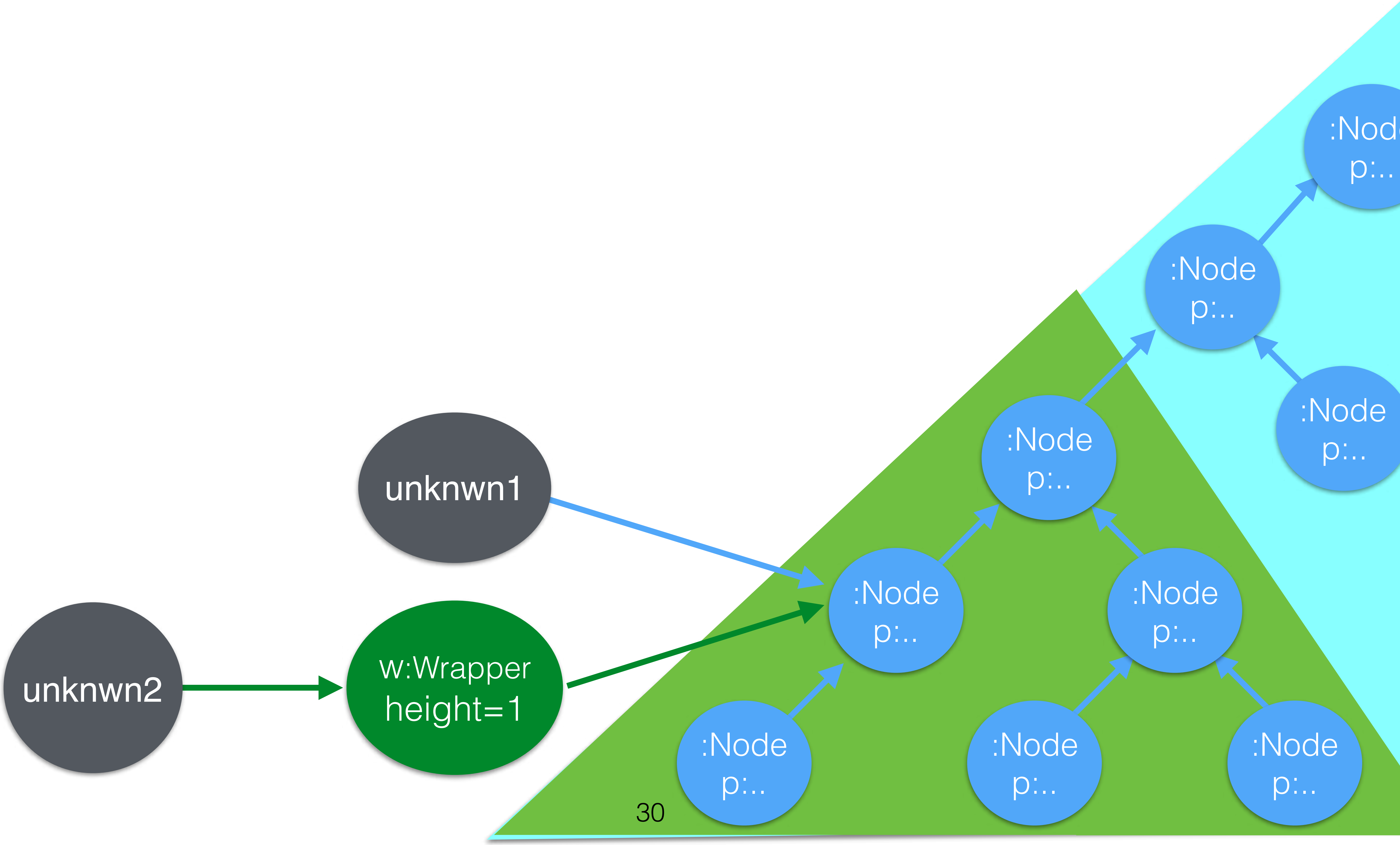
Does not modify nd.p



holistic


unknwn1
:Node
p:..
:Node
p:..
:Node
p:..
:Node
p:..
:Node
p:..
:Node
p:..
:Node
p:..
:Node
p:..
:Nod
p:..

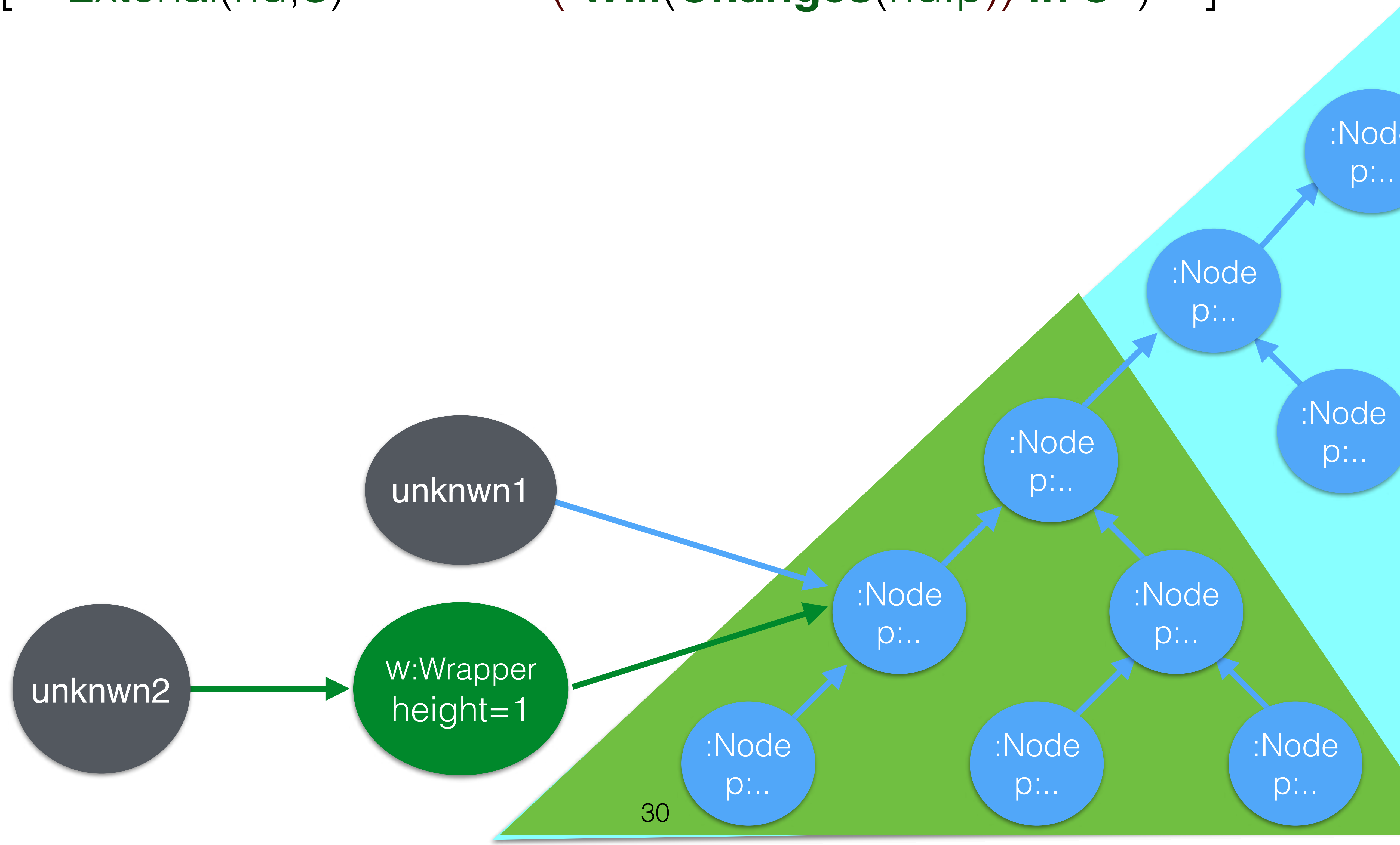
holistic


:Nod
p:..
:Node
p:..
:Node
p:..
:Node
p:..
unknwn1
:Node
p:..
:Node
p:..
unknwn2
w:Wrapper
height=1
:Node
p:..
:Node
p:..
:Node
p:..

holistic

∀S:Set. ∀nd:Node.

[Extenal(nd,S) → ¬ (**Will**(**Changes**(nd.p)) **in** S)]

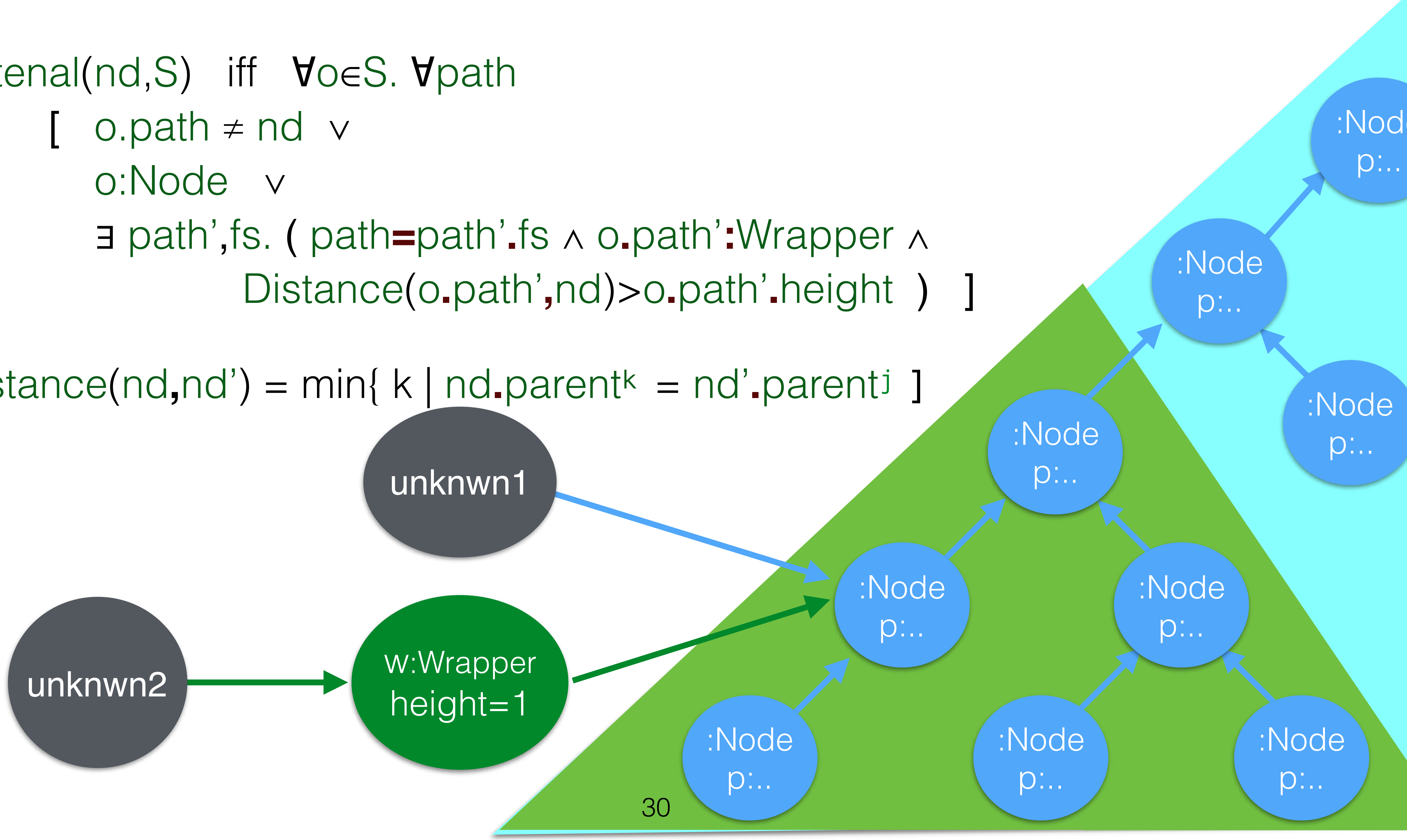


holistic

∀S:Set. ∀nd:Node.
[Extenal(nd,S) → ¬ (**Will**(**Changes**(nd.p)) **in** S)]

Extenal(nd,S) iff ∀o∊S. ∀path
[o.path ≠ nd ∨
o:Node ∨
∃ path’,fs. (path=path’.fs ∧ o.path’:Wrapper ∧
Distance(o.path’,nd)>o.path’.height)]

