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Syntactic Variety in Boundary Logic

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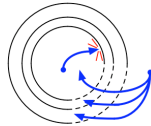
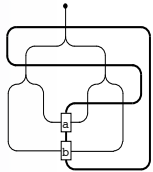
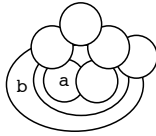
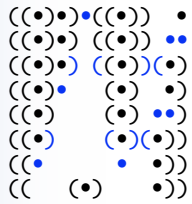
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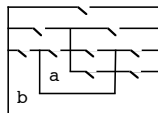
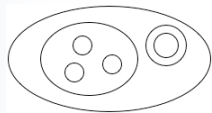
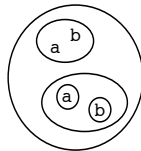
June 28, 2006

bricken@halcyon.com

Contents



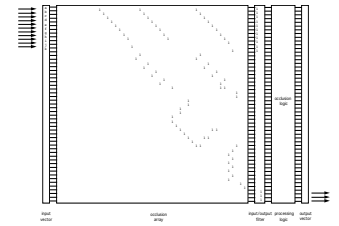
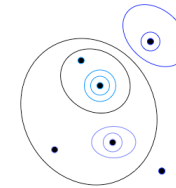
$$(A ()) = A \{A B\} = A \{B\}$$



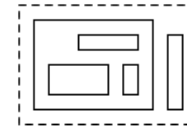
Boundary Math De Novo

Boundary Math Concepts

void and mark
sharing and bounding
boundary permeability
pattern variables and equations
first-class featureless void



$$\begin{aligned} (((a)((a) b))) & b \\ (a)((a) b) & b \\ (a)() & b \\ () & \end{aligned}$$

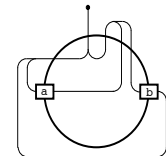
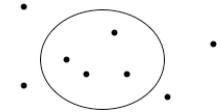
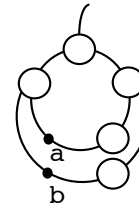


Boundary Integers

read, standardize, add, multiply

Boundary Logic

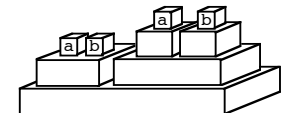
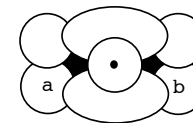
arithmetic
algebra
transformation
void substitution
deep rules
metatheory
alpha existential graphs



$$\begin{aligned} \alpha \rightarrow \beta &= (\alpha) \beta \\ \alpha \vdash \beta &= (\alpha) \beta \\ \alpha \models \beta &= (\alpha) \beta \\ \alpha, (\alpha \models \beta) \models \beta &= ((\alpha) ((\alpha) \beta)) \beta \end{aligned}$$

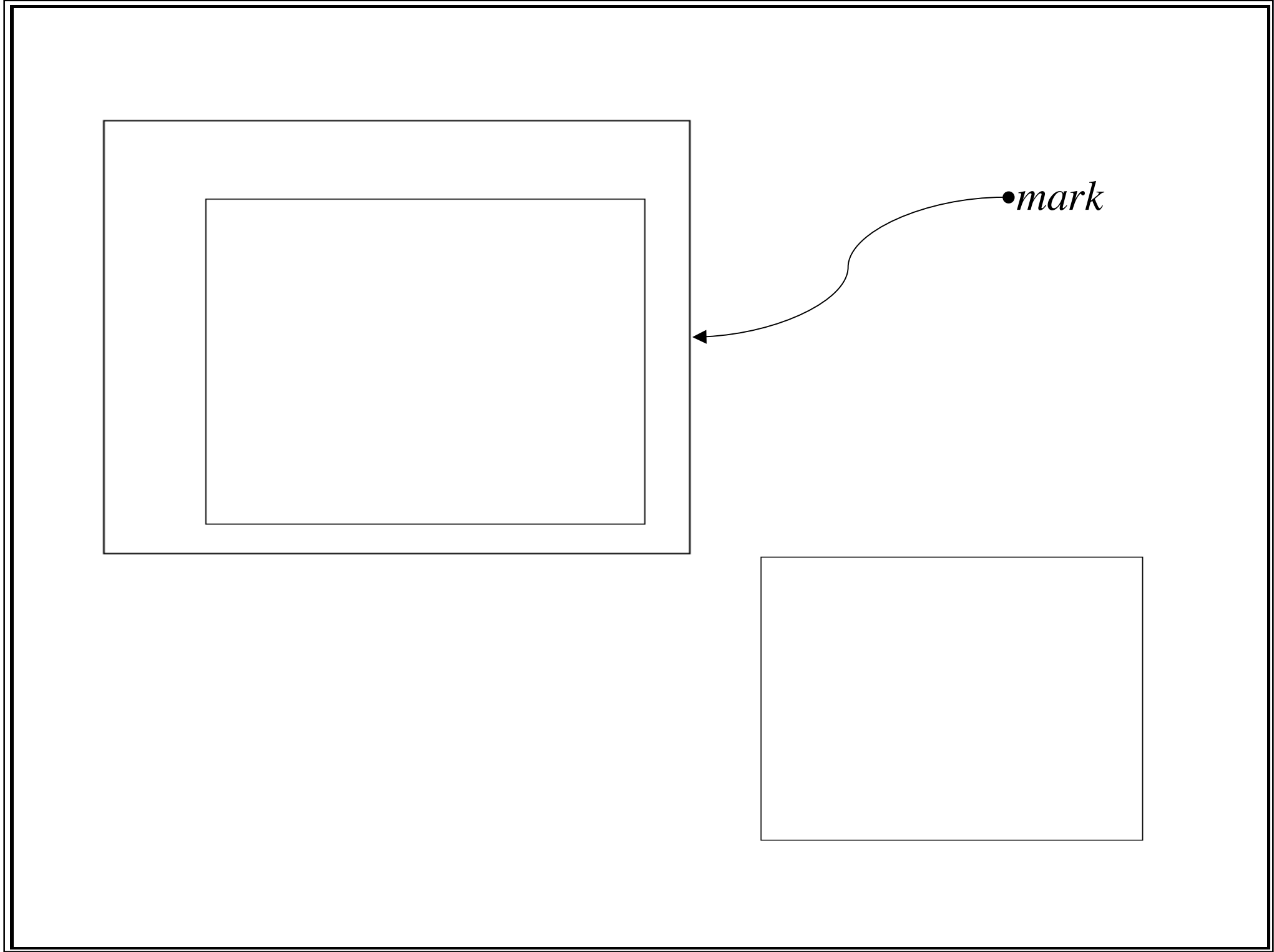
Syntactic Variety

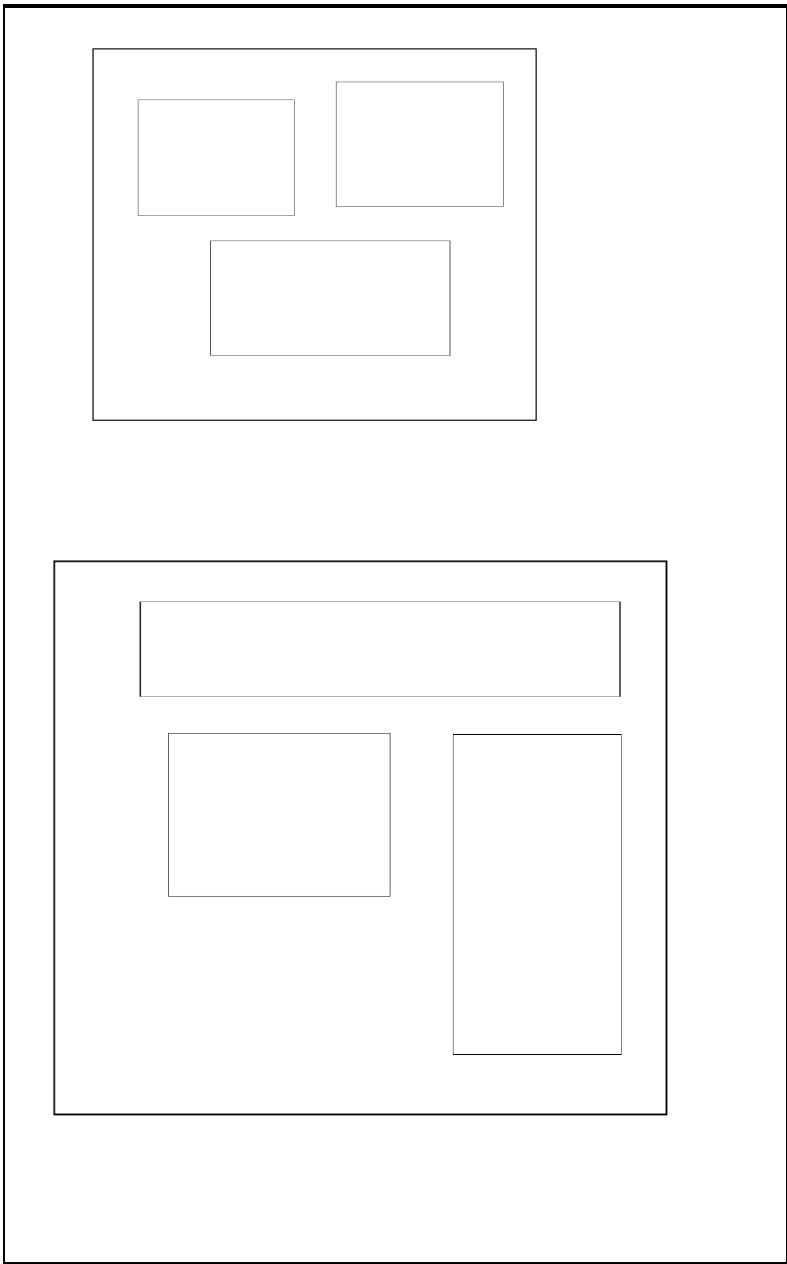
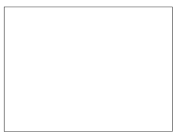
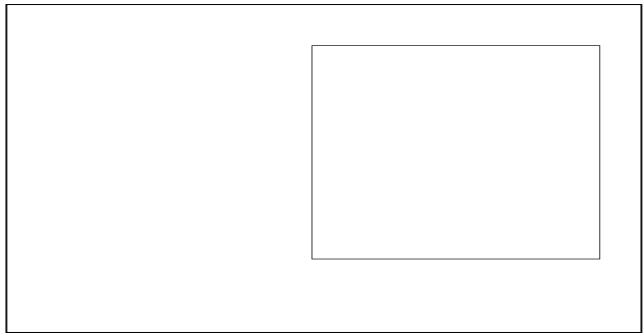
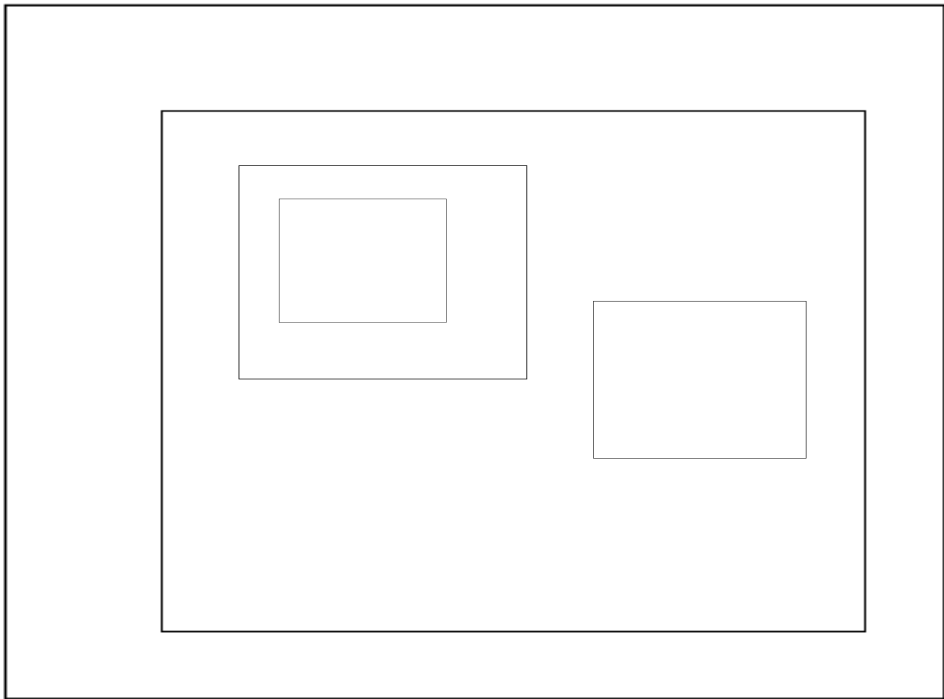
representation
concepts
transformation
animations



$$(()) (()) (()) \implies ()$$

DE NOVO





Void and Mark

We construct a particular space of representation by framing it.

In the beginning there is **no structure**, there is only the frame.

Void space within the frame is featureless.

- void space is not filled with points, nor is it continuous



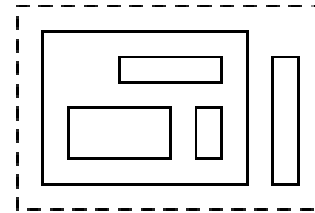
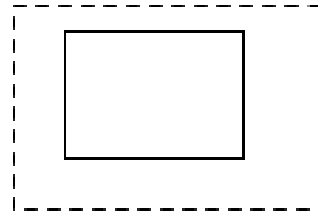
A **frame** is singular and cannot be decomposed.

- absence of decomposition means absence of the concept of intersection

A **mark** is a representation of the frame within itself.

- marks support both an inside and an outside (just like frames)

Replication of marks constructs a language of boundary forms.

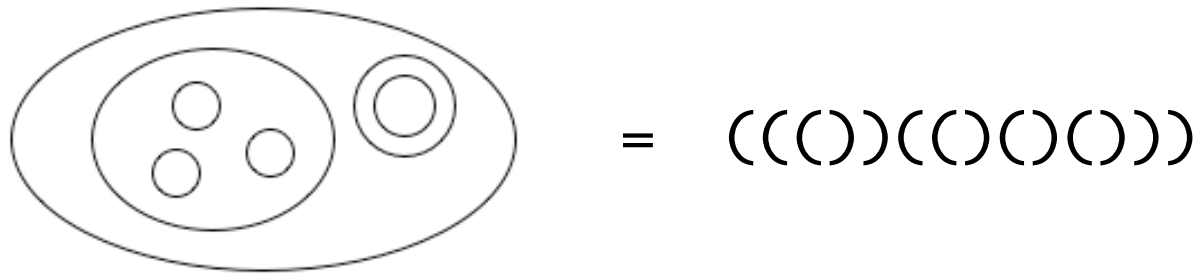


Typographical Delimiters as Marks

A **delimiting pair of tokens** (parentheses, braces, brackets, quotations, etc.) can be used as a **typographical representation of a mark**.

Parentheses used as spatial boundaries are called *parens*.

(inside) outside
parens boundary



Parens introduce these **accidental properties** (which must be ignored):

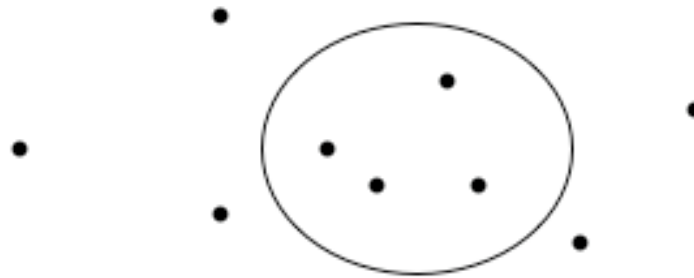
- fragmentation of the boundary into two tokens "left" and "right"
- linear ordering of boundaries in a string

Two Types of Composition

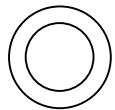
A *boundary form* is a composition of non-intersecting closed curves.

Boundaries support two types of composition

- **SHARING** is composition on the outside
- **BOUNDING** is composition on the inside
- **neither operation requires a concept of arity**



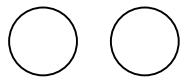
Bounding



Forms are bounded (contained or enclosed) by an outer boundary.

Any number of forms can be contained by the same boundary.

Sharing



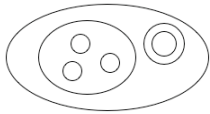
Forms sharing a space are structurally independent.

Any number of forms can share a space.

Forms within a common boundary share the interior space of that boundary.

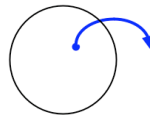
Two Types of Crossing

Boundaries impose structure on a featureless representational space by distinguishing their contents, nothing more.

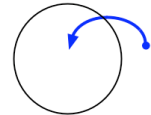


Boundaries have **two sides**, permitting two types of crossing:

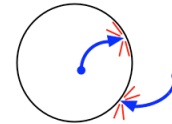
from the inside to the outside



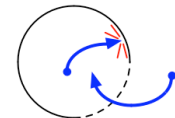
from the outside to the inside



Impermeable boundaries deny crossing of both types.

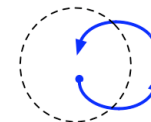


Semipermeable boundaries permit crossing in one direction only.



Fully permeable boundaries do not distinguish their contents.

(They are indistinguishable from the absence of a boundary.)



By convention, the **semantic viewpoint** is on the outside.*

(That is, *we* are on the outside of a representational space.)

* W. Bricken (1994) Inclusive Symbolic Environments. in K. Duncan and K. Krueger (eds.)
Proceedings of the 13th World Computer Congress, v3, Elsevier Science, 163-170.

Pattern-Variables and Pattern-Equations

Pattern-variables stand in place of any form (i.e. universal quantification), including

- an outer boundary and its contents $A = ((()()))$
- forms sharing a space $A = (()()) ()$
- the absence of a form $A = <\text{void}>$

Pattern-templates are forms (usually with variables) that identify an equivalence class.

Example: $(A ((B)))$ matches $((()()) ())$, with $A= (()())$ and $B=<\text{void}>$
as well as $((()())) ()$, with $A=()$ and $B=()$
but not $(() ((())))$

Pattern-equations collapse specific equivalence classes.

- transformation of patterns is based on **substitution and replacement of equals**
- pattern-equations can be applied **in parallel** when matches do not overlap structurally
- pattern-equations define the **semantics** of the boundary language

Example: $(A)(B) = (A B)$

$((()())())$	
$((()())())$	two parallel substitutions
$((() ()))$	one resultant sequential substitution
$((()))$	

First Class Void

Empty containers permit the semantic use of non-representation.

() contains *nothing* on the inside

Void-equivalence

- forms and pattern-templates can be equated to <void>.

(A ()) = <void>

Void-based pattern transformation

- substitution of <void> for a void-equivalent form is **deletion** of the form

(B (A ())) = (B)

Void-substitution

- void-equivalent forms can be deleted at will
- void-equivalent forms can be constructed anywhere throughout a form