Distance(nd,nd’) = min{ k | nd.parent^k = nd’.parent^j]



external

Extenal(nd,S)   iff   ∀o∈S. ∀path

[o.path ≠ nd ∨

o:Node   ∨

∃ path',fs. (path=path'.fs ∧ o.path':Wrapper ∧

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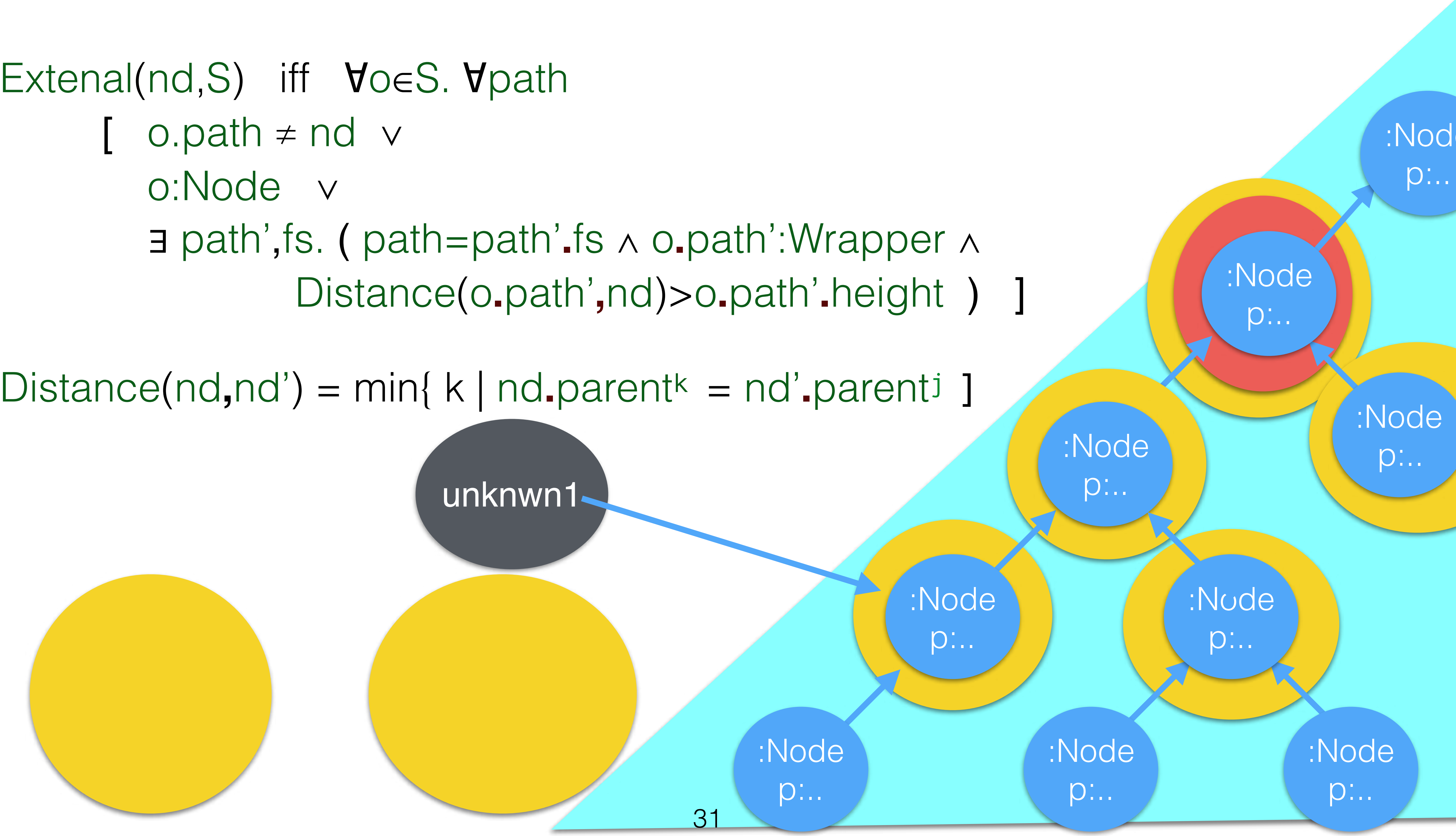

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Extenal(nd,S) iff $\forall o \in S.\ \forall path$

$[\ o.path \neq nd\ \vee$

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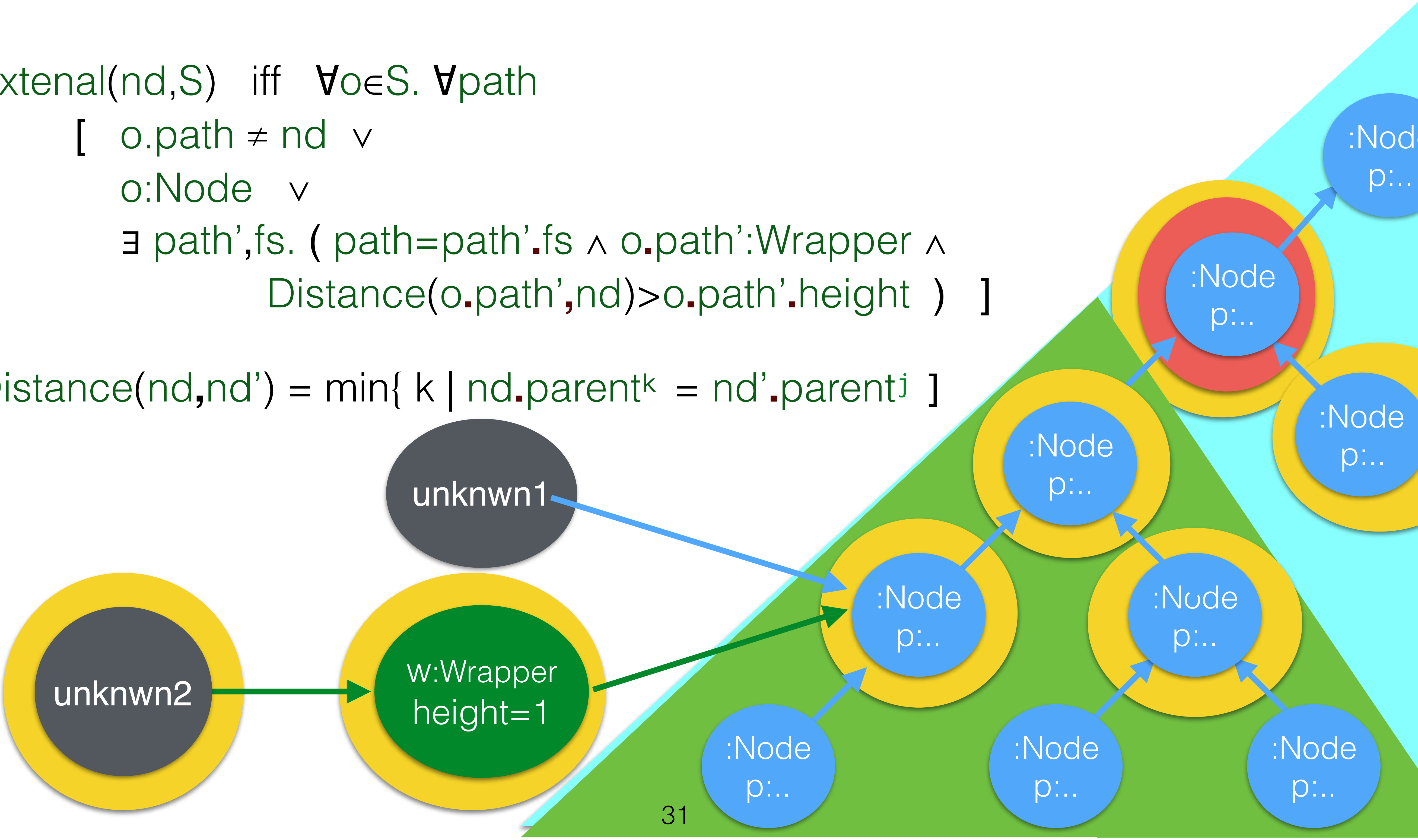

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Extenal(**RedNode**, **YellowSet**)

$\text{Extenal}(nd,S) \quad \text{iff} \quad \forall o \in S.\ \forall path$

$\quad [\quad o.path \neq nd \quad \vee$

$\quad\quad o{:}\text{Node} \quad \vee$

$\quad\quad \exists\ path',fs.\ (\ path = path'.fs \wedge o.path'{:}\text{Wrapper} \wedge$

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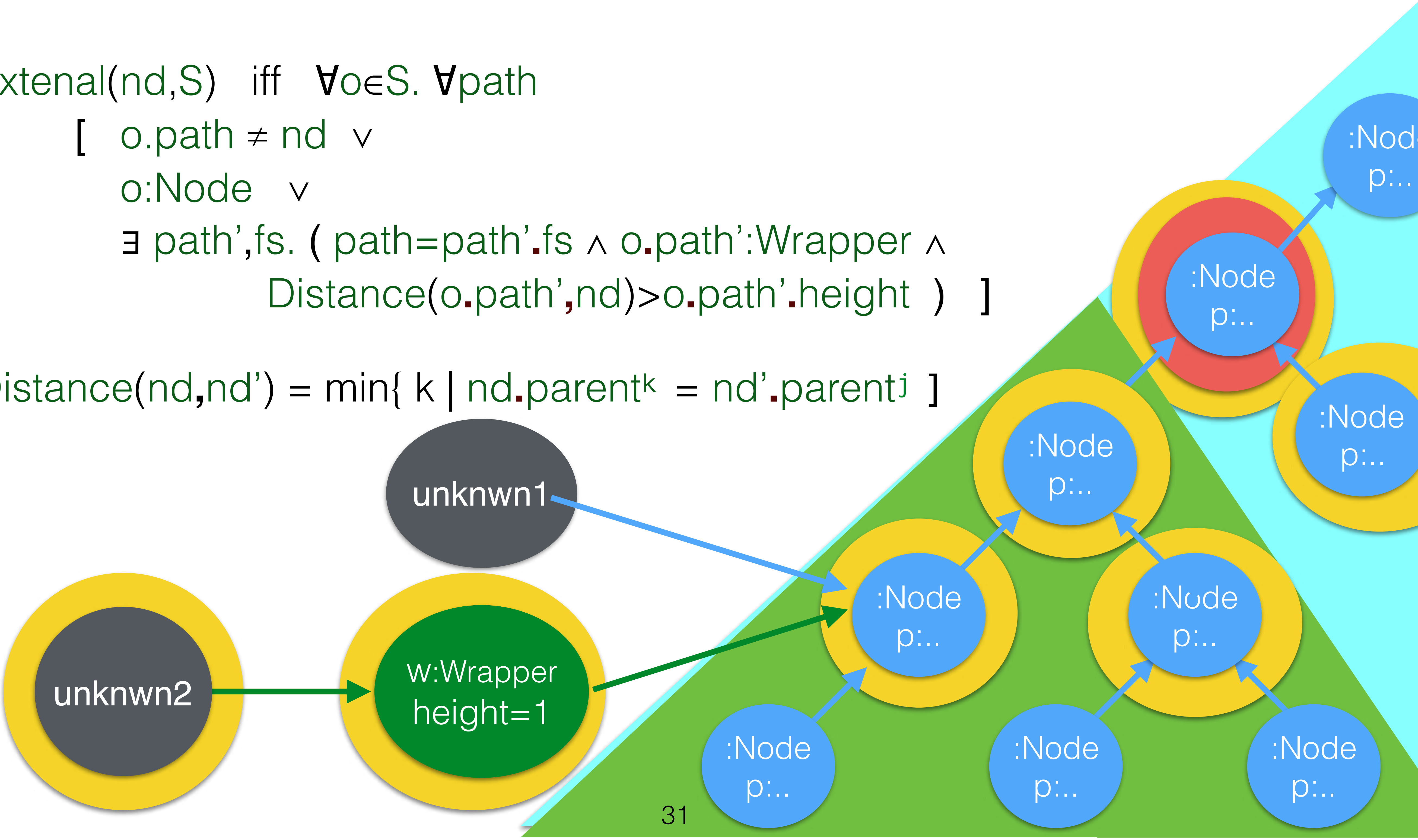

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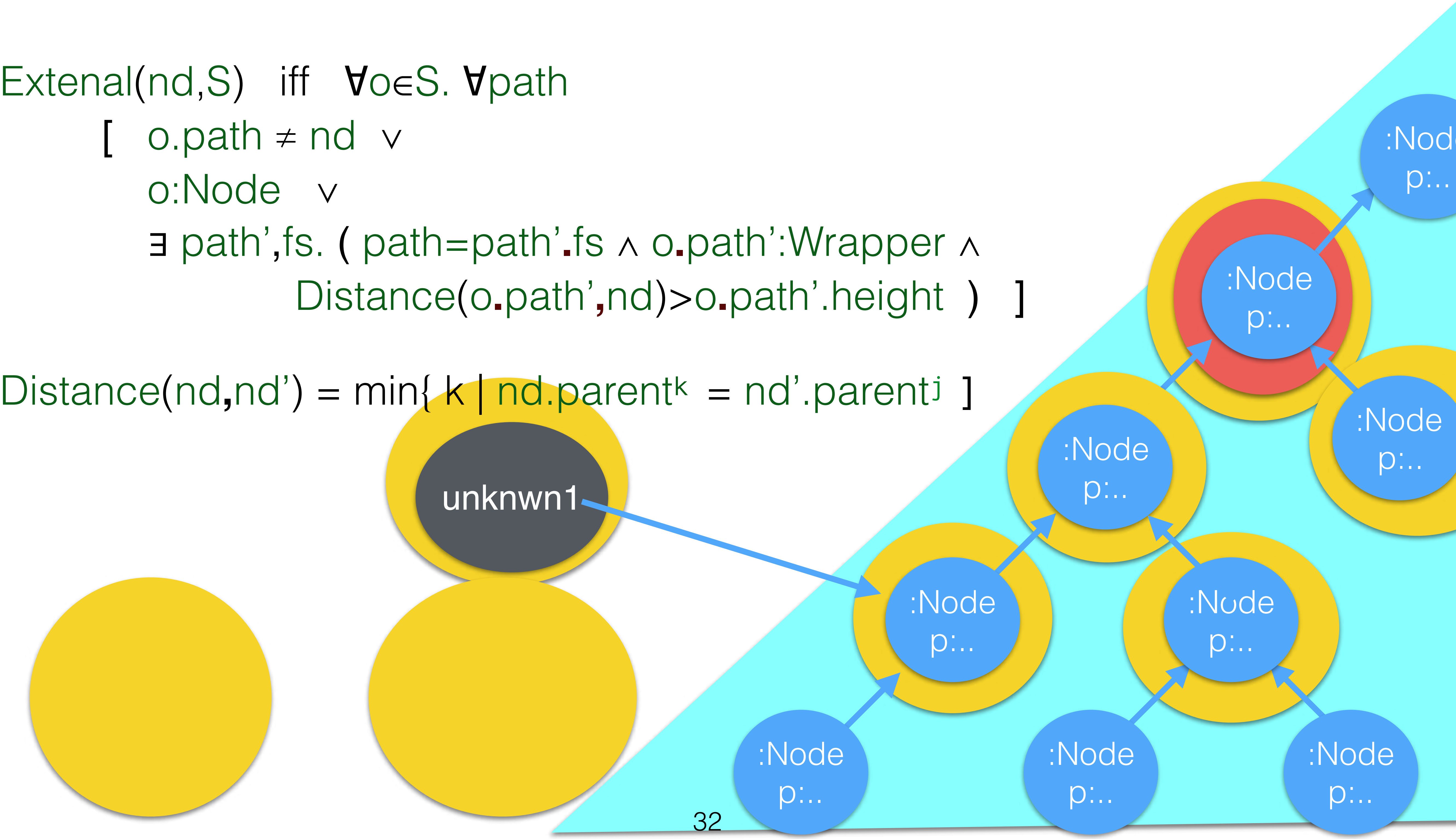