(B) = (A ()) (B (A ()) (A ()))

~~~ The Principle of Void-Equivalence ~~~

*Void-equivalent forms are syntactically irrelevant and semantically inert.*

# Two Interpretations

*A (semantic) **interpretation** is a mapping of boundary forms to objects in a domain of interest, together with pattern-equations that specify the calculus of the domain.*

Many interpretations of boundary mathematics have been developed, including knot theory, Boolean algebra, real numbers, and imaginary logic and numerics.\*

Two interpretations follow, **integer arithmetic** and **propositional logic**.

|                           |                                                   |                                                     |
|---------------------------|---------------------------------------------------|-----------------------------------------------------|
| Object mapping:           | $\emptyset = \langle \text{void} \rangle, 1 = ()$ | FALSE = $\langle \text{void} \rangle$ , TRUE = $()$ |
| Corresponding operations: | Addition is SHARING<br>Multiplication is BOUNDING | Disjunction is SHARING<br>Negation is BOUNDING      |
| Pattern-equations:        | $(( )) = ()()$                                    | $() = ()()$ , $(( )) = \langle \text{void} \rangle$ |

The **syntactic varieties** presented later apply to any interpretation.

\* W. Bricken (1991) A Formal Foundation for Cyberspace. *Proceedings of Virtual Reality '91, The Second Annual Conference on Virtual Reality, Artificial Reality, and Cyberspace*, San Francisco, Meckler, 9-37

\* W. Winn and W. Bricken (1992) Designing Virtual Worlds for Use in Mathematics Education: The Example of Experiential Algebra. *Educational Technology*, v32(12), 12-19.

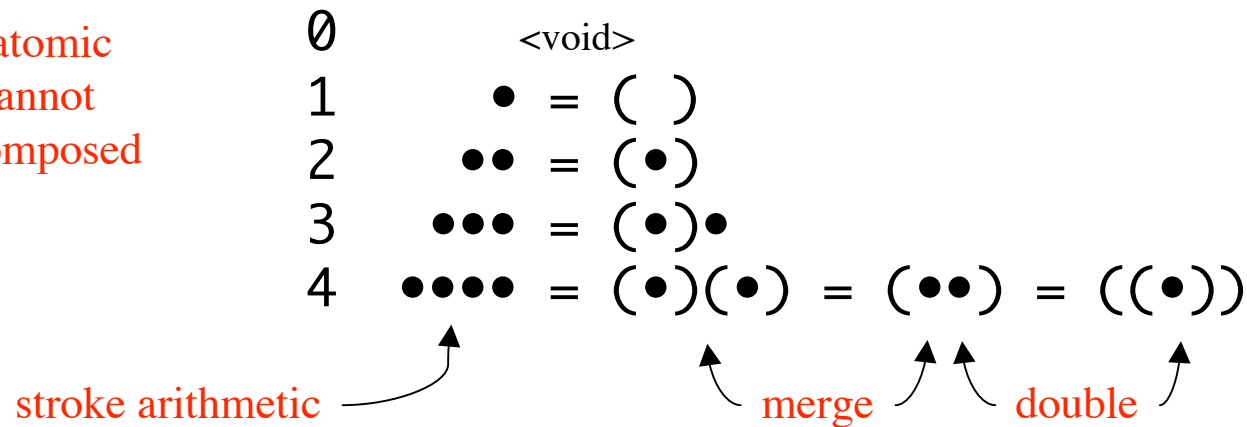
# BOUNDARY INTEGERS

# Boundary Integer Arithmetic\*, Representation

## Boundary place notation

uses depth of nesting rather than location in sequence for place notation.

**()** is atomic  
and cannot  
be decomposed



Pattern-equations for **standardizing forms**:

$$\bullet\bullet = (\bullet)$$

**Double**

$$(A)(B) = (A\ B)$$

**Merge**

**Standardization** constructs an equivalent form with the fewest number of boundaries.

\*Kauffman, L.H. (1995) Arithmetic in the Form. *Cybernetics and Systems* 26: 1-57.

# Boundary Integer Arithmetic, Operations

**Addition** is sharing the same space:

$$A + B \implies A \ B$$

**Multiplication** is unit substitution:

$$A * B \implies \text{substitute}[B \text{ for } \bullet \text{ in } A] = \text{substitute}[A \text{ for } \bullet \text{ in } B]$$

Addition occurs by placing forms in the same void-space

- no ordering, grouping, or arity in void-space

Multiplication occurs by placing replicate forms in •-space

- no ordering, grouping, or arity in •-space

**Neither operation requires additional computation.**

- no number facts, no "carrying"

*All computation is form standardization.*



# Boundary Integer Operations, Example

5: ((•))•

7: ((•)•)•

7+5: ((•)•)• ((•))•

5\*7: (( • )) • • \* (( • ) • • ) •  
 (( 7 )) 7 = (( 5 ) 5 ) 5  
 (( ((•)•)• )) ((•)•)• = (( ((•))• ) ((•))• ) ((•))•

*Standardizing the results:* (D = double M = merge L = linear artifact)

7+5: put 7 and 5 in space

((•)•)•((•)) • L  
 ((•)•) ((•)) •• D  
 ((•)•) ((•))((•)) M  
 ((•)•) ((•) •) L  
 ((•) ((•) ••) D  
 ((•) ((•)•) M  
 ((•) • •) D  
 (( (•) •))

5\*7: substitute 7 for • in 5

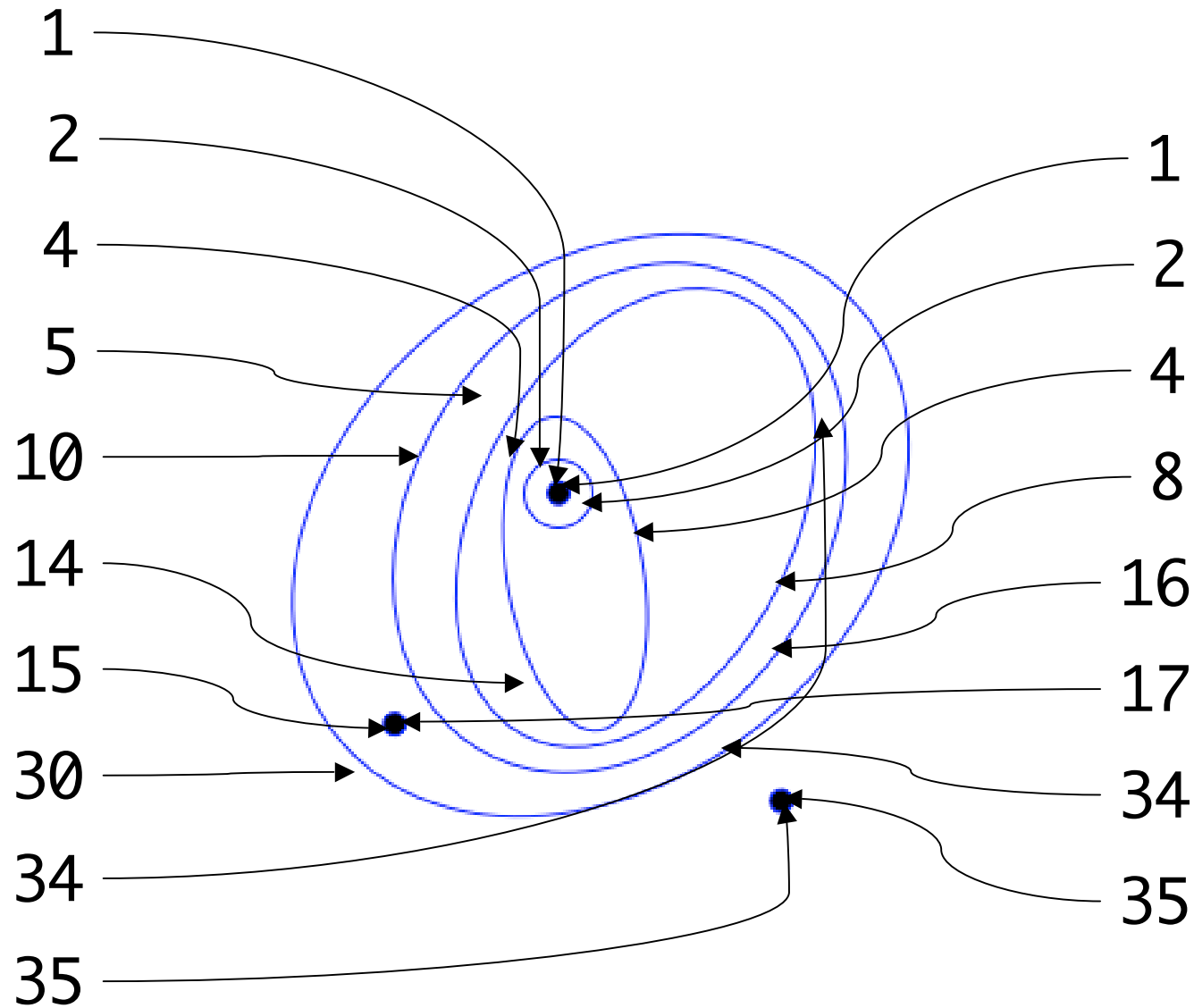
(((((•)•)•))((•)•)• M  
 (((((•)•)•) ((•)•)•) M  
 ((((((•)•)•) •) •)•) D  
 ((((((•)•) ((•) •)•)•) M  
 ((((((•)•) •) •) •)•) D  
 ((((((•) ((•) •) •)•)•) M  
 ((((((•) •) •) •) •)•) D  
 ((((((•) •) •) •) •)•) D

7\*5: substitute 5 for • in 7

(((((•)•)•)((•) •)•)(( •) •)• M  
 ((((((•)•) •) •) •) (( •) •)•) L  
 ((((((•)•) ((•) •) •) •) (( •) •)•) M  
 ((((((•)•) •) •) •) •)•) D  
 ((((((•)•) •) •) •) •)•) M  
 ((((((•)•) •) •) •) •)•) D  
 ((((((•)•) •) •) •) •)•) M  
 ((((((•)•) •) •) •) •)•) D  
 ((((((•)•) •) •) •) •)•) D

# Reading Boundary Integers

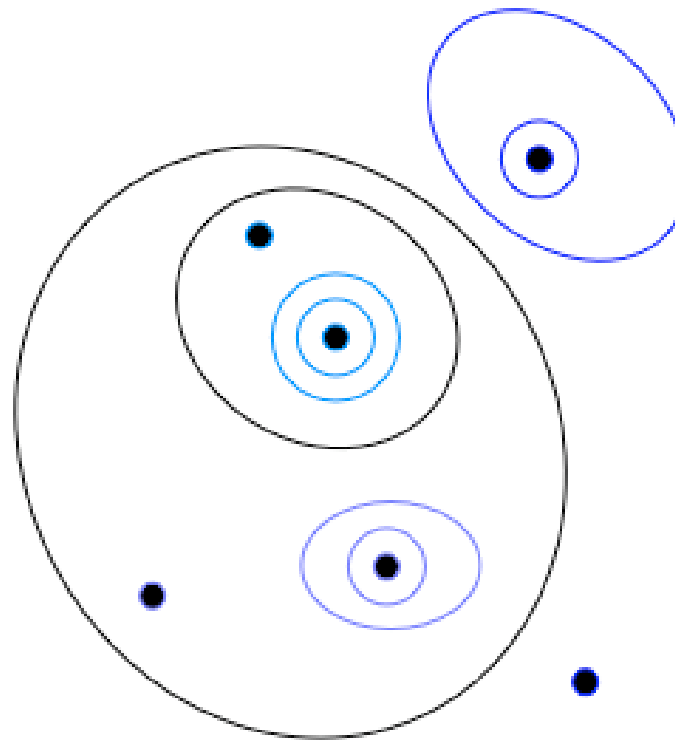
begin  
innermost



begin  
innermost

# Standardizing Boundary Integers

Standardization reduces  
the boundary form of 35  
from 14 to 8 boundaries



# BOUNDARY LOGIC

# The Evolution of Boundary Logic

Originated by the *founders of formal logic*

- 1879 Gottlob Frege -- network notation based on implication  
the German logician who invented formal mathematics
- 1896 Charles S. Peirce -- enclosure notation based on conjunction  
the American logician who invented semiotics

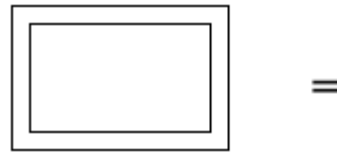
|       |                             |                                                                                     |
|-------|-----------------------------|-------------------------------------------------------------------------------------|
| 1890s | C.S. Peirce                 | entitative and existential graphs, boundary notation                                |
| 1963  | I. Calvino                  | "A Sign in Space" (literature)                                                      |
| 1967  | G. Spencer Brown            | "Laws of Form" (mathematics)                                                        |
| 1975  | F. Varela (and L. Kauffman) | "A Calculus for Self-reference" (imaginaries)                                       |
| 1982  | W. Bricken                  | Losp Deductive Engine (computer science)                                            |
| 1985  | First Sign/Space Conference | (cybernetics)                                                                       |
| 1992  | R. Shoup                    | "A Complex Logic for Computation with Simple Interpretations for Physics" (physics) |
| 2001  | L. Kauffman                 | "The Mathematics of Charles Sanders Peirce" (mathematics)                           |

# A Boundary Arithmetic for Logic

*Common boundaries cancel* (when empty on the inside)



**Call**




**Cross**

## *Interpretation*



The outside is TRUE.

T = 

The inside is FALSE.

F = <void>

**One spatial form provides two symbolic values.**

# Boundary Logic Pattern-Equations

*SHARING EVALUATION*

*(idempotency)*

$$( ) ( ) = ( )$$

**Call**

composition on the outside  
is disjunction

*BOUNDING EVALUATION*

*(involution)*

$$(( )) = \text{<void>}$$

**Cross**

composition on the inside  
is negation

Spencer Brown's radical innovation



Each **pattern-equation** is implemented by pattern-matching and substitution.  
Each proceeds from left to right by **void-substitution**.

# Evaluation via Deletion

*FALSE* = 0 = <void>

To evaluate a **FALSE** variable: *delete* the variable.

*TRUE* = 1 = ( )

To evaluate a **TRUE** variable: *delete the container* of the variable.

*Example:*

a IFF b --> (a b) (( a)( b)) transcribe

Let a=0, b=0: ( ) (( )( )) ==> ( ) call, cross

---

Let a=0, b=1: ( ( )) (( )( )) ==> <void> cross 3 times

---

Let a=1, b=1: (( )) (( )( )) ==> ( ) call, cross 3 times



# Transcribing Boolean and Boundary Logics

| BOOLEAN        | BOUNDARY      |
|----------------|---------------|
| FALSE          | <void>        |
| TRUE           | ( )           |
| NOT a          | (a)           |
| a OR b         | a b           |
| NOT (a OR b)   | (a b)         |
| IF a THEN b    | (a) b         |
| a AND b        | ((a)(b))      |
| a EQUIVALENT b | (a b)((a)(b)) |

*The boundary logic "constant" set:* {  }

*The boundary logic "function" set:* {  }

# One-to-Many Mapping

One boundary form represents *many different conventional logic expressions*.

A one-to-many mapping is necessary for one system to be *simpler*.

The particular logical interpretation of a given boundary form is a *free choice*.\*

( )

1  
NOT 0  
1 OR 0  
0 OR 1 OR 0  
0 NOR 0  
(NOT 0) OR 0  
NOT (0 OR 0)  
NOT (0 OR 0) OR (0 OR 0)  
...

((a)(b))

a AND b  
b AND a  
NOT (NOT a OR NOT b)  
NOT a NOR NOT b  
NOT (a NAND b)  
(a AND b) OR 0  
NOT (a NAND (0 OR b)) OR 0  
NOT (b NOR 0) OR NOT a OR 0  
...

<void> = 0 = 0 OR 0 = 0 OR 0 OR 0 = ...

\*Shin, S. (2002) *The Iconic Logic of Peirce's Graphs*. MIT Press

# Algebraic Pattern-Equations

## Axioms

remarkably  
succinct

$$(A \ ()) = \text{<void>}$$

**Occlusion**

$$A \{A \ B\} = A \ {B}$$

**Pervasion**

Curly braces refer to *any* deeper intervening structure.  
There is no analogy in conventional mathematical techniques.

## Useful Theorems

$$((A)) = A$$

**Involution**

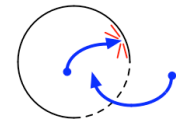
$$() \ A = ()$$

**Dominion**

Each **pattern-equation** is implemented by pattern-matching and substitution.  
Each proceeds from left to right by **void-substitution**.

# Deep Transformation

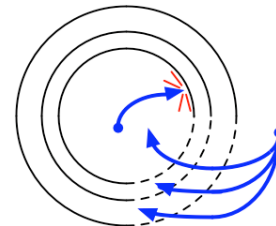
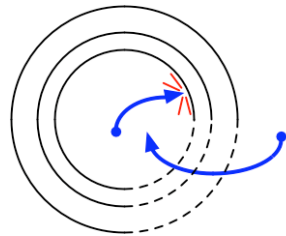
Any form on the outside of a boundary pervades all inside spaces.  
From the outside, boundaries are *transparent* (semipermeable).



$$A \{A \ B\} = A \{B\}$$

**Pervasion**

Forms in an exterior space are arbitrarily present in every interior space.



*Example:*

a (b (a c (d (a b e))))

a (b ( c (d ( b e))))

a (b ( c (d ( e))))

pervasion a

pervasion b

*Therefore:* a (b (a c (d (a b e)))) = a (b (c (d (e))))

# Boundary Logic Proof of *Modus Ponens*

$$\alpha, (\alpha \models \beta) \models \beta \longrightarrow ((\alpha) ((\alpha) \beta)) \beta$$

*Transcribe*

(a AND (a IMPLIES b)) IMPLIES b  
 (a AND (a IMPLIES b)) IMPLIES b  
 (a AND (a) b ) IMPLIES b  
 ((a) ( (a) b ) ) IMPLIES b  
 ( ((a) ( (a) b ) ) ) b

*modus ponens*

a IMPLIES b  $\longrightarrow$  (a) b

a AND X  $\longrightarrow$  ((a)(X))

X IMPLIES b  $\longrightarrow$  (X) b

*Reduce*

(((a)((a) b))) b  
 (a)((a) b) b  
 (a)( ) b  
 ( )

transcription

involution ((A))  $\implies$  A

pervasion A (A B)  $\implies$  A (B)

dominion A ( )  $\implies$  ( )

*Interpret*

TRUE

# Pathways Through Metatheory

## Void-equivalence

$$\langle\langle A \ () \rangle\rangle = ( \langle A \ () \rangle ) = ( \langle A \rangle \ \langle () \rangle ) = ( \langle A \rangle \ () ) = ( \ \ () ) = \langle \text{void} \rangle$$

## The map to logic

Metatheory is invariant under provable equivalence.

- the maps from Boolean logic and from AEG to boundary logic preserve validity\*

## Algebraic deduction

Entailment transcribes into Birkoff's rules of equational deduction\*\*.

- validity is maintained by bidirectional equations
- substitution and replacement are domain independent

$$\begin{aligned} A=B \text{ IF } A \Rightarrow B \\ A=B \text{ IF } A \Rightarrow C \text{ AND } B \Rightarrow C \\ A=B \text{ IF } A \Rightarrow () \text{ AND } B \Rightarrow () \\ \text{OR } A \Rightarrow \text{ AND } B \Rightarrow \\ A=B \text{ IMPLIES } \phi[A]=\phi[B] \end{aligned}$$

## Algebraic structure

Completeness follows from the maximal ideal theory\*\*\*.

## Pattern rewrite system

Void-substitution assures both termination and convergence.

## Induction over boundary patterns

Ground cases:  $()$  and  $\langle \text{void} \rangle$ .

Given  $(A)$ , show  $A$

Given  $A \ B$ , show  $A \ , \ B$  separately

Net result:

$$\begin{aligned} \alpha \rightarrow \beta &= (\alpha) \ \beta \\ \alpha \mid - \beta &= (\alpha) \ \beta \\ \alpha \mid = \beta &= (\alpha) \ \beta \\ \alpha, (\alpha \mid = \beta) \mid = \beta &= ((\alpha) \ ((\alpha) \ \beta) \ )) \ \beta \end{aligned}$$

\*Dau, F. (2005) *Mathematical Logic with Diagrams*. [www.dr-dau.net/publications.shtml](http://www.dr-dau.net/publications.shtml)

\*\*Birkoff, G. (1935) On the Structure of Abstract Algebras. *Proceedings of the Cambridge Philosophical Society*, 31 417-429

\*\*\*Halmos, P. and Givant, S. (1998) *Logic as Algebra*. Mathematical Association of America.

# Alpha Existential Graphs

Peirce's [five rules for Alpha Graphs](#)\* map directly to boundary logic pattern-equations:

| RULE                  | EXISTENTIAL               | ENTITATIVE               | BOUNDARY                |
|-----------------------|---------------------------|--------------------------|-------------------------|
| <b>R1. Erase</b>      | $((A) B) \models (( ) B)$ | $((A) B) \models ((A) )$ | } $(A ( )) =$           |
| <b>R2. Insert</b>     | $(A) \models (A B)$       | $A \models A B$          |                         |
| <b>R3. Iterate</b>    | $A (B) \models A (A B)$   | $A (B) \models A (A B)$  | } $A \{B\} = A \{A B\}$ |
| <b>R4. Deiterate</b>  | $A (A B) \models A (B)$   | $A (A B) \models A (B)$  |                         |
| <b>R5. Double cut</b> | $((A)) = A$               | $((A)) = A$              | $((A)) = A$             |

Boundary logic provides a more modern algebraic transformation system, uniting pairs of asymmetrical implicative rules into symmetrical equations.

The Erase and Insert rules of AEG fail to provide a clear termination goal. Boundary logic uses a single void-equivalence rule, [Occlusion](#), as a termination condition.