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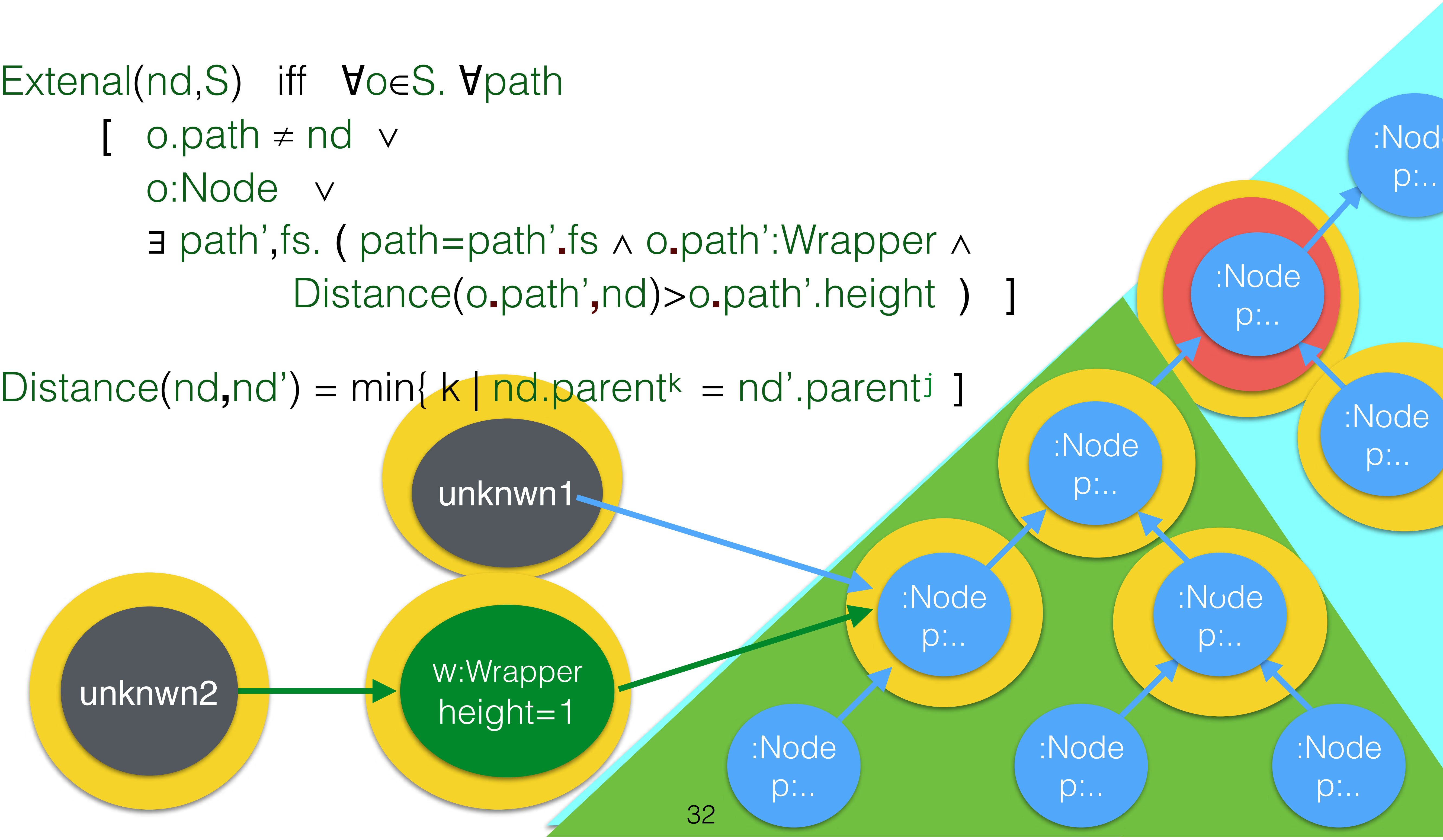

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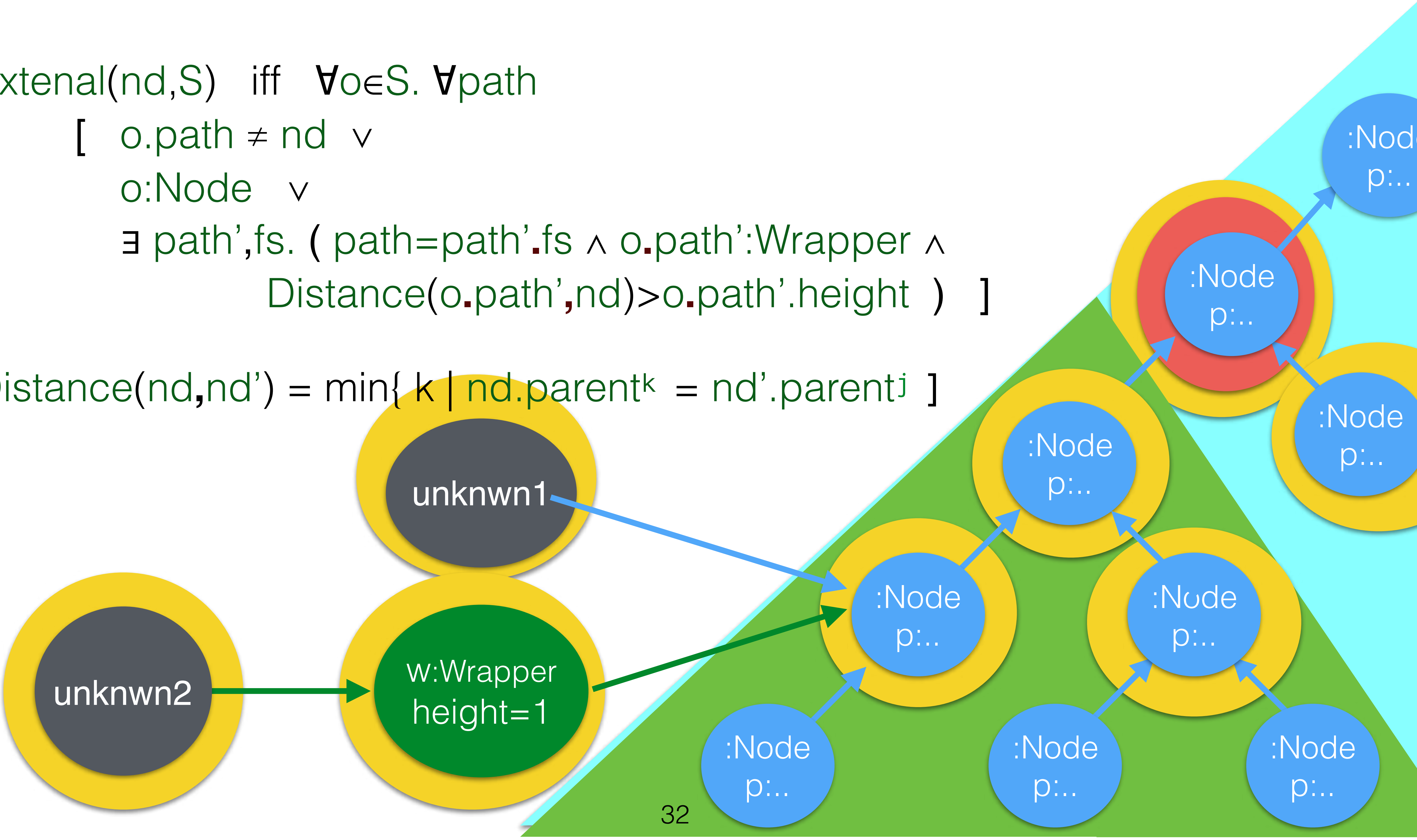

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$$\neg\ \text{Extenal}(\textbf{RedNode}, \textbf{YellowSet})$$

$$\begin{aligned}
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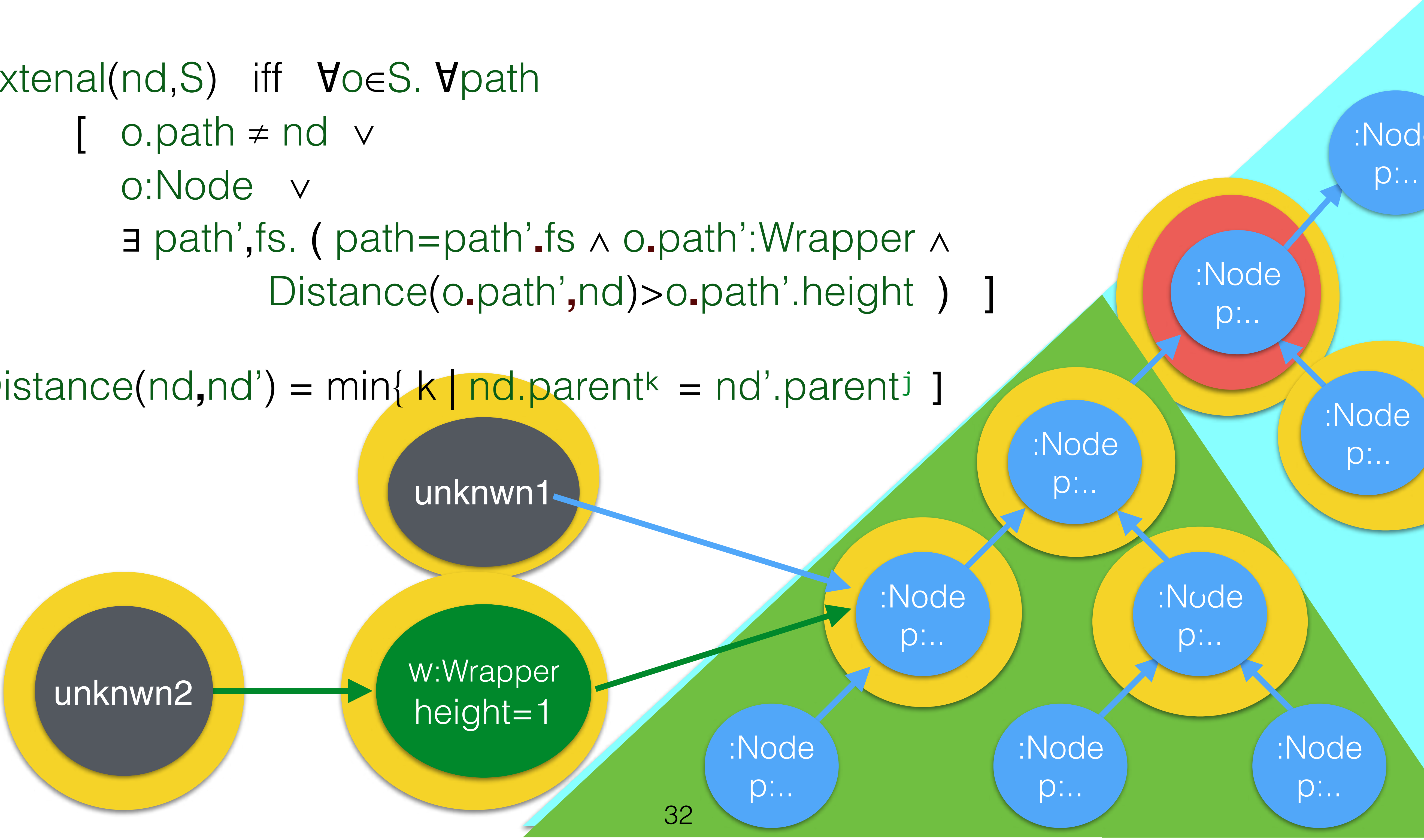