\* Peirce, C.S. (1931-58) *Collected Papers of Charles Sanders Peirce*. Hartshorne, C. Weiss, P., Burks, A. (eds.) Harvard Univ Press.

# SYNTACTIC VARIETY: REPRESENTATION



# Syntactic Varieties (textual)

Each syntactic variety that follows assumes **Occlusion** and **Pervasion**, the two pattern-equations that define boundary *logic*.

## Topological varieties

- different spatial data structures with different implementation behavior
- analogous to conventional data structures

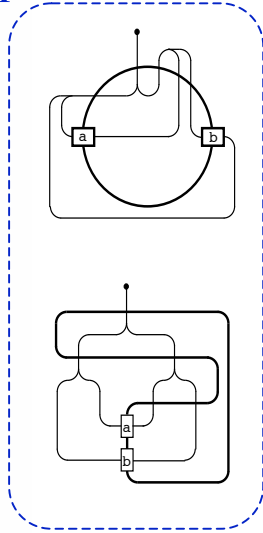
## Geometric varieties

- different metric structures with similar implementation behavior
- analogous to exchanging tokens in a string-based language

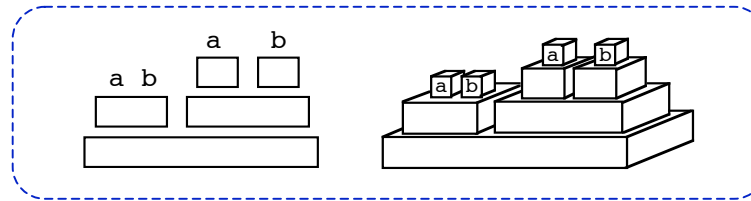
| VARIETY                | DIMENSION | BOUNDING | SHARING         | POINT OF VIEW |
|------------------------|-----------|----------|-----------------|---------------|
| <b>parens</b>          | 1         | nest     | space           | outside       |
| <b>enclosures</b>      | 2         | enclose  | space           | outside       |
| <b>trees</b>           | 2         | link     | branch          | outside       |
| <b>maps</b>            | 2         | border   | common neighbor | outside       |
| <b>centered maps</b>   | 2         | border   | common neighbor | inside        |
| <b>rooms</b>           | 2/3       | door     | common neighbor | inside        |
| <b>graphs/networks</b> | 3         | link     | branch          | both          |
| <b>paths</b>           | 3         | cross    | fork            | both          |
| <b>blocks</b>          | 3         | stack    | common floor    | outside       |

# Syntactic Varieties (diagrammatic)

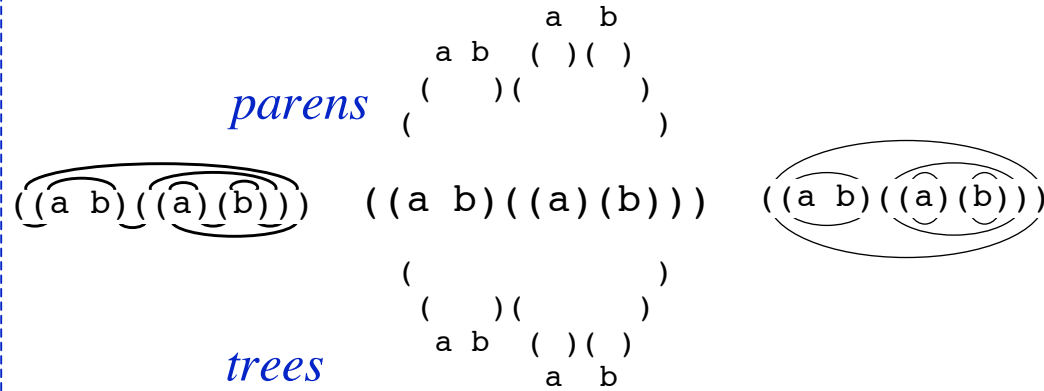
*paths*



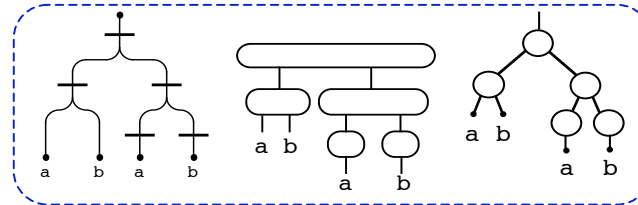
*blocks*



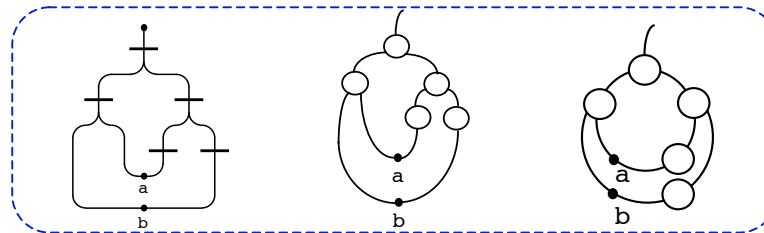
*parens*



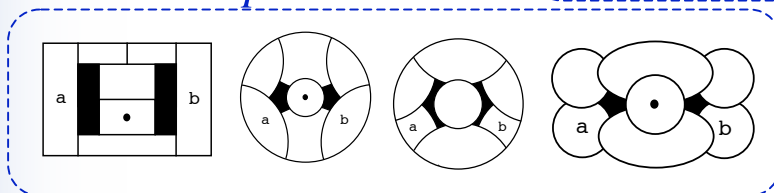
*trees*



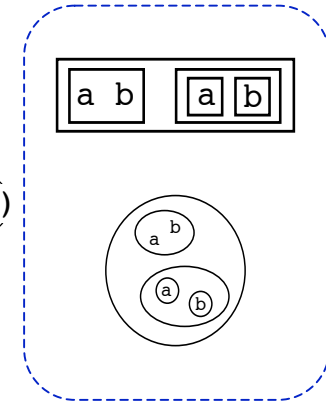
*graphs*



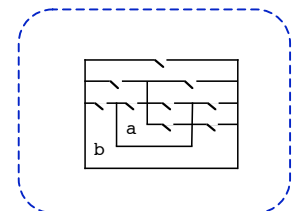
*centered maps*



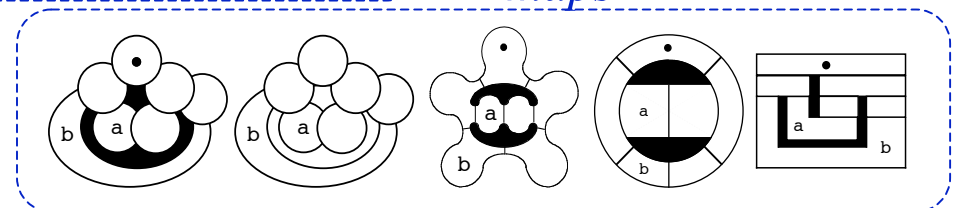
*enclosures*



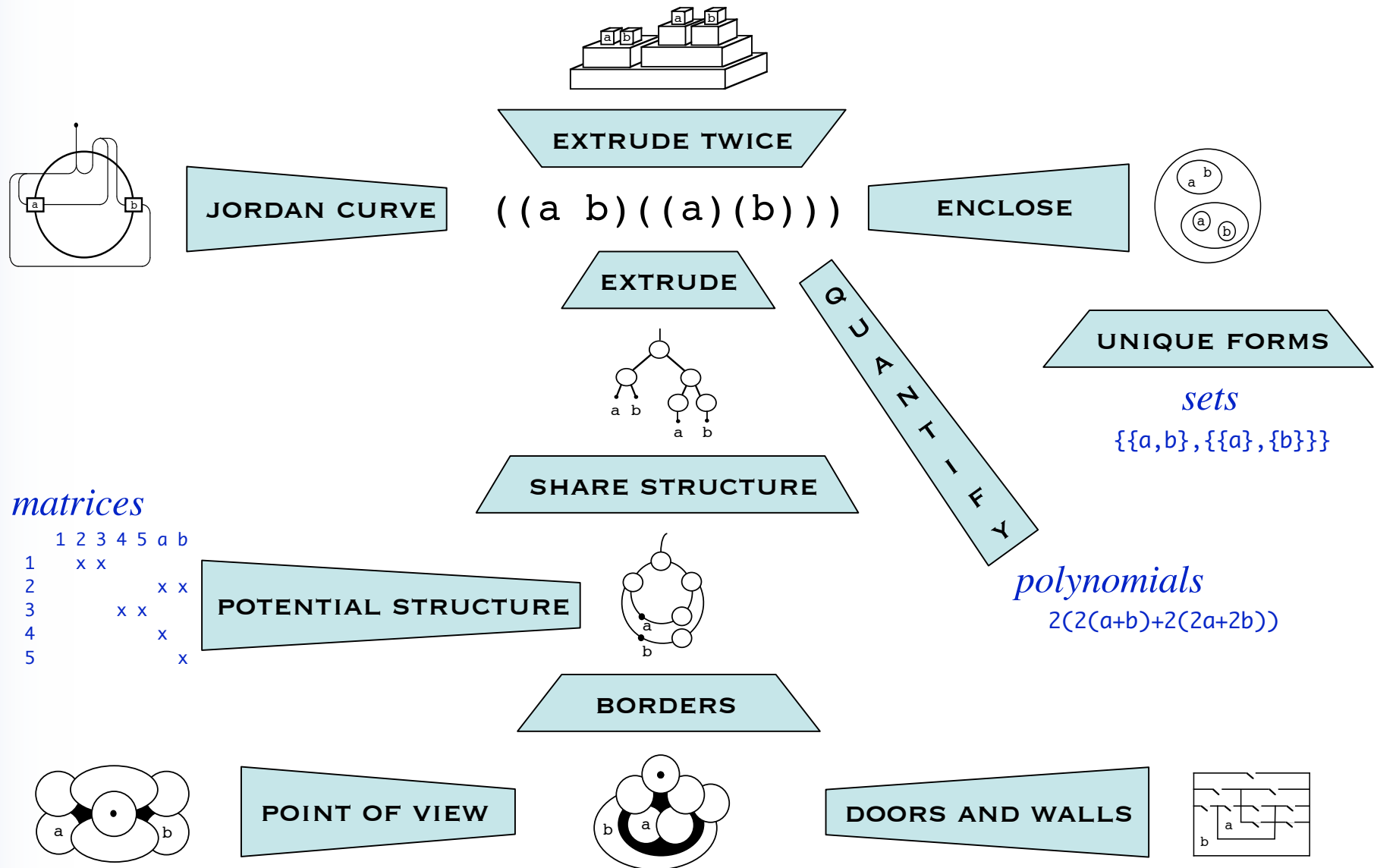
*rooms*



*maps*



# Mappings Between the Syntactic Varieties



# Syntactic Concepts

## Dimensionality of representation

1-space fractures containment, 2-space limits structure sharing

## Top and bottom

represents outermost and innermost

## Point of view

read from outside (objectively) or from inside (subjectively)

## Anthropomorphism

some forms are physically familiar, others are abstract

## Surrounding space

map varieties incorporate the background substrate

## Geometric varieties

rubber sheet geometry

## Topological varieties, generated by

extrude and rotate in higher dimensional space

structure sharing (unique objects)

convert links to borders

exterior or interior point of view

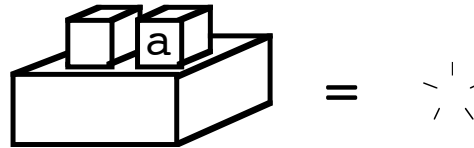
exchange objects for processes

# SYNTACTIC VARIETY: TRANSFORMATION

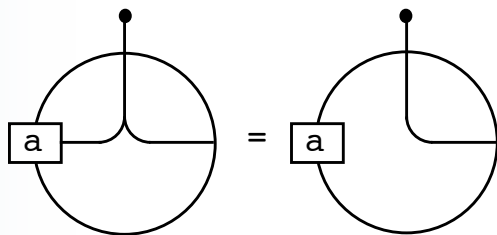
# Occlusion

delete structure

*blocks*



*paths*

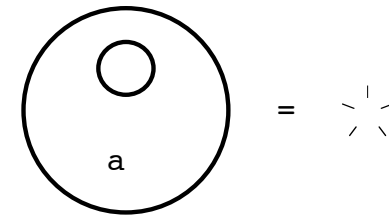


delete path

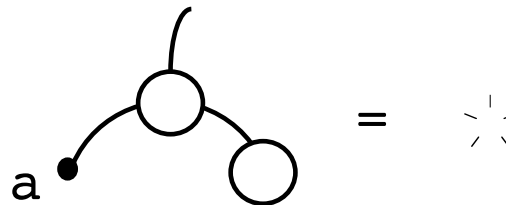
*parens*



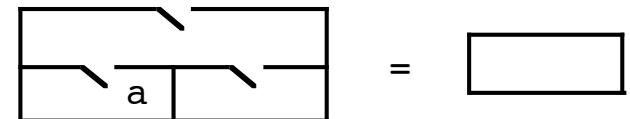
*enclosures*



*graphs*

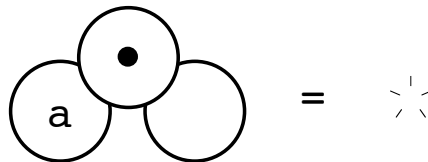


*rooms*



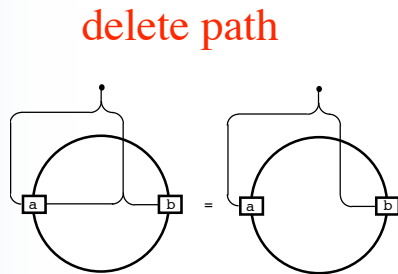
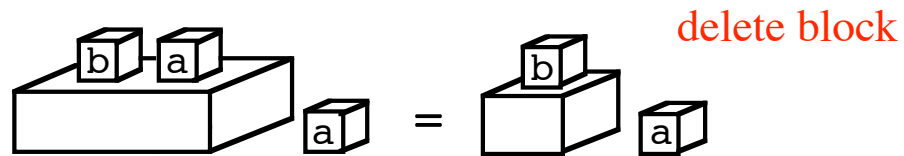
close door

*maps*



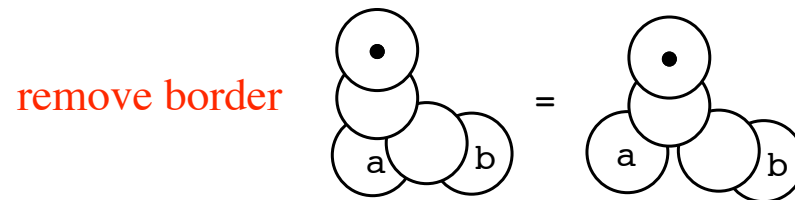
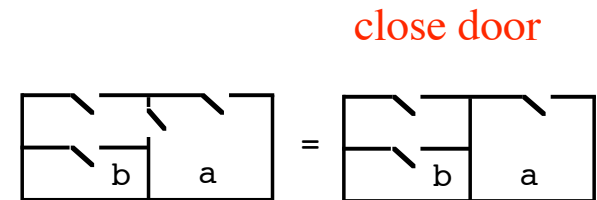
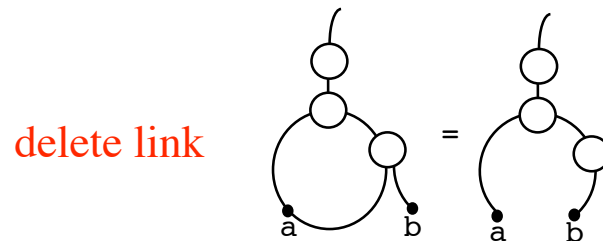
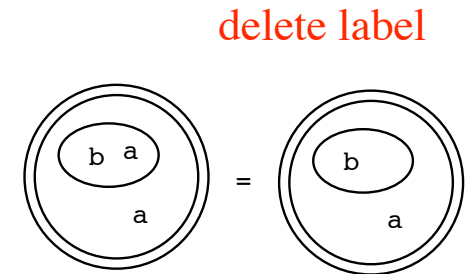
# Shallow Pervasion

Deep pervasion operates across any depth of nesting.



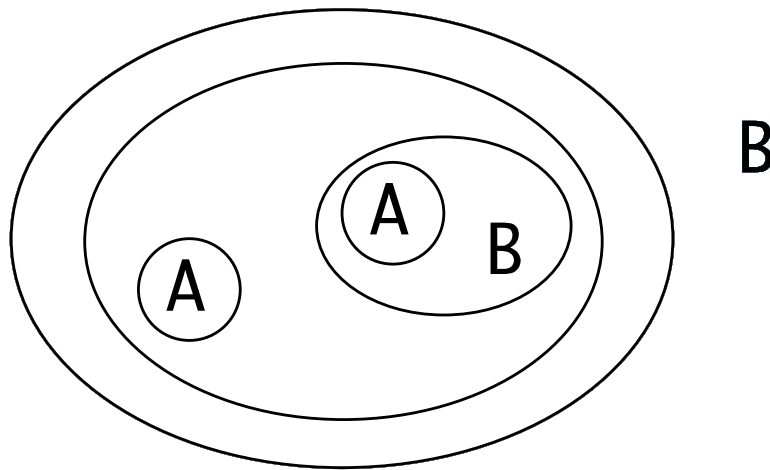
$$A (B A) = A (B)$$

delete variable



# *Modus Ponens: Parens and Enclosures*

$( ((A) ((A) B)) ) B = ()$

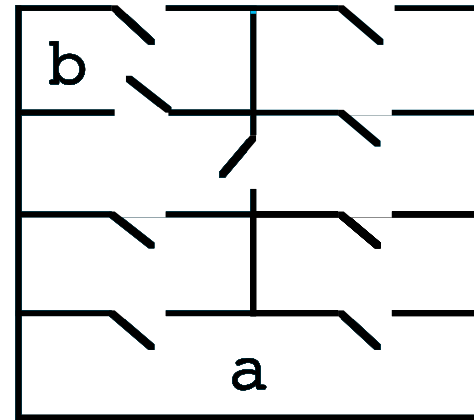
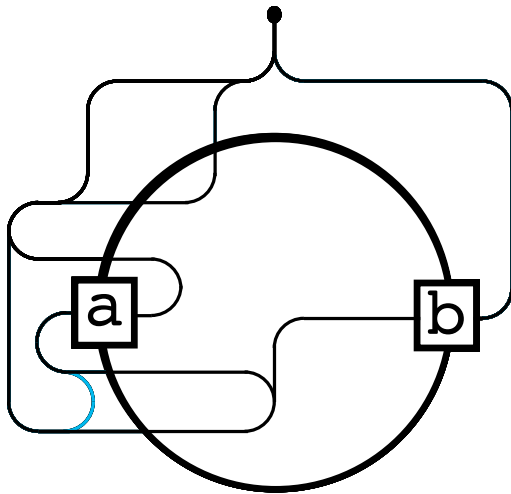


interpret as TRUE

|                    |                 |
|--------------------|-----------------|
| $((A) ((A) B))) B$ | transcription   |
| $((A) ( )) B$      | pervasion (A) B |
| $( ) B$            | occlusion       |
| $( )$              | dominion        |



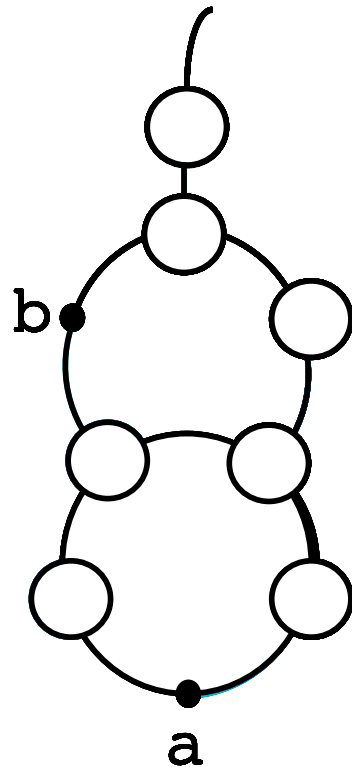
# *Modus Ponens: Paths and Rooms*



(((a) ((a) b))) b  
 (a) ((a) b) b  
 (a) ((a) ) b  
 (a) a b  
 ( ) a b  
 ( )

transcription  
 involution  
 pervasion b  
 involution  
 pervasion a  
 dominion

# Modus Ponens: Distinction Networks



|                        |               |
|------------------------|---------------|
| (( ((a) ((a) b))) b )) | transcription |
| (( ((a) ((a) )) b ))   | pervasion b   |
| (( ((a) a )) b ))      | involution    |
| (( (( ) a )) b ))      | pervasion a   |
| (( ( ) b ))            | occlusion     |
| ( )                    | occlusion     |

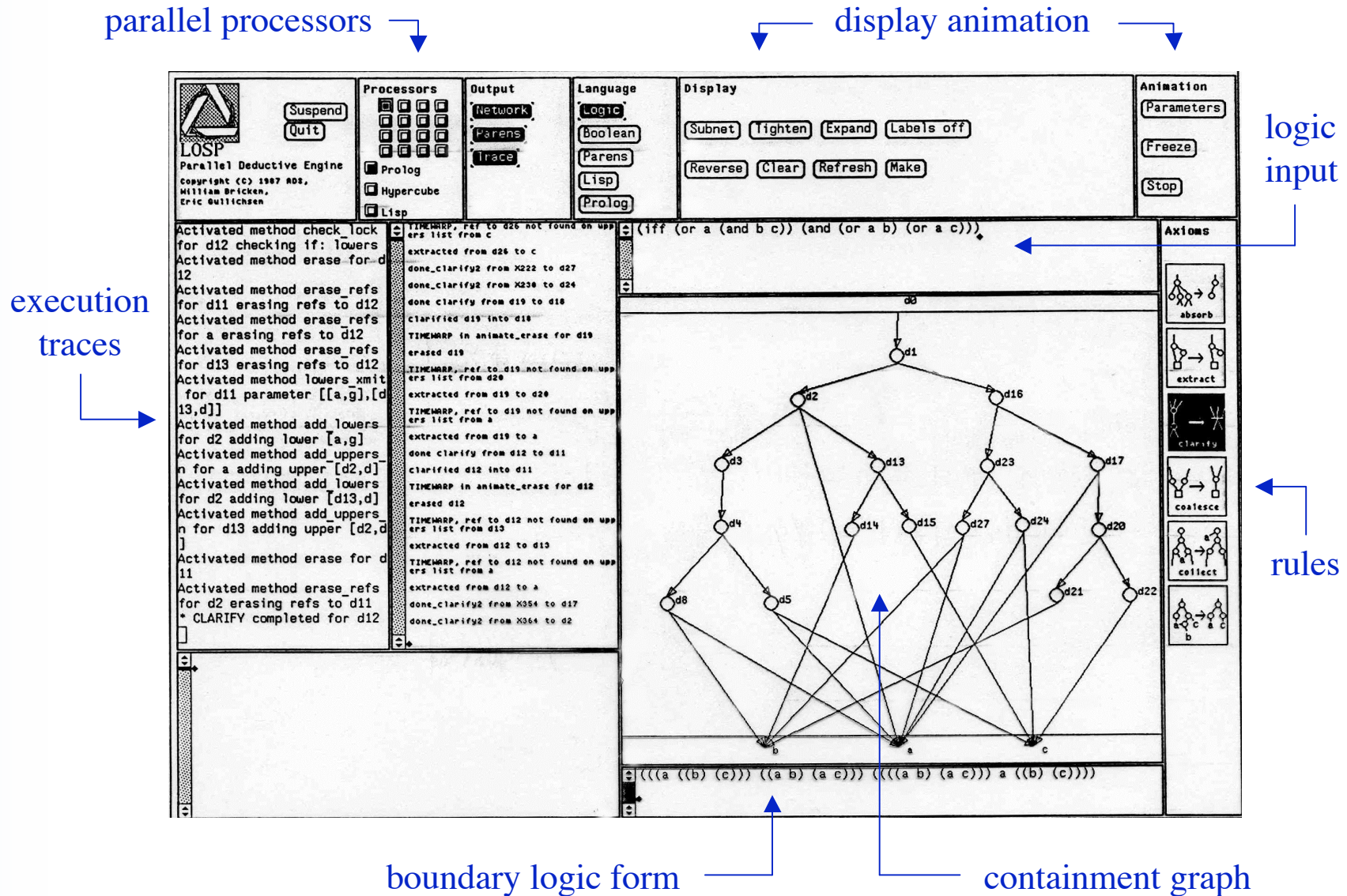
## Concurrent, asynchronous network reduction\*

- each node is an atomic autonomous agent
- communication with direct neighbors only
- local interaction leads to

global deduction without global coordination

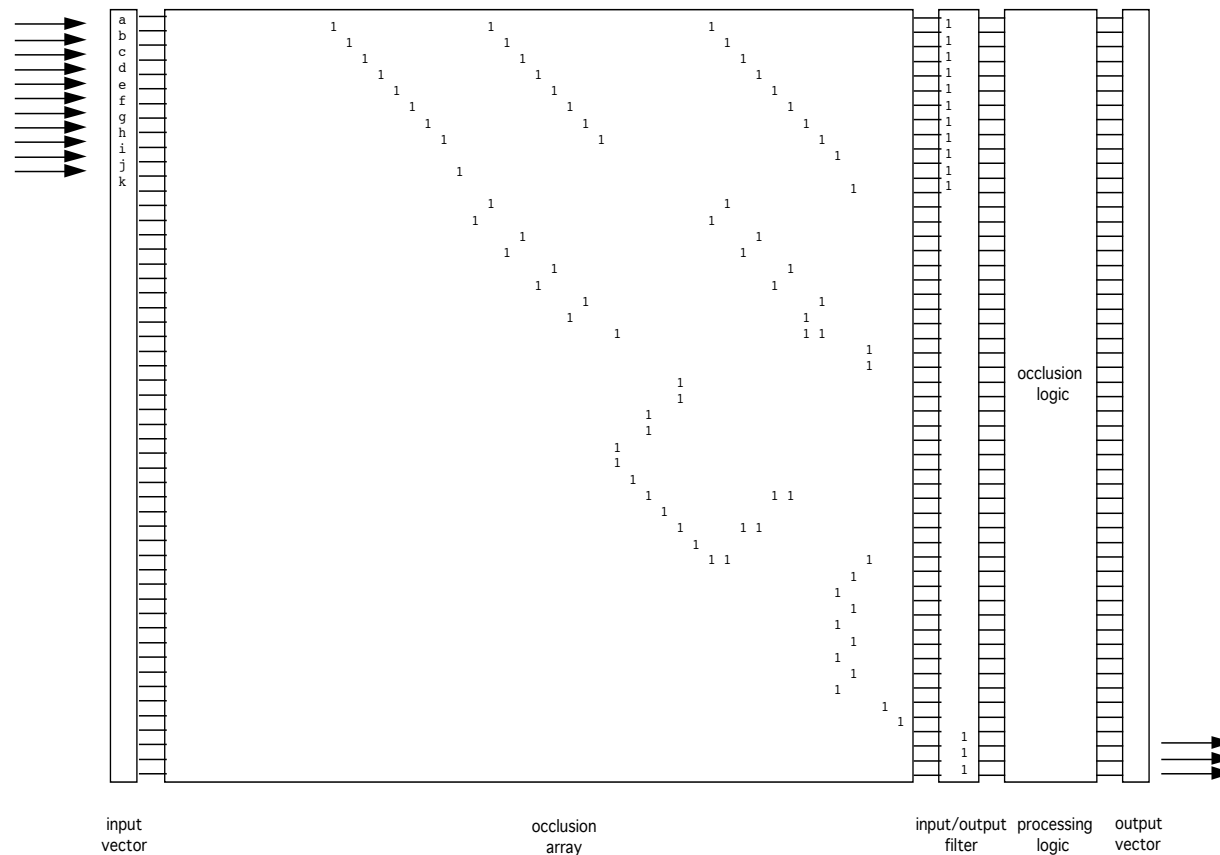
\*W. Bricken (1995) Distinction Networks. in I. Wachsmuth, C.R. Rollinger & W. Brauer (eds.)  
KI-95: *Advances in Artificial Intelligence.*, Springer, 35-48.

# The Losp Parallel Deduction Engine\* (1987)



\* W. Bricken and E. Gullichsen (1989) An Introduction to Boundary Logic with the Losp Deductive Engine, *Future Computing Systems* 2(4), 1-77.

# Sparse Containment Matrix (2002)



Distinction networks implemented on a reconfigurable silicon hardware substrate.  
Matrix entries route signals locally.  
Signals traversing the **containment matrix** implement logic network functionality.

# In Conclusion

**Boundary logic** is an efficient, scalable, robust diagrammatic logic based on pattern-substitution.

**Boundary integers** exchange the effort of addition and multiplication for a single standardization process.

**Both are interpretations** of the same simple diagrammatic language of non-intersecting spatial enclosures.

**Boundary languages** have unique syntactic varieties generated by topological and geometric transformation of structure.

This presentation is available at [www.wbricken.com/01bm/0103notate](http://www.wbricken.com/01bm/0103notate)

I'll be available throughout the conference to demonstrate an implementation of boundary logic used for **minimization of commercial semiconductor circuits**.

*Thank you!*

Comments and questions gladly accepted.  