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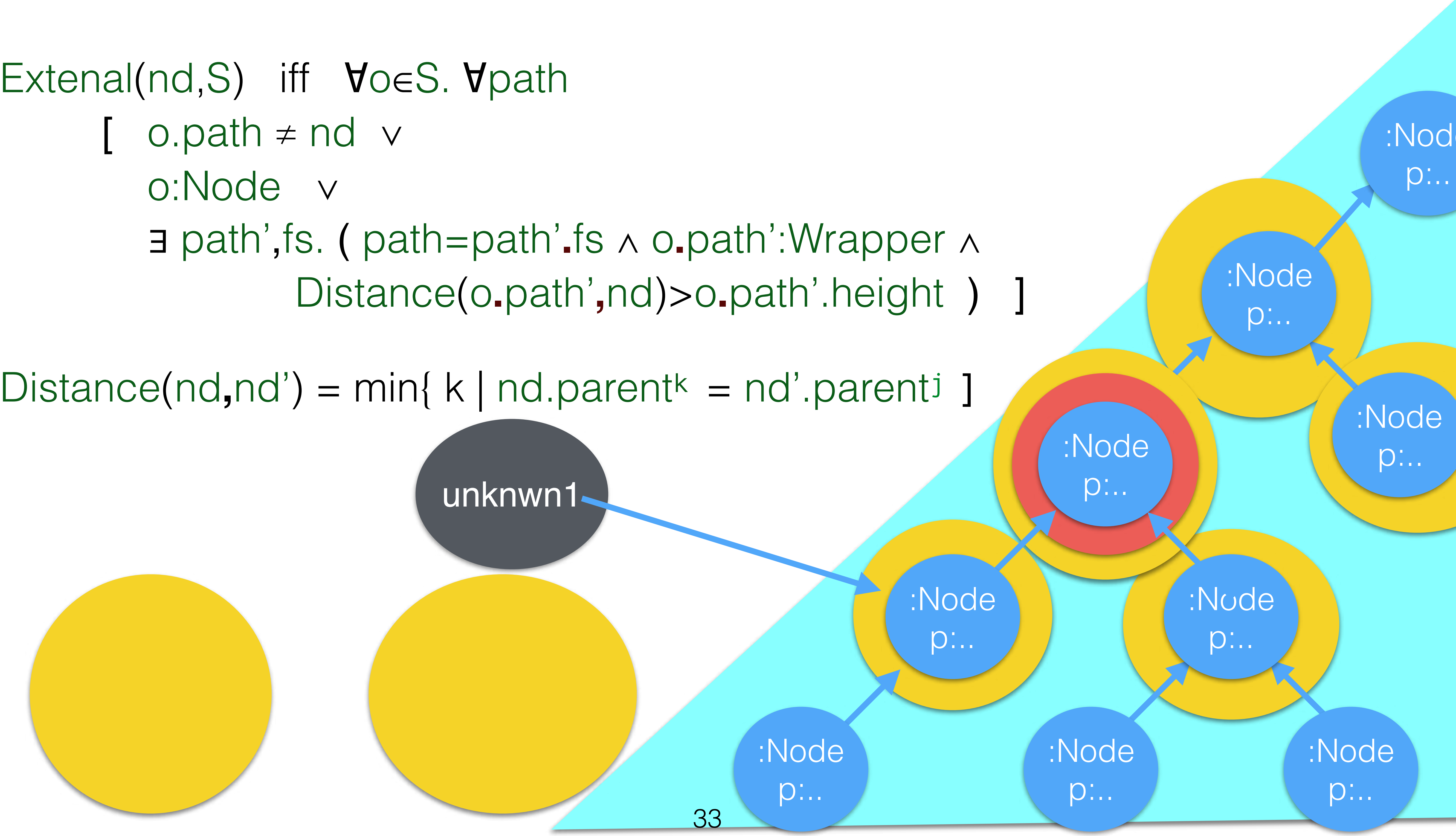

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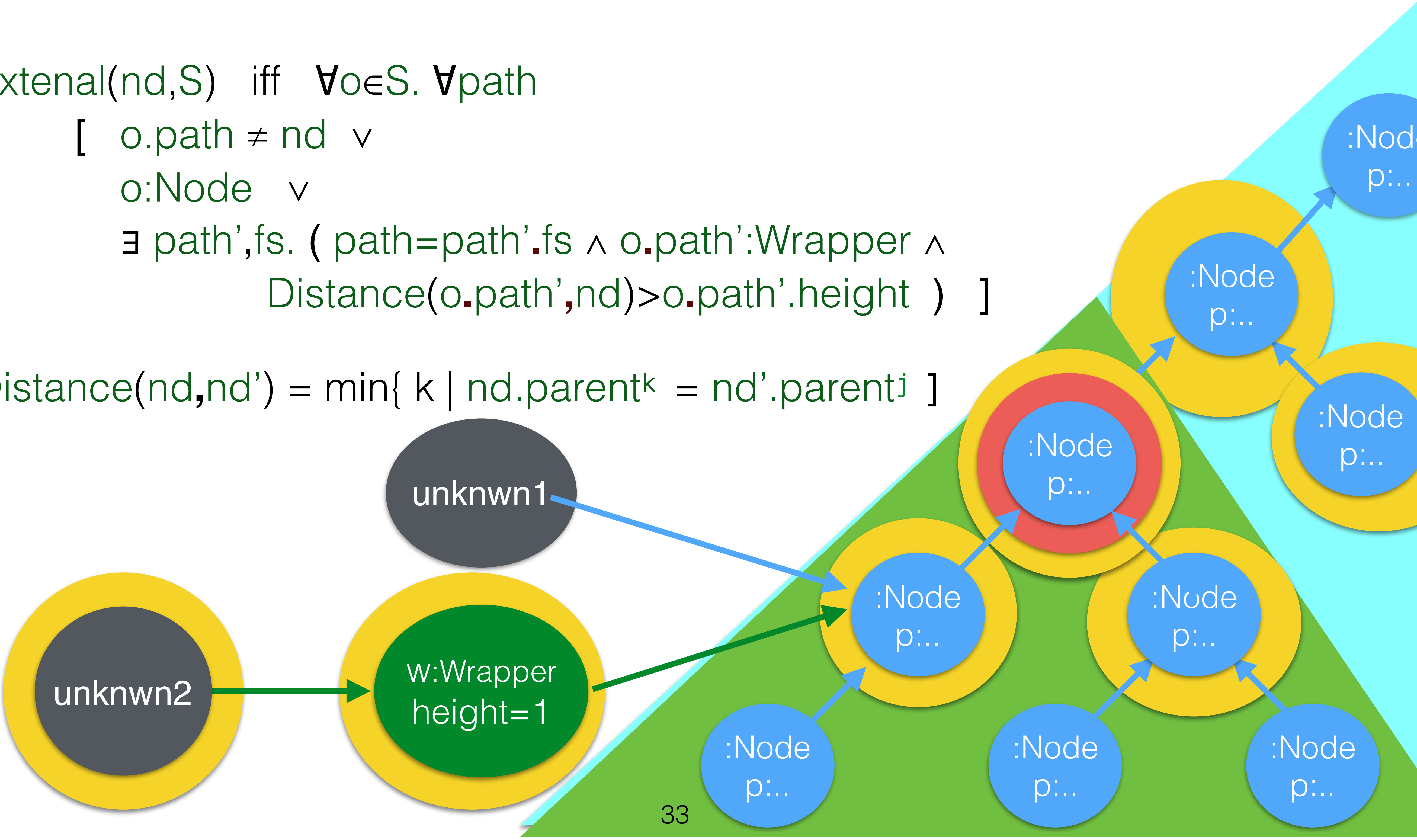

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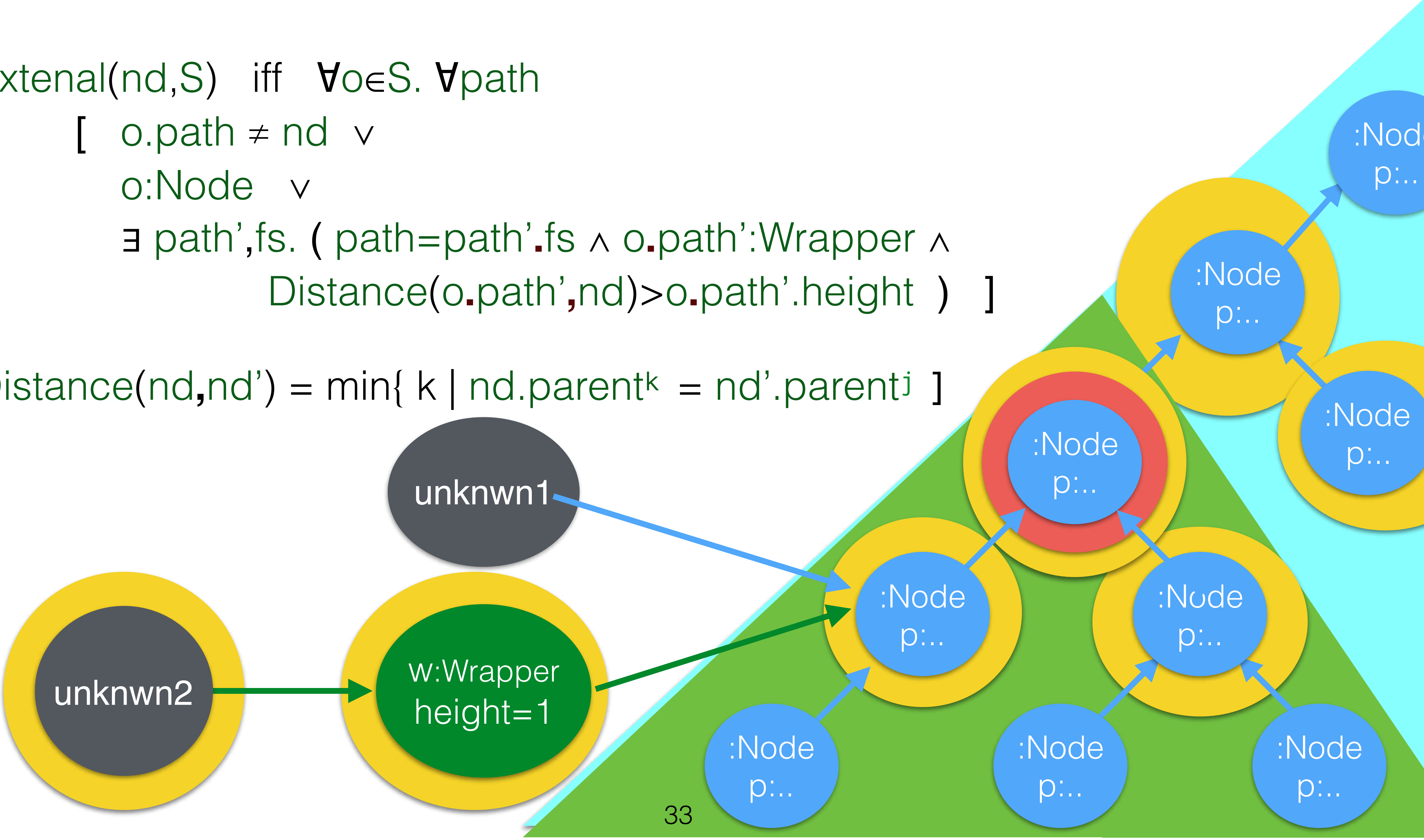

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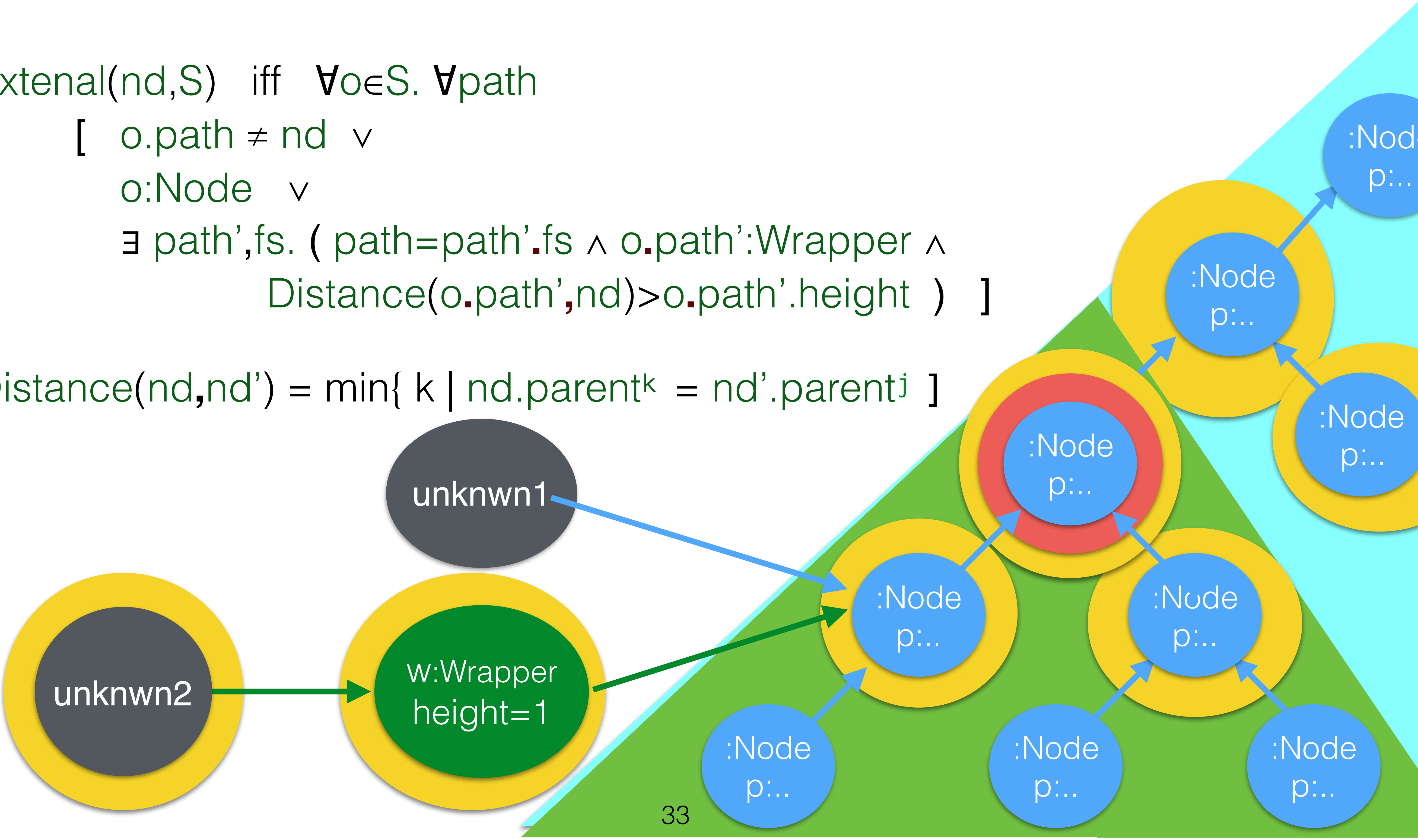
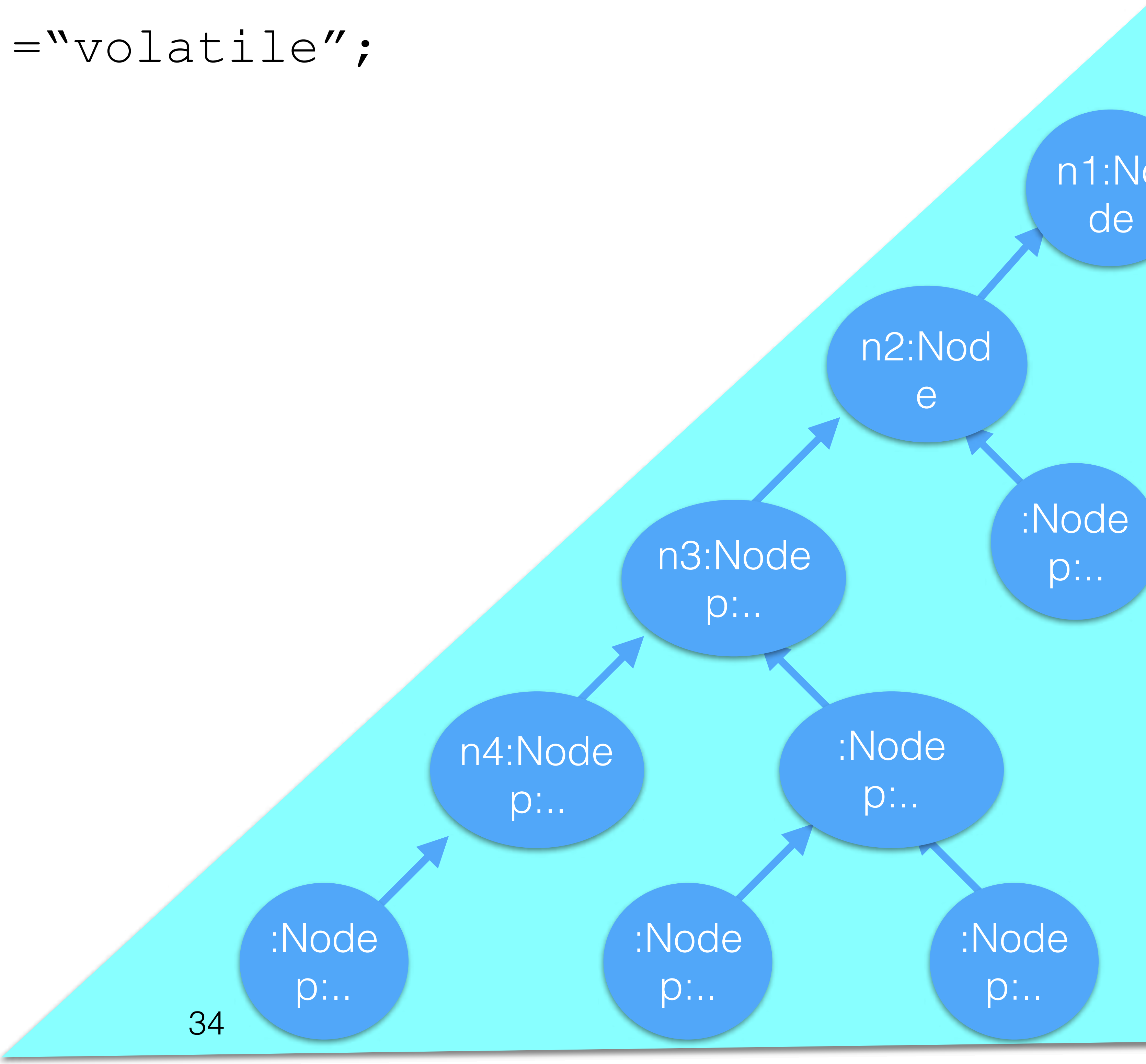


using holistic spec

```
function mm(unknwn){
  n1:=Node(…); n2:=Node(n1,…);n3:=Node(n2,…);n4:=Node(n3,…);
  n2.p:=“robust”; n3.p:=“volatile”;
```



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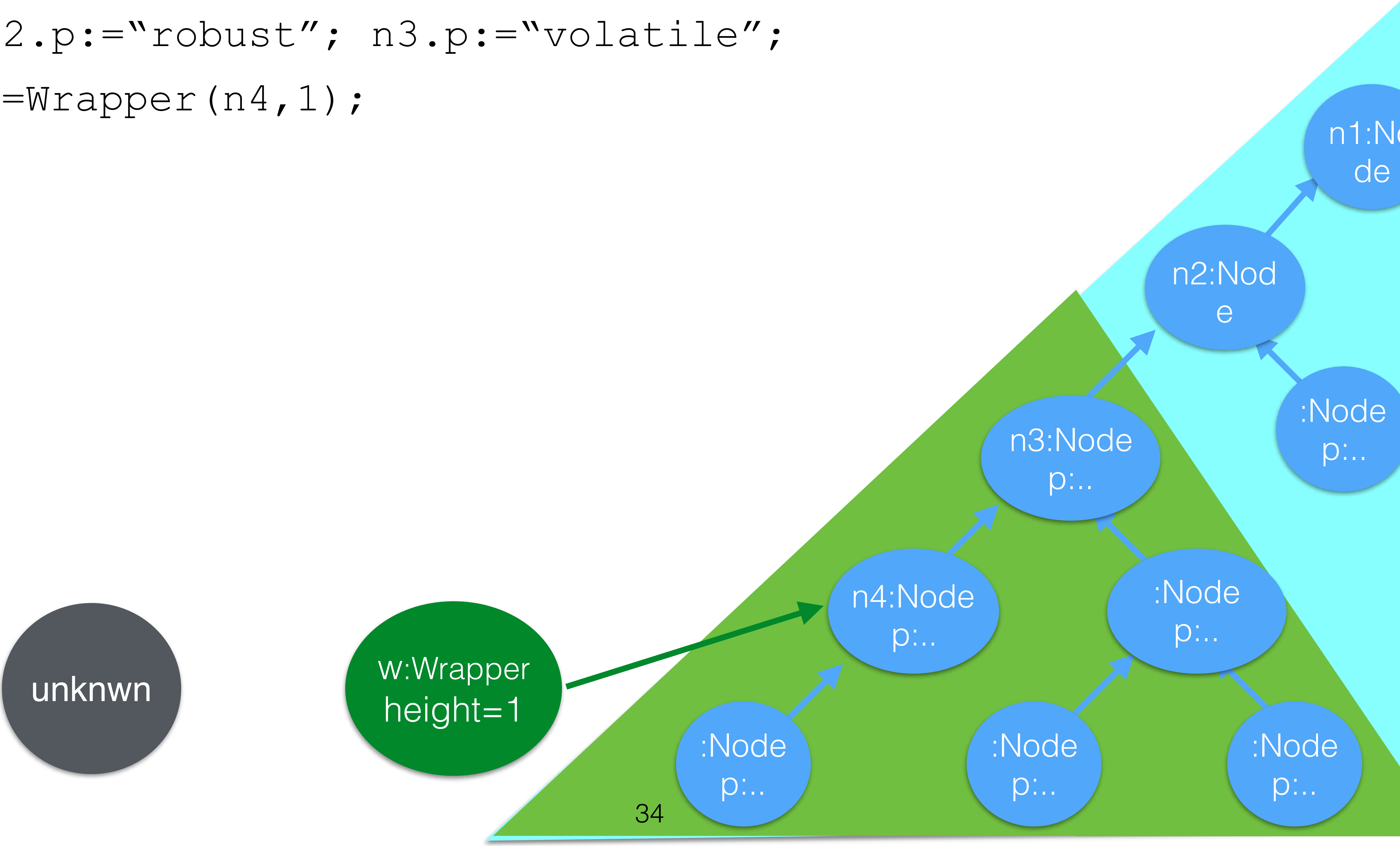