[bricken@halcyon.com](mailto:bricken@halcyon.com)

# SUMMARIES

# Presentation Notes

Boundary mathematics is a *fundamental innovation in mathematics* (!).

The entertaining challenge:

- do not force-fit these ideas into pre-existing conceptual structures
- very easy to understand on its own ground
- somewhat difficult to understand using conventional concepts

These mathematical techniques have been extensively tested.

- implemented in literally dozens of programming languages
- applied to SAT problems, theorem proving, expert systems
- applied to industrial strength problems in semiconductor minimization

The presentation style is unorthodox.

- rapid visual exposure to relatively dense information
- seeds for contemplation rather than an immediate explanation

Some slides are included for completeness, and will not be discussed in depth.

The presentation (and lots of other material on Boundary Math) is available at

[www.wbricken.com/01bm/0103notate](http://www.wbricken.com/01bm/0103notate)



# Non-Conventional Mathematics Warning

*If a concept or a representation is not explicitly permitted, it is forbidden.*

Void space means with **no pre-assumed mathematical or structural concepts**.

- the space of representation is unstructured
- drawing a mark introduces a distinction; it does not introduce a topology (no points) or a geometry (no metric)

In specific, **absence of the concept of arity** implies

- absence of the capability to count
- no conventional functions or relations
- associativity and commutativity are not relevant structural concepts
- the inside/outside distinction made by boundaries is not relational (boundaries are not set objects)

In general, these mathematical concepts have **not** been explicitly introduced:

- sets  $\{a, b\}$
- points  $(a, b)$
- counting and arity  $1, 2, 3, \dots$
- functions and relations  $f(a) \quad r(a, b)$
- logic  $a \text{ AND } b$
- group theory  $a \diamond a^{-1} = i$
- categories  $f(a) \diamond f(b) = f(a \diamond b)$

# Boundary Mathematics

## Representation

- **Forms**: a language of configurations of closed non-overlapping curves

○ is a form

If A is a form, so is (A)

If A and B are forms, so is A B

- **Variables**: tokens standing in place of arbitrary forms
- **Patterns**: forms serve as structural templates to identify members of an equivalence class
- **Pattern-equations**: pairs of patterns that collapse equivalence classes

## Transformation

- defined solely by pattern-equations
- substitution and replacement of equivalent patterns

## Strategy

- extreme minimalist
- begin on entirely new conceptual ground
- semantic use of void-space (forms can be void-equivalent)

# Novel Concepts

## Semantic void/single constant

Void is everywhere; boundaries distinguish their contents. Nothing more.

## Inside and outside of forms

Enclosure has an interpretation as a partial order.

## Void-equivalence

Void-equivalent structure is semantically irrelevant and semantically inert.

## Semipermeable boundaries/operational transparency

Boundaries are barriers to their contents, but can be transparent to their context.

## Object/operator unification

Patterns are both objects and operators.

## Spatial (non-linear) notation

Inherent computational parallelism.

Syntactic varieties are generated from spatial transformation of forms.

# Why Isn't Boundary Logic Better Known?

## Avoidance of **the void**

- “concepts must have symbolic representations”
- non-existence cannot contribute to computation
- separate concepts must have unique representations
- computation occurs in discrete, unambiguous steps

0110101100  
\_11\_1\_11\_  
11 1 11

## The **politics** of symbolic mathematics

- “diagrams cannot be computational objects”
- Cartesian duality (17th century)
- Russell and Whitehead, *Principia Mathematica* (1910)

## The danger of **eccentrics**

- “just another Boolean algebra” (the isomorphism critique)
- “the foundations of mathematics are well understood”

## Many **misconceptions and misinterpretations**

- representing <void> with a token
- assuming a relational structure
- some trade secrecy

<void> = { } =  $\Phi$

a b = a R b

|      |                                                                                                    |                                                               |
|------|----------------------------------------------------------------------------------------------------|---------------------------------------------------------------|
| 124  | MATHEMATICAL LOGIC                                                                                 | [PART 1]                                                      |
| 4015 | $t: p \supset q, v, p \supset \sim q$                                                              |                                                               |
| Dem. | $t, \#401, \supset t: \sim(p \supset q), \supset, p, \sim q,$                                      |                                                               |
|      | $\#401$                                                                                            | $\supset, p \supset \sim q$                                   |
|      | $\#404$                                                                                            | $\supset t: p \supset q, v, p \supset \sim q$                 |
|      | $t, \#401, \supset t: \sim(p \supset q), \supset, q, \sim p,$                                      | (1)                                                           |
|      | $\#401$                                                                                            | $\supset, p \supset \sim q$                                   |
|      | $\#404$                                                                                            | $\supset t: p \supset q, v, p \supset \sim q$                 |
|      | $t, (1), (2), \#401, \supset t, Prop$                                                              | (2)                                                           |
| 4016 | $t, \sim(p \supset q), p \supset \sim q$                                                           |                                                               |
| Dem. | $t, \#405, \supset t: p \supset q, p \supset \sim q, \supset, p \supset q, p \supset \sim q,$      |                                                               |