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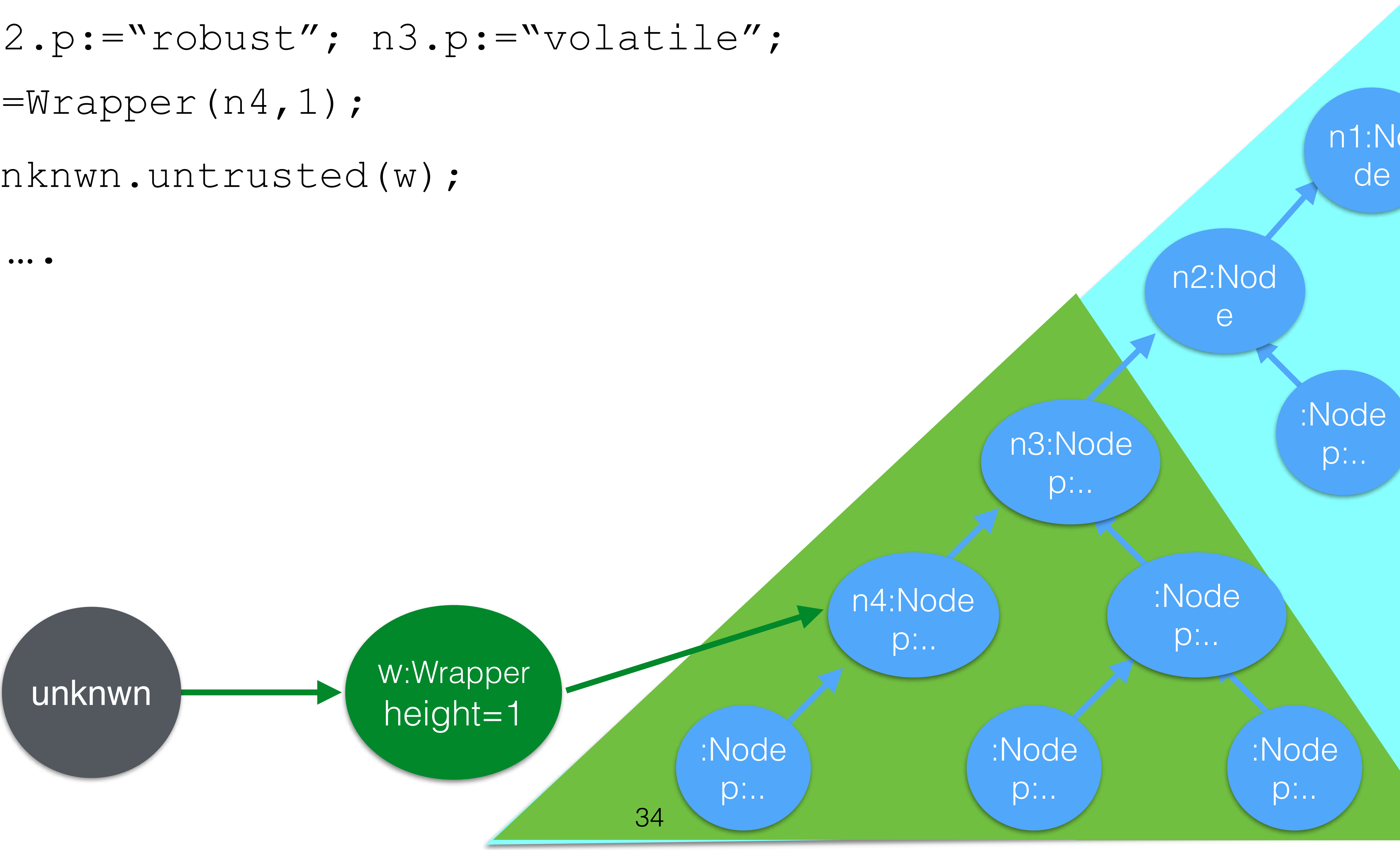
   ….
```



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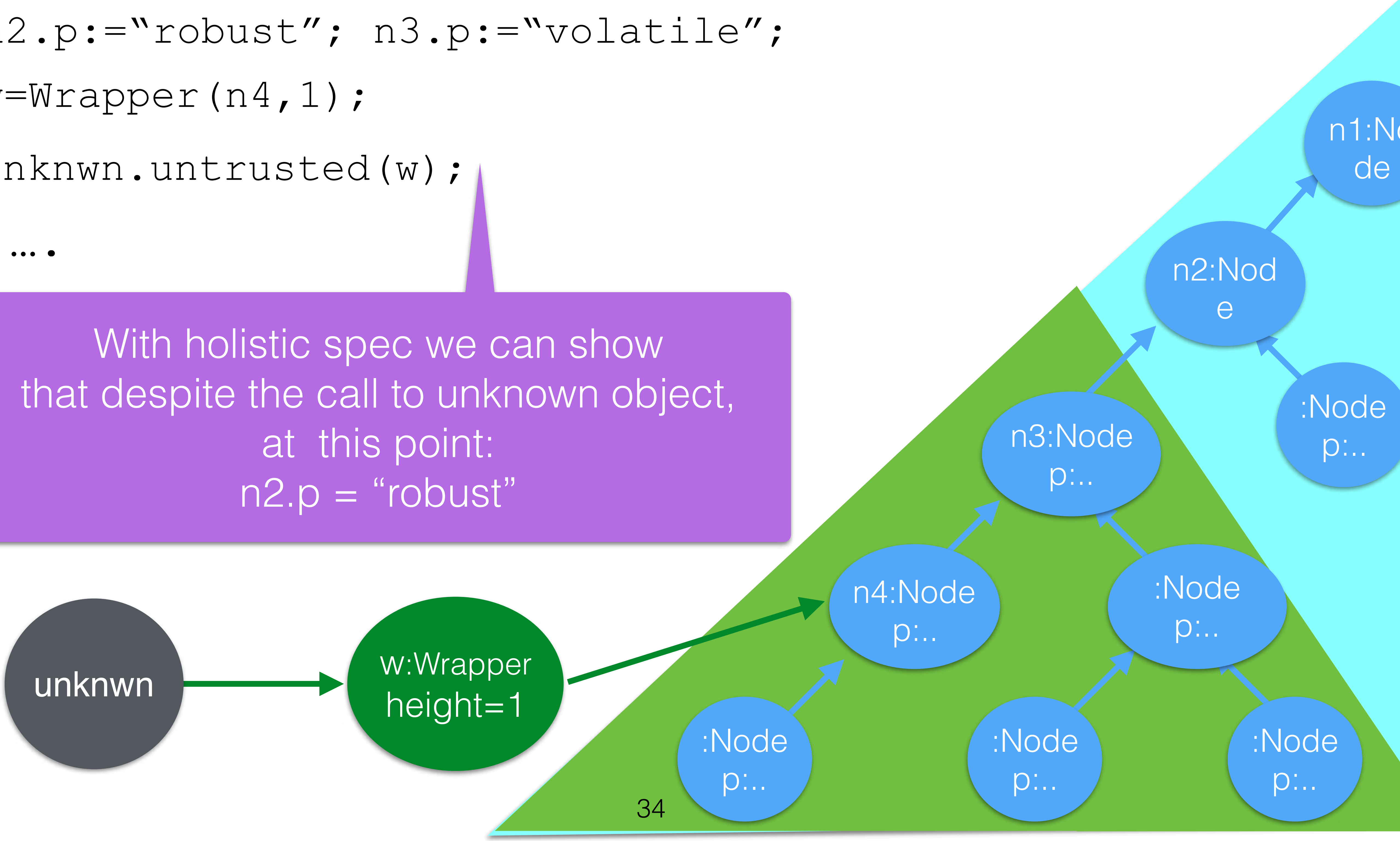
With holistic spec we can show
that despite the call to unknown object,
at this point:
n2.p = “robust”



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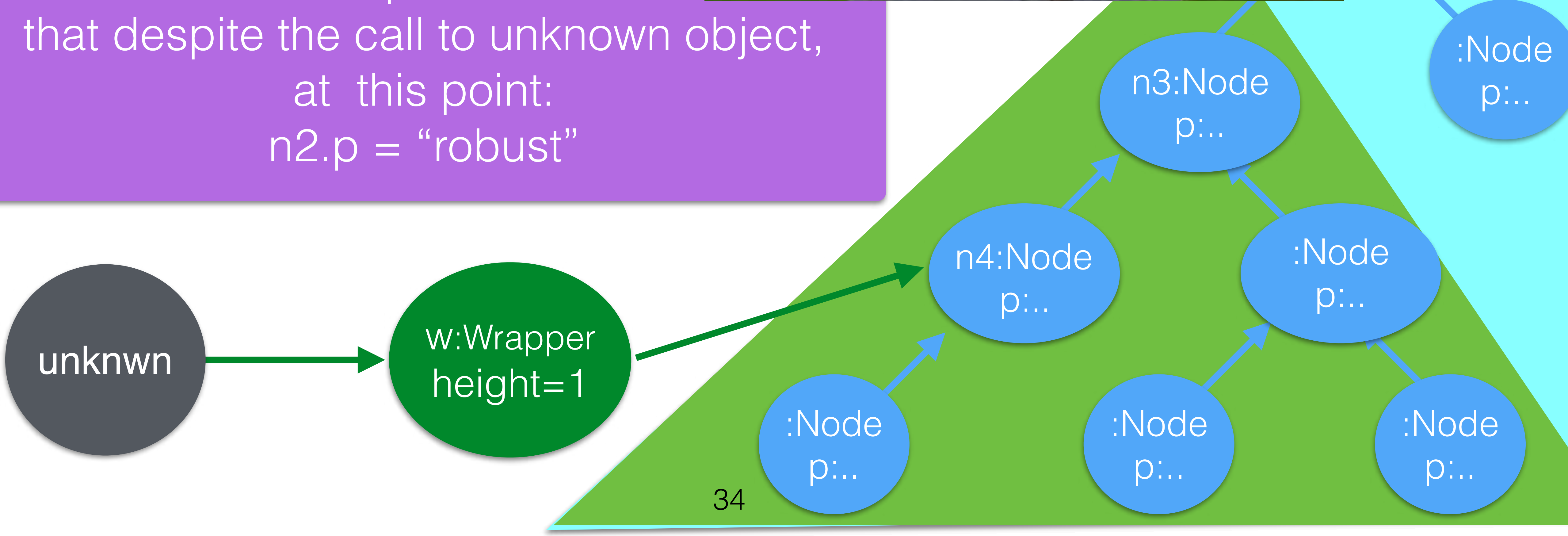

Bank and Account

- Banks and Accounts
- Accounts hold money
- Money can be transferred between Accounts
- A banks' currency = sum of balances of accounts held by bank

[Miller et al, Financial Crypto 2000]

Bank/Account - 2

classical

robustness

- **Pol_1**: With two accounts of same bank one can transfer money between them.
- **Pol_2**: Only someone with the Bank of a given currency can violate conservation of that currency
- **Pol_3**: The bank can only inflate its own currency
- **Pol_4**: No one can affect the balance of an account they do not have.
- **Pol_5**: Balances are always non-negative.
- **Pol_6**: A reported successful deposit can be trusted as much as one trusts the account one is depositing to.

[Miller et al, Financial Crypto 2000]

Pol_4 — holistic

- **Pol_4**: No-one can affect the balance of an account they do not have

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a:Account ∧ **Will** (**Changes**(a.balance)) **in** S)

→

Pol_4 — holistic

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$$a{:}\mathrm{Account} \quad \wedge \quad \mathbf{Will}\ (\ \mathbf{Changes}(a.\mathrm{balance})\ )\ \mathbf{in}\ S\ \ )$$

$$\rightarrow$$

$$\exists o{\in}S.\ \mathrm{Access}(o,a)$$

Pol_4 — holistic

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$$\exists \mathrm{o} \in \mathrm{S}.\ \mathrm{Access}(\mathrm{o},\mathrm{a})$$

This says: If some execution starts now and involves at most the objects from S, and modifies a.balance at some future time, then at least one of the objects in S can access a directly now.

Pol_4 — holistic

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necessary condition

$$\exists o \in S.\ \mathrm{Access}(o,a)$$

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???? 😕 😕 😕 ????

Today

- Traditional Specifications do not adequately address Robustness
- Holistic Specifications — Summary and by Example
- **Holistic Specification Semantics**

Giving meaning to holistic Assertions

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We define in a“conventional” way (omit from slides):

module	$M : \text{Ident} \longrightarrow \text{ClassDef} \cup \text{PredicateDef} \cup \text{FunctionDef}$
configuration	$\sigma : \text{Heap} \times \text{Stack} \times \text{Code}$
execution	$M, \sigma \rightsquigarrow \sigma'$

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Define module concatenation * so that

$M * M'$ undefined, iff $dom(M) \cap dom(M') \neq \emptyset$

otherwise

$(M * M')(id) = M(id)$ if $M'(id)$ undefined, else $M'(id)$

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module	M : Ident —-> ClassDef ∪ PredicateDef ∪ FunctionDef
configuration	σ : Heap × Stack × Code
execution	M, σ ⇝ σ’

Define module concatenation * so that

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otherwise

(M*M’)(id) = M(id) if M’(id) undefined, else M’(id)

Lemma

- M*M’ = M’*M
- (M1*M2)*M3 = M1*(M2*M3)
- M, σ ⇝ σ’ ∧ M*M’ defined ⟶ M*M’, σ ⇝ σ’

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We will define

$M, \sigma \models A$

$Initial(\sigma)$ and $Arising(M)$

$M \models A$

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Holistic Assertions — summary

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e ::= this | x | e.fld | …

Holistic Assertions — summary

e ::= this | x | e.fld | …

A ::= e>e | e=e | …

Holistic Assertions — summary

$$
\begin{array}{lll}
e & ::= & \mathrm{this} \mid x \mid e.\mathrm{fld} \mid \ldots \\
A & ::= & e>e \mid e=e \mid \ldots \\
 & \mid & A \to A \mid A \land A \mid \exists x.\ A \mid \ldots
\end{array}
$$

Holistic Assertions — summary

e ::= this | x | e.fld | …

A ::= e>e | e=e | …

| A → A | A ∧ A | ∃x. A | …

| **Access**(e,e’)

Holistic Assertions — summary

e ::= this | x | e.fld | …

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| **Access**(e,e’)
| **Changes**(e)

Holistic Assertions — summary

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| **Changes**(e)

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| A **in** S

| x.**Call**(y,m,z1,..zn)

Holistic Assertions — summary

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| **Changes**(e)
| **Will**(A) | **Was**(A)
| A **in** S
| x.**Call**(y,m,z1,..zn)
| x **obeys** A

Holistic Assertions — summary

e ::= this | x | e.fld | …

A ::= e>e | e=e | …
| A → A | A ∧ A | ∃x. A | …

| **Access**(e,e’) permission

| **Changes**(e) authority

| **Will**(A) | **Was**(A) time

| A **in** S space

| x.**Call**(y,m,z1,..zn) control

| x **obeys** A trust

Semantics of Expressions

e ::= this | x | e.fld | func(e1,…en) | …

Define $\lfloor e \rfloor_{M,\sigma}$ as expected

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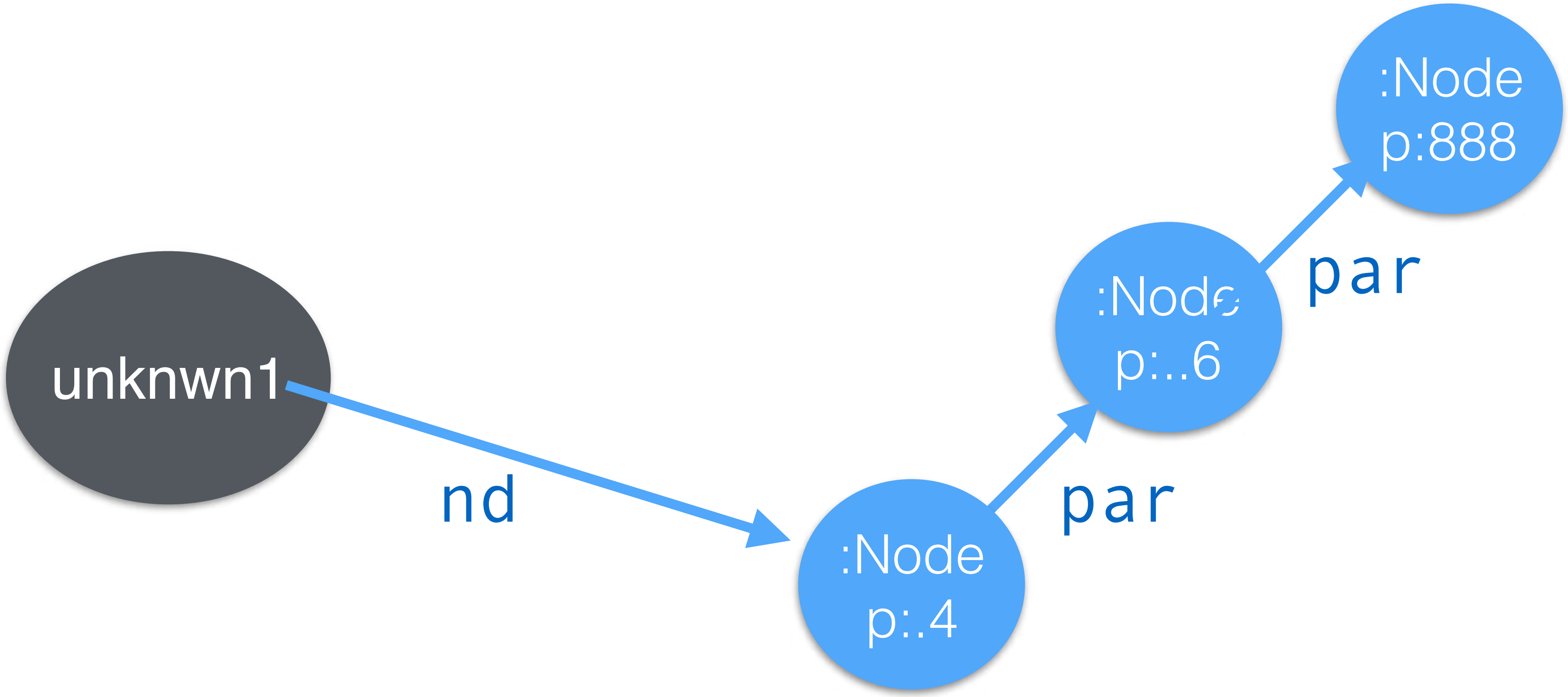

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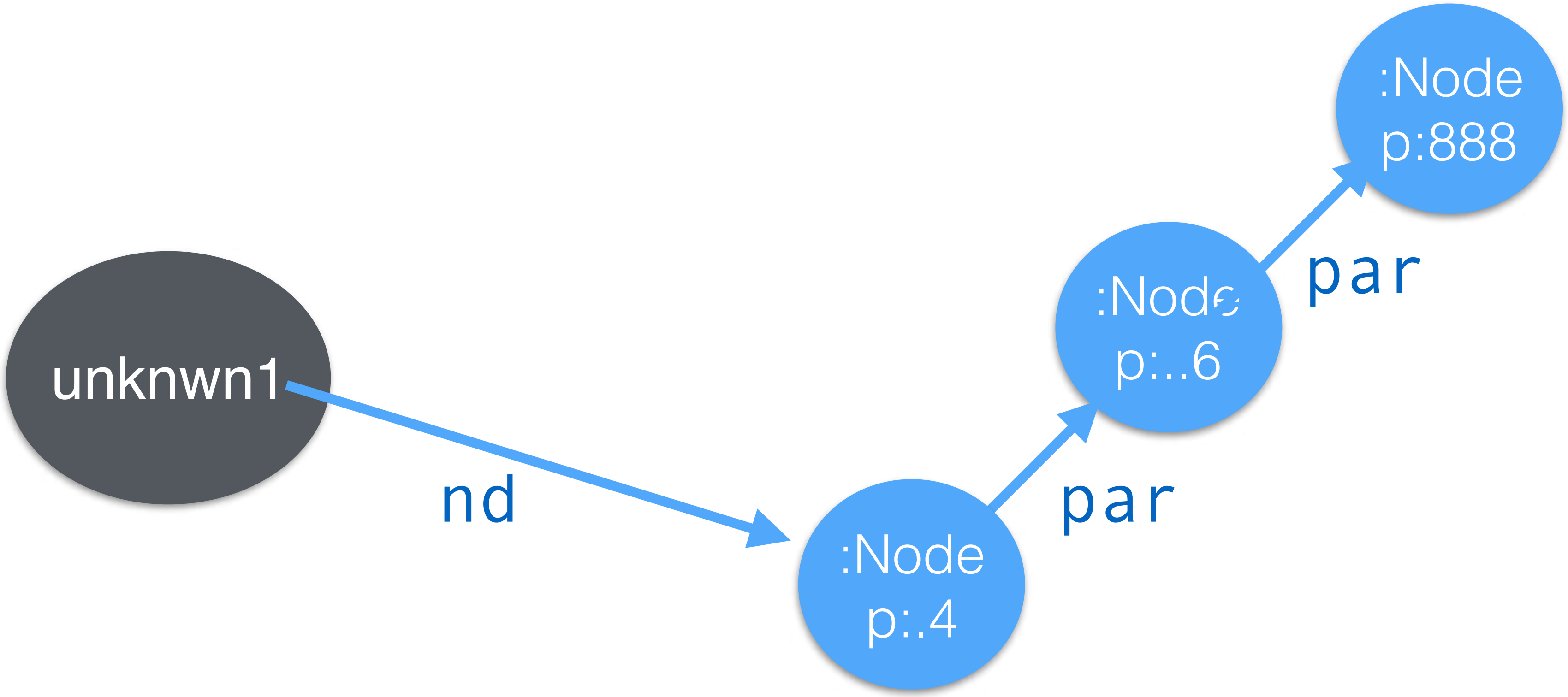

Eg, $\lfloor \text{unknwn1.nd.par.par.p} \rfloor_{M,\sigma} = 888$

Semantics of holistic Assertions

“Conventional part”

$A \ ::= \ e>e \ \mid \ A \rightarrow A \ \mid \ \exists x.A \mid \ \ldots$

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We define $M, \sigma \models A$

Semantics of holistic Assertions

“Conventional part”

$A \ ::= \ e>e \ \mid \ A \rightarrow A \ \mid \ \exists x.A \mid \ \dots$

We define $M, \sigma \models A$

$M,\sigma \models e>e'$ iff $\lfloor e \rfloor_{M,\sigma} > \lfloor e' \rfloor_{M,\sigma}$

$M,\sigma \models A \rightarrow A'$ iff $M,\sigma \models A$ implies $M,\sigma \models A'$

$M,\sigma \models \exists x.A$ iff $M,\sigma[z \mapsto \iota] \models A[x \mapsto z]$
for some $\iota \in dom(\sigma.heap)$, and z free in A

Semantics of holistic Assertions

“Unconventional part”

A ::= **Access**(x,x') | **Changes**(e) | **Will**(A) | A **in** S | x.**Calls**(y,m,z_1,..z_n)

Semantics of holistic Assertions

“Unconventional part”

$A ::= \mathbf{Access}(x,x') \;|\; \mathbf{Changes}(e) \;|\; \mathbf{Will}(A) \;|\; A\ \mathbf{in}\ S \;|\; x.\mathbf{Calls}(y,m,z_1,..z_n)$

$M,\sigma \models \mathbf{Access}(x,x')$ iff $\lfloor x \rfloor_{M,\sigma} = \lfloor x' \rfloor_{M,\sigma} \quad \vee$

$\lfloor x.fld \rfloor_{M,\sigma} = \lfloor x' \rfloor_{M,\sigma}$ for some field $fld \quad \vee$

$\lfloor this \rfloor_{M,\sigma} = \lfloor x \rfloor_{M,\sigma} \wedge \lfloor y \rfloor_{M,\sigma} = \lfloor x' \rfloor_{M,\sigma}$

$\wedge$ y is formal parameter of current function

Semantics of holistic Assertions

“Unconventional part”

$A ::= \textbf{Access}(x,x') \mid \textbf{Changes}(e) \mid \textbf{Will}(A) \mid A\ \textbf{in}\ S \mid x.\textbf{Calls}(y,m,z_1,..z_n)$

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$M,\sigma \vDash \textbf{Changes}(e)$ iff $M, \sigma \rightsquigarrow \sigma' \wedge \lfloor e \rfloor_{M,\sigma} \neq \lfloor e \rfloor_{M,\sigma'}$

Semantics of holistic Assertions

"Unconventional part"

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$M,\sigma \vDash \textbf{Changes}(e)$ iff $M, \sigma \rightsquigarrow \sigma' \land \lfloor e \rfloor_{M,\sigma} \neq \lfloor e \rfloor_{M,\sigma'}$

$M,\sigma \vDash \textbf{Will}(A)$ iff $\exists \sigma'.[\ M,\sigma \rightsquigarrow^* \sigma' \land M, \sigma' \vDash A\ ]$

Semantics of holistic Assertions

“Unconventional part”

$A \ ::= \ \textbf{Access}(x,x') \ \mid \ \textbf{Changes}(e) \ \mid \ \textbf{Will}(A) \ \mid \ A \ \textbf{in} \ S \mid \ x.\textbf{Calls}(y,m,z_1,..z_n)$

$M,\sigma \models \textbf{Access}(x,x')$ iff $\lfloor x \rfloor_{M,\sigma} = \lfloor x' \rfloor_{M,\sigma} \quad \vee$

$\lfloor x.fld \rfloor_{M,\sigma} = \lfloor x' \rfloor_{M,\sigma}$ for some field fld $\quad \vee$

$\lfloor this \rfloor_{M,\sigma} = \lfloor x \rfloor_{M,\sigma} \wedge \lfloor y \rfloor_{M,\sigma} = \lfloor x' \rfloor_{M,\sigma}$

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$M,\sigma \models A \ \textbf{in} \ S$ iff $M,\sigma@_{Os} \models A$ where $Os = \lfloor S \rfloor_{M,\sigma}$

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$M,\sigma \models x.\textbf{Calls}(y,m,z_1,..z_n)$ iff $\lfloor this \rfloor_{M,\sigma} = \lfloor x \rfloor_{M,\sigma} \;\wedge\; \sigma.code{=}y'.m(z_1'..z_n') \;\wedge$ ..