|      | $\#405$                                                                                            | $\supset, \sim p$                                             |
|      | $t, \#407, \supset t: p \supset q, p \supset \sim q, \supset, q \supset p, p \supset \sim q,$      | (1)                                                           |
|      | $\#407$                                                                                            | $\supset, q \supset \sim q$                                   |
|      | $\#408$                                                                                            | $\supset, \sim q$                                             |
|      | $t, (1), (2), Comp, \supset t: p \supset q, p \supset \sim q, \supset, \sim p, \sim q,$            | (2)                                                           |
|      | $\#408$                                                                                            | $\supset, \sim(\sim q \supset p)$                             |
|      | $t, (3), Sup, \supset t: p \supset q, \supset, p \supset \sim q, \supset, \sim(\sim q \supset p),$ |                                                               |
|      | $\#408$                                                                                            | $\supset, \sim(p \supset \sim q), v, \sim(\sim q \supset p),$ |
|      | $\#408$                                                                                            | $\supset, \sim(p \supset \sim q), \supset t, Prop$            |
| 4017 | $t: p \vee q, \sim(p, q), \sim, p \supset \sim q$                                                  |                                                               |
| Dem. | $t, \#40401, \supset t: p \vee q, \sim, \sim q \supset p$                                          | (1)                                                           |
|      | $t, \#403, Transp, \supset t: \sim(p, q), \sim, p \supset \sim q$                                  | (2)                                                           |
|      | $t, (1), (2), \#40301, \supset t, Prop$                                                            |                                                               |
| 4018 | $t: p \supset q, \sim(p \supset \sim q)$                                                           | $\left[ \begin{array}{l} \#4010, \#4017 \end{array} \right]$  |
| 4019 | $t, \sim(p \supset \sim q)$                                                                        | $\left[ \begin{array}{l} \#4010, \#4017 \end{array} \right]$  |
| 4020 | $t: \sim p, \sim q, \supset, p \supset q$                                                          | $\left[ \begin{array}{l} \#401, \#4011 \end{array} \right]$   |
| 4021 | $t: \sim(p \supset q), \supset, p, \sim q, v, q, \sim p$                                           | $\left[ \begin{array}{l} \#4010101 \end{array} \right]$       |
| 4022 | $t: p \supset q, \supset, p, q, v, \sim p, \sim q$                                                 | $\left[ \begin{array}{l} \#4010, \#4021 \end{array} \right]$  |
| 4023 | $t: \sim(p, q), \supset, p, \sim q, v, q, \sim p$                                                  | $\left[ \begin{array}{l} \#4020, \#4021 \end{array} \right]$  |
| 4024 | $t: p \supset q, v, \sim p, \sim q, \supset, p, \sim q, v, q, \sim p$                              | $\left[ \begin{array}{l} \#4020, \#4021 \end{array} \right]$  |
| 4025 | $t: p \supset q, \supset, p \supset q, \supset, q$                                                 | $\left[ \begin{array}{l} \#4020, \#4021 \end{array} \right]$  |

# Boundary Logic Computation

An **algebraic** system

- primary semantics is *equality*
- primary process is *pattern-matching and substitution*
- axiomatized by two simple pattern-equations

A **single concept** system

- the primary object is the *boundary*
- the only structure is *enclosure (inclusion)*
- maps *one-to-many* onto Boolean techniques

A **spatial** system

- ordering, grouping and arity are not concepts within the system
- transformations within a space are in *parallel*

A **void-based** system

- *deletion* (void-substitution) rather than rearrangement
- boundaries are *transparent* from the outside
- forms sharing a space are *independent*

# Algebra of Boundary Constants -- Metatheory

Void-equivalence is unorthodox.

no proofs here

*For all boundary forms,  
show that mark-equivalence,  $\langle\langle \rangle\rangle$ , and void-equivalence,  $\langle \rangle$ ,  
never intermix during fully reductive pattern-substitution.*

|                                                                   |                                                                                                           |                                                                                                       |              |
|-------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------|--------------|
| $\langle\langle \rangle\rangle = \langle \langle \rangle \rangle$ | $\boxed{\langle \rangle} \langle \rangle = \boxed{\phantom{\langle \rangle}}$                             | $\langle \rangle = \langle \text{void} \rangle$                                                       |              |
|                                                                   | $\boxed{\langle \rangle} \langle\langle \rangle\rangle = \boxed{\phantom{\langle \rangle}}$               | $\boxed{\phantom{\langle \rangle}} \langle\langle \rangle\rangle = \boxed{\phantom{\langle \rangle}}$ | <b>Call</b>  |
|                                                                   | $\boxed{\langle\langle \rangle\rangle} \langle\langle \rangle\rangle = \boxed{\phantom{\langle \rangle}}$ | $A \langle\langle \rangle\rangle = \langle \rangle$                                                   | <b>Call</b>  |
| $\langle\langle \rangle\rangle \neq \langle \rangle$              | $\boxed{\langle\langle \rangle\rangle} \langle \rangle \neq \boxed{\phantom{\langle \rangle}}$            | $[ \langle\langle \rangle\rangle ] = \langle \text{void} \rangle$                                     | <b>Cross</b> |

**Cross** and **Call** are the constructors of the language.

sound and  
consistent

$$\begin{aligned}
 \langle \langle \rangle \rangle &\leftrightarrow A \langle \rangle \leftrightarrow A (A) \leftrightarrow A (A \langle \rangle) \langle \rangle \leftrightarrow \dots \\
 \langle \rangle &\leftrightarrow \langle\langle \rangle\rangle \leftrightarrow (A \langle \rangle) \leftrightarrow (A (A)) \leftrightarrow \dots
 \end{aligned}$$

# Different Interpretations of the Same Language

*The **semantics**, or interpretation, of a boundary form is determined by the set of pattern-equations taken to be axiomatic.*

**Logic**, under **Occlusion** and **Pervasion**

$$(((a)((a) b))) b \implies ()$$

interpret () as TRUE

**Integers**, under **Double** and **Merge**

$$(((a)((a) b))) b \implies (((a) (a) b))) b$$

interpret as  $2*2*2(a+2a+b) + b = 24a + 9b$

# For Contemplation

*New mathematical systems, particularly for logic,  
question our understanding of rationality, and  
tend to question our understanding of reality.*

Do syntactic diagrammatic varieties suggest **new cognitive techniques**?

Which aspects of our mathematical knowledge are **purely historical**,  
and which are fundamental? (eg why is diagrammatic logic not preferred?)

Are algebraic concepts such as commutativity and transitivity  
**fundamental to cognition**, or could they be artifacts of notation?

What is the interaction between syntax (ie data structure) and learning?

Do specific representations have **affordances** for errors?

What do **void-equivalence** and **semipermeable boundaries** have to do  
with the logic embedded in language (other than functional equivalence)?

...



# DIAGRAMMATIC REPRESENTATION

# Wanted: A Theory of Representation

Variation in syntax is not addressed by mathematical morphism.

In Computer Science, data structures and algorithms that implement isomorphic structures **vary profoundly**, in succinctness, efficiency and understandability.

In Math Education, **meaning is ignored** in favor of manipulation of representations.

**Semantic density** (the amount of information carried by a representation) changes qualitatively with the dimension of a representation.

"house"



Representation alone can introduce **new concepts**. For example, the expression " $4 - 7$ " is either invalid, or requires an extension of the positive integers.

Operations are **not independent** of representation. How a positive integer is represented determines how addition and multiplication are performed.

# Read/Operate Tradeoff: Positive Integers

| SYSTEM          | EXAMPLE   | READ                             | STANDARDIZE                                   | ADD                                  | MULTIPLY                                               |
|-----------------|-----------|----------------------------------|-----------------------------------------------|--------------------------------------|--------------------------------------------------------|
| <b>stroke</b>   | //// //   | <i>very hard</i><br>count result | <i>trivial</i><br>unique integers             | <i>trivial</i><br>push together      | <i>easy</i><br>substitute replicate<br>for each stroke |
| <b>Roman</b>    | XVII      | <i>moderate</i><br>add groups    | <i>moderate</i><br>collect,<br>promote groups | <i>trivial</i><br>push together      | <i>very hard</i><br>compound rules                     |
| <b>decimal</b>  | 17        | <i>easy</i><br>place<br>notation | <i>easy</i><br>fixed places,<br>decimal point | <i>hard</i><br>100 facts,<br>carry   | <i>hard</i><br>100 facts,<br>accumulate                |
| <b>binary</b>   | 10001     | <i>easy</i><br>place<br>notation | <i>trivial</i><br>fixed places                | <i>moderate</i><br>4 facts,<br>carry | <i>moderate</i><br>4 facts,<br>accumulate              |
| <b>boundary</b> | ((((•)))• | <i>easy</i><br>depth<br>notation | <i>moderate</i><br>double, merge              | <i>trivial</i><br>push together      | <i>easy</i><br>substitute replicate<br>for each •      |

# Representational Spaces

A *representational space* is that space set aside by a boundary between physicality and virtuality.

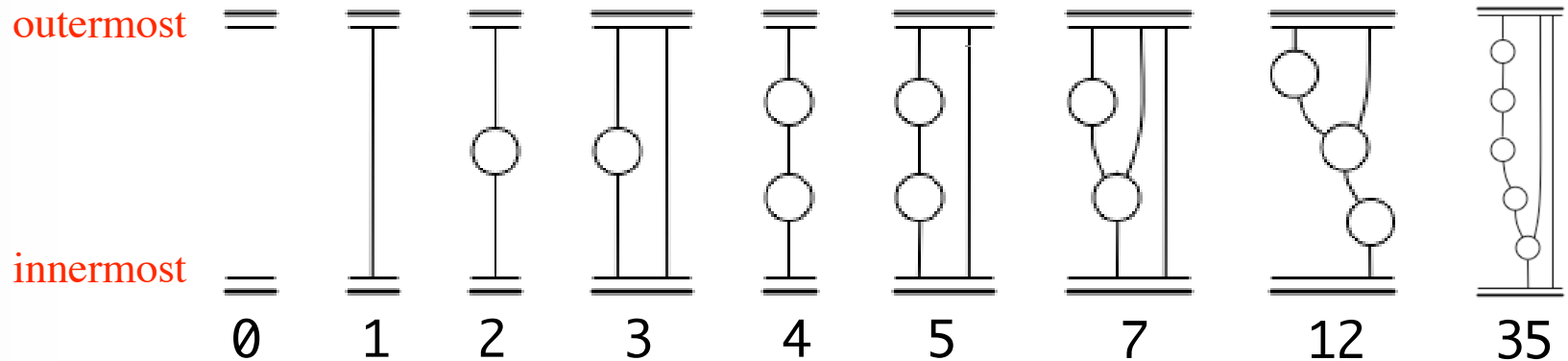
We are surrounded by instances of representational space:

a page  
the blackboard  
the projector screen  
the frame of a painting  
a transmission line  
this slide  
the television screen  
the computer monitor  
a book  
where our voices are when we use a telephone



# BOUNDARY INTEGERS: GRAPH VARIETY

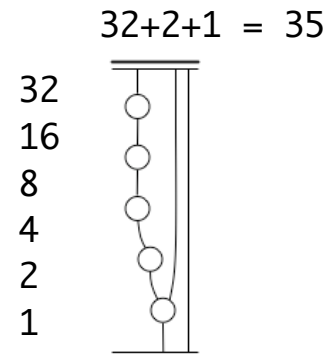
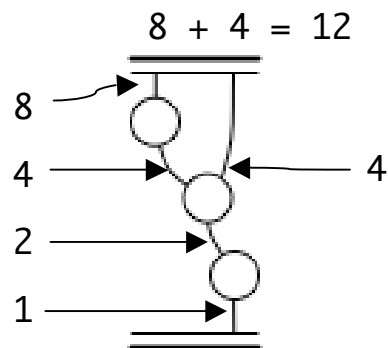
# Boundary Integers, Network Variety



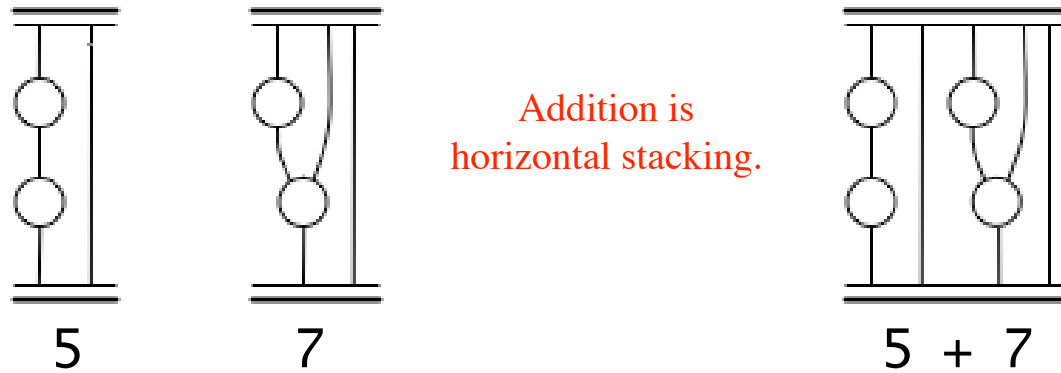
To **read** the network variety of boundary integers:

- follow each path from bottom-to-top
- for each path, begin with 1 at the bottom
- double the current result when passing through a node
- add paths together at the top

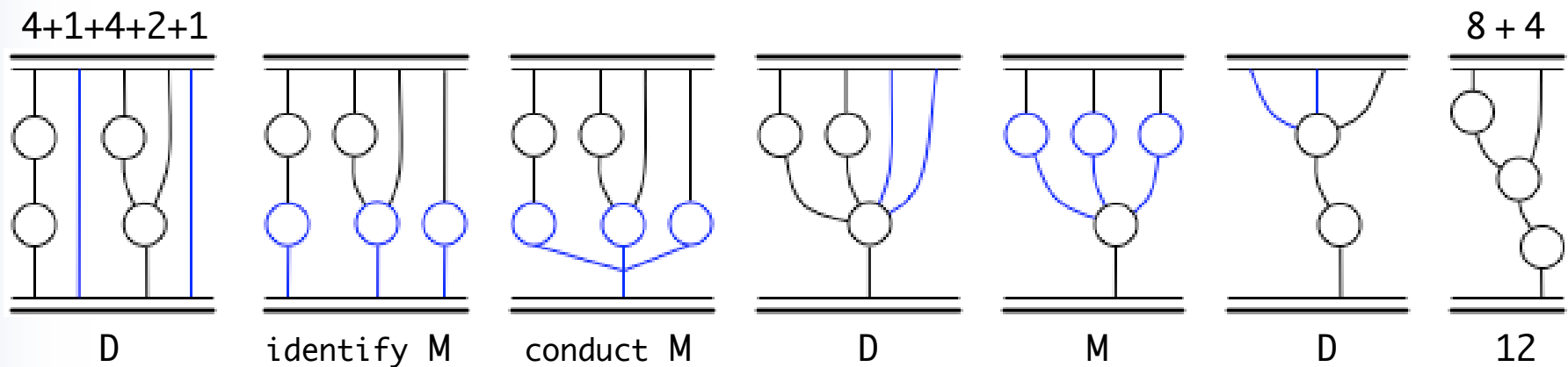
This is the same procedure used to read binary numbers.



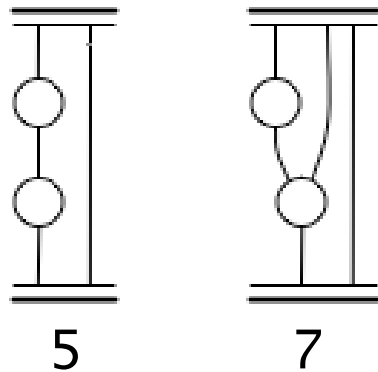
# Boundary Integers, Network Add



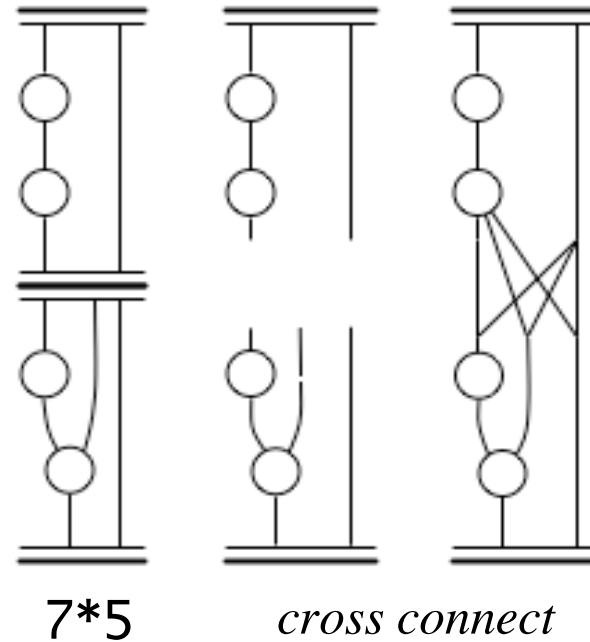
*Standardizing the result:*



# Boundary Integers, Network Multiply I

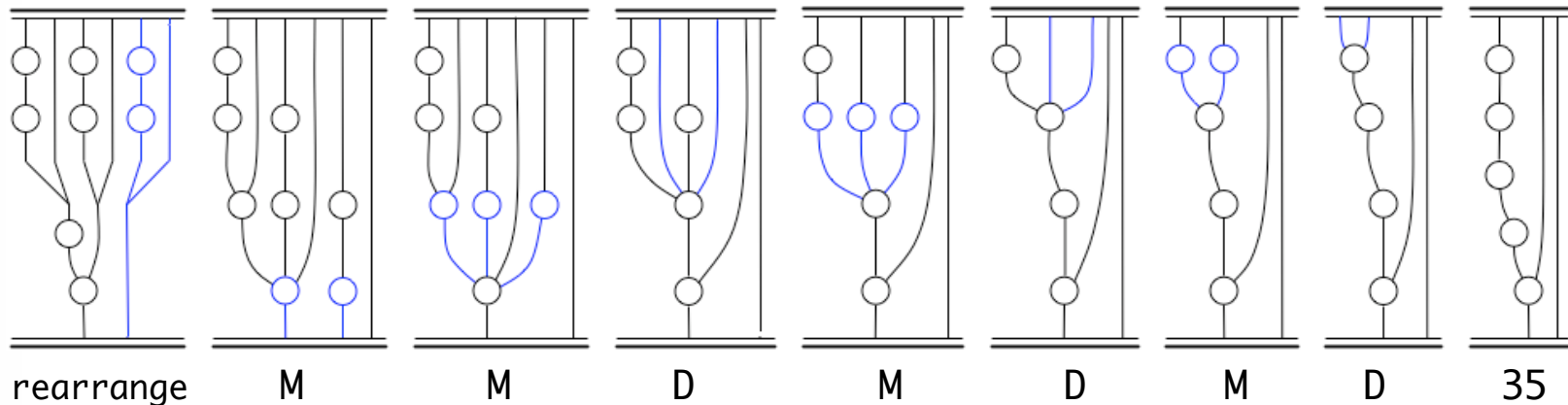


Multiplication is vertical stacking.



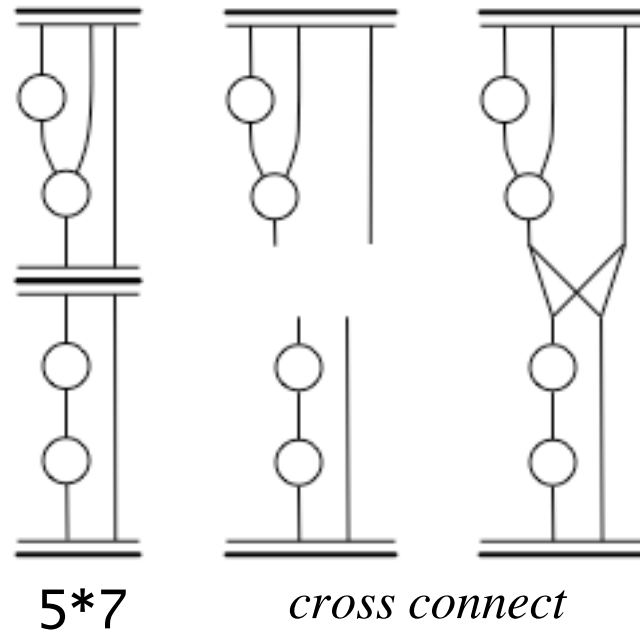
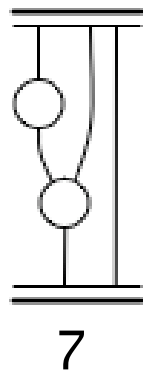
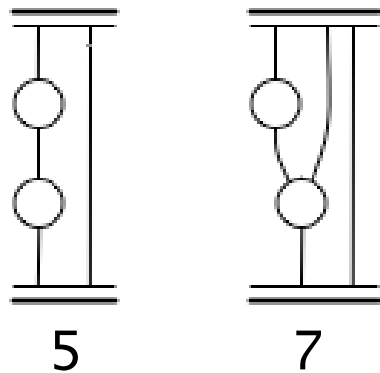
Double and Merge apply to structure sharing networks.

Structure is replicated here for reading ease.

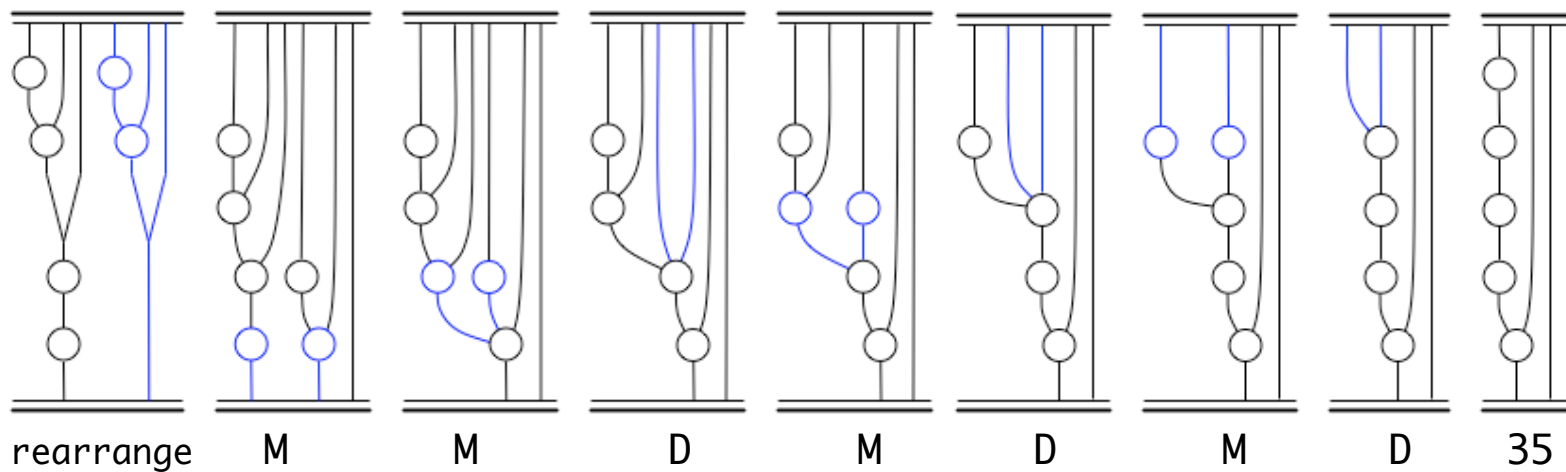




# Boundary Integers, Network Multiply II



*cross connect*



# BOUNDARY LOGIC: SUPPORT MATERIAL

# Reading Mark as Implication

In **implicative** logic, valid implications maintain the truth value of an expression.

In **algebraic** logic, valid substitutions maintain the truth value of an equation.

In **boundary** logic, void-substitutions cannot change the truth value of a form.

| BOOLEAN                    |                 | BOUNDARY |          |
|----------------------------|-----------------|----------|----------|
| FALSE IMPLIES FALSE = TRUE | [     ]         | = (   )  | identity |
| FALSE IMPLIES TRUE = TRUE  | [     ] (   )   | = (   )  | call     |
| TRUE IMPLIES FALSE = FALSE | [ (   ) ]       | =        | cross    |
| TRUE IMPLIES TRUE = TRUE   | [ (   ) ] (   ) | = (   )  | cross    |

# Several Proofs of a Simple Theorem

$$A ( ) =?= ( )$$

*Direct transformation:*

$$\begin{array}{c} A ( ) \\ (( A ( ) )) \\ ( \quad ) \end{array}$$

lhs  
involution  $A ==> ((A))$   
occlusion, rhs  $(A ( )) ==>$

*Mutual transformation:*

$$\begin{array}{c} A ( ) =?= ( ) \\ (A ( )) =?= (