Semantics of holistic Assertions
- the full truth -

$M,\sigma \models \textbf{Access}(e,e')$ iff … as before …

$M,\sigma \models \textbf{Changes}(e)$ iff $M, \sigma \rightsquigarrow \sigma' \ \wedge\ \lfloor e \rfloor_{M,\sigma} \neq \lfloor e[z\mapsto y] \rfloor_{M,\sigma'[y\mapsto\sigma(z)]}$

where $\{z\}=\text{Free}(e) \wedge y$ fresh in e, σ,σ'

$M,\sigma \models \textbf{Will}(A)$ iff $\exists\sigma',\sigma'',\phi.[\ \sigma = \sigma'.\phi \wedge\ M,\phi \rightsquigarrow^{*}\sigma' \ \wedge$

$M, \sigma'[y\mapsto\sigma(z)] \models\ A[z\mapsto y]\ ]$

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Semantics of holistic Assertions

- the full truth -

$M,\sigma \models$ **Access**(e,e') iff … as before …

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$M,\sigma \models$ **Will**(A) iff $\exists \sigma',\sigma'',\phi.[\ \sigma = \sigma'.\phi \ \wedge\ M,\phi \rightarrow^* \sigma' \ \wedge$

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where $\{z\}=Free(A) \wedge y$ fresh in A, σ,σ'

$M,\sigma \models A$ **In** S iff $M,\sigma@_{Os} \models A$ where $Os = \lfloor S \rfloor_{M,\sigma}$

$M,\sigma \models x.$**Calls**$(y,m,z_1,..z_n)$ iff … as before …

Arising Configurations

A runtime configuration is *initial* iff
1) The heap contains only one object, of class Object
2) The stack consists of just one frame, where this points to that object.

The code can be arbitrary

$$\text{Initial}(\sigma) \quad \text{iff} \quad \sigma.\text{heap}=(1\mapsto(\text{Object},\ldots)\,) \;\wedge\; \sigma.\text{stack}=(\text{this}\mapsto 1).[\,]$$

A runtime configuration σ *arises* from a module M if there is some initial configuration σ_0 whose execution M in reaches σ in a finite number of steps.

$$\text{Arising}(M) = \{\ \sigma \mid \exists\, \sigma_0.\ \text{Initial}(\sigma_0) \;\wedge\; M, \sigma_0 \rightarrow^* \sigma \ \}$$

Arising expresses “defensiveness”

Assume a Tree-module, $\mathtt{M}_{\mathtt{tree}}$.

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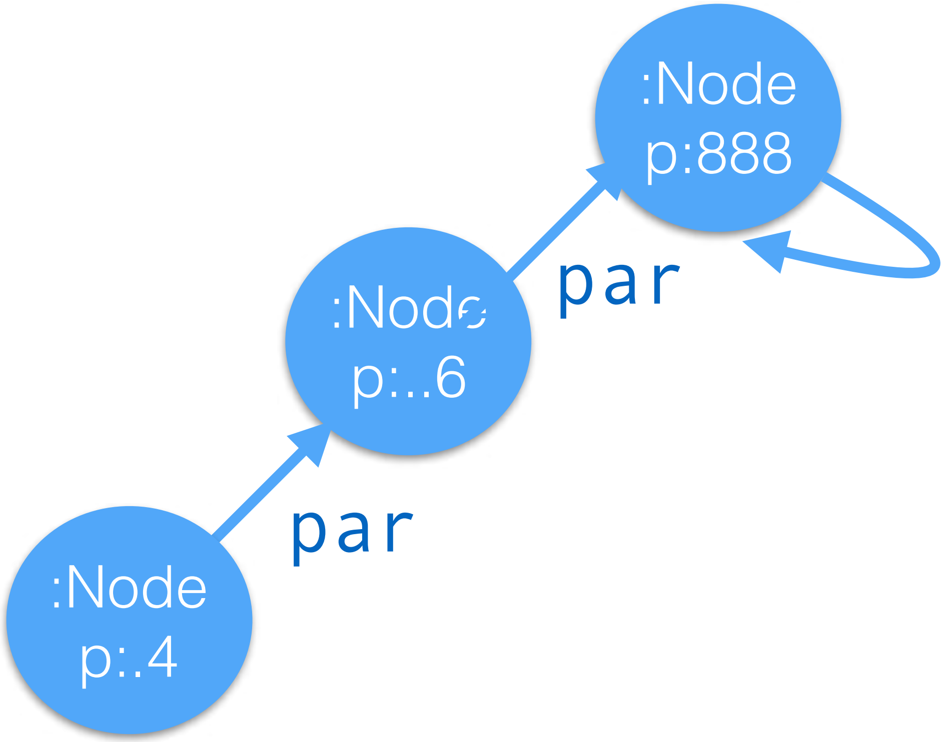

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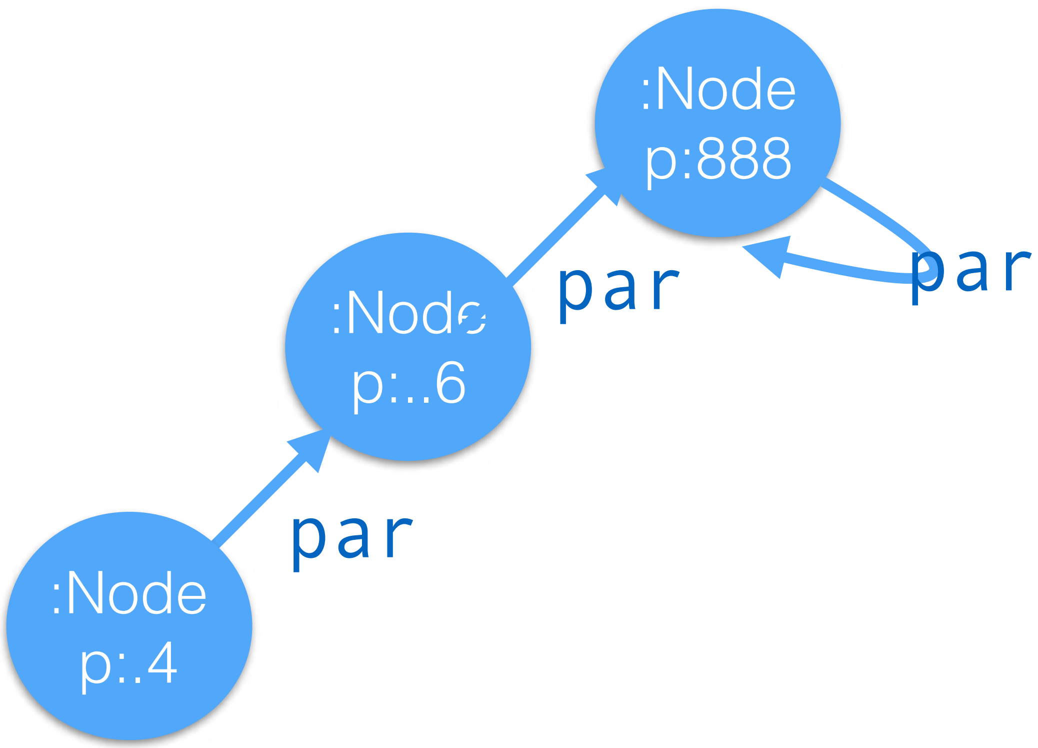

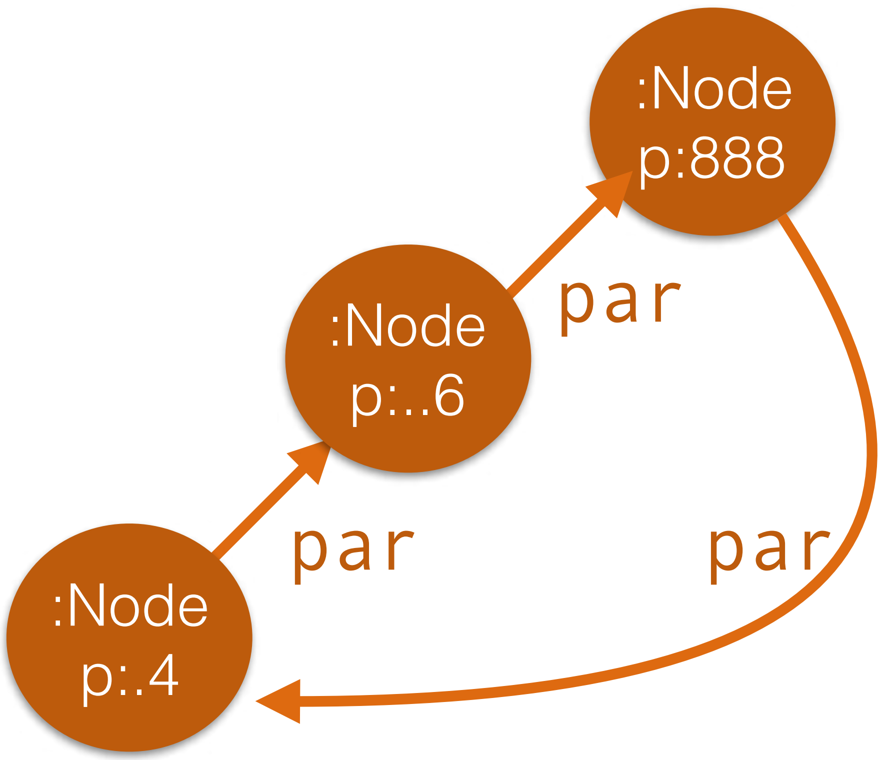

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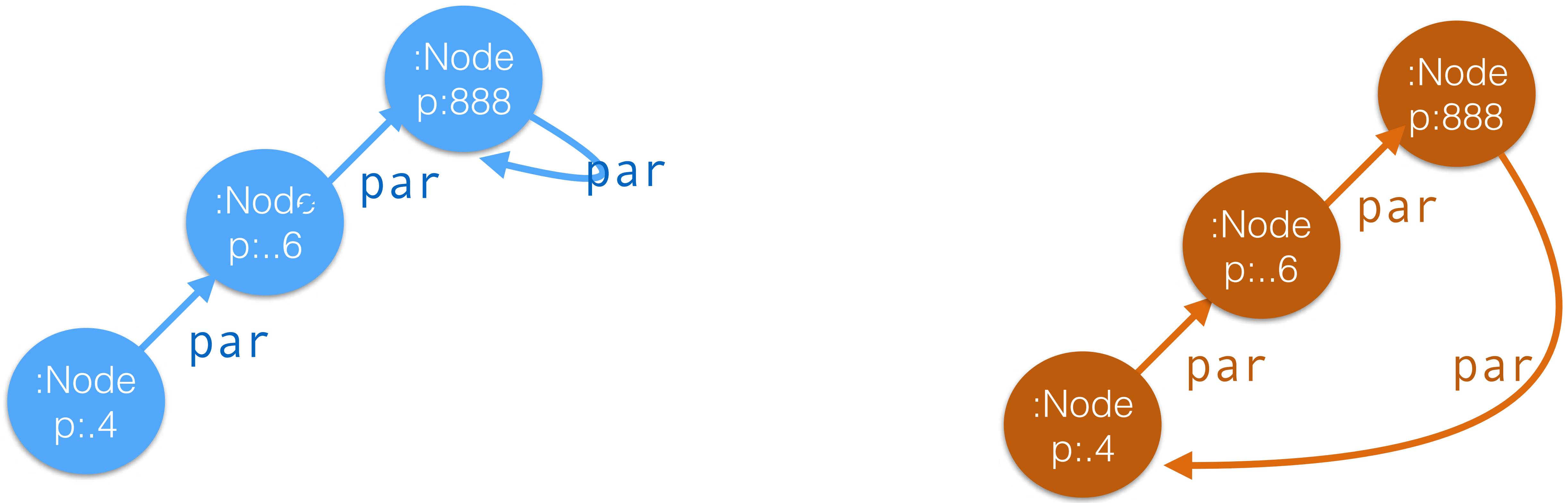
`blue configuration` *arises*
from $M_{tree}*M'$ for some module M'

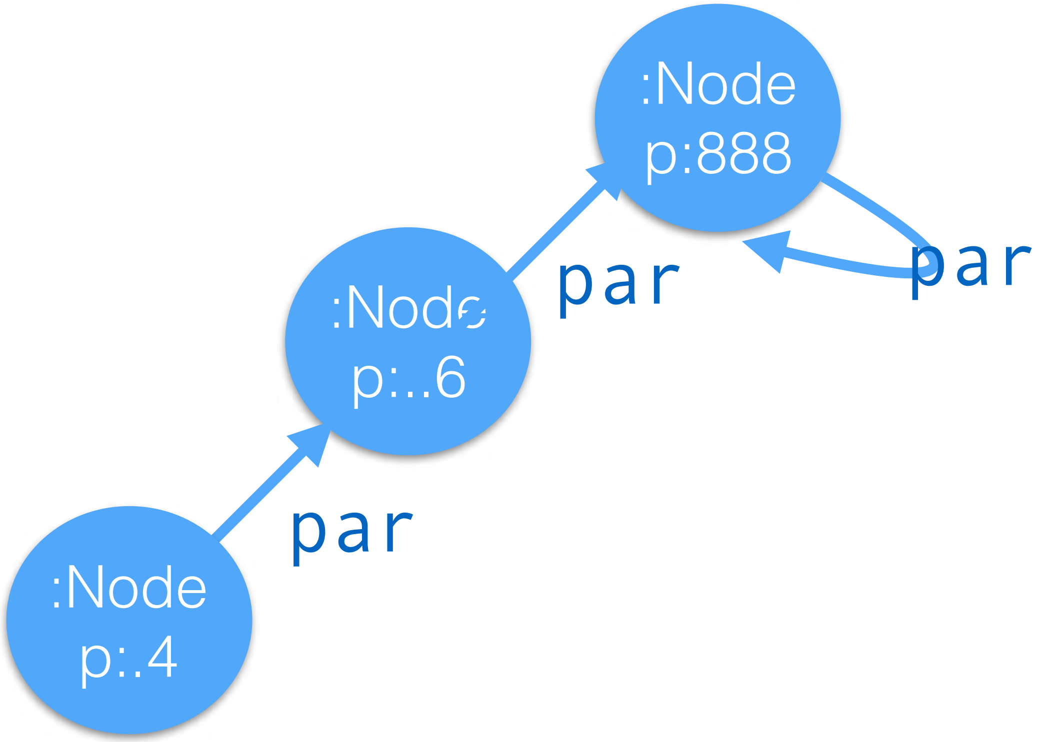


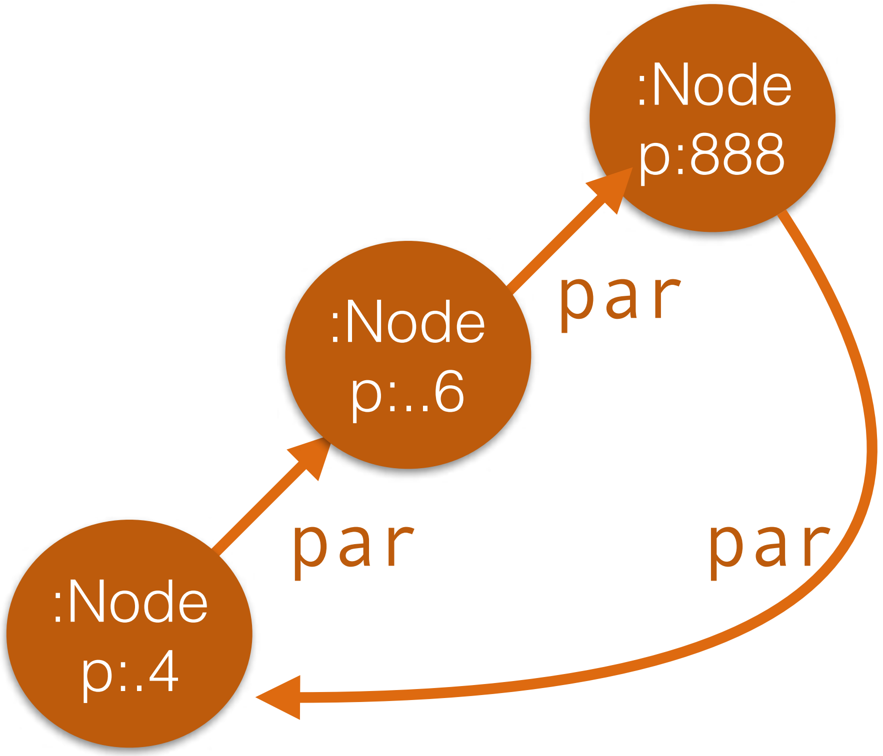
Arising expresses “defensiveness”

Assume a Tree-module, M_{tree}.

blue configuration *arises* from M_{tree}*M’ for some module M’

brown configuration *does not arise* from M_{tree}*M’ for *any* module M’





Giving meaning to Assertions

$M \models A \quad \text{iff} \quad \forall M'.\forall \sigma \in \text{Arising}(M^*M').\ \ M^*M', \sigma \models A$

A module M satisfies an assertion A if all runtime configurations σ which arise from execution of code from M*M’ (for any module M’), satisfy A.

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open world

Summary of our Proposal

A ::= e>e | e=e | f(e1,..en) | …
| A → A | A ∧ A | ∃x. A | …

| **Access**(x,y)	permission
| **Changes**(e)	authority
| **Will**(A) | **Was**(A)	time
| A **in** S	space
| x.**Calls**(y,m,z1,..zn)	call

$M, \sigma \models A$

Arising(M)

$M \models A$

Classical Specification vs Holistic Specification

- fine-grained
- per function

- ADT as a whole
- emergent behaviour

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“Closed” ADT with classical spec implies holistic spec.
(closed: no functions can be added, all functions have classical specs, ghost state has known representation)

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- ADT as a whole
- emergent behaviour

Which is "stronger"?
"Closed" ADT with classical spec implies holistic spec.
(closed: no functions can be added, all functions have classical specs, ghost state has known representation)

Why do we need holistic specs?
* "closed ADT" is sometimes too strong a requirement.
* Holistic aspect is cross-cutting (eg no payment without authorization)
* Allows reasoning in open world (eg DOM wrappers)

Thank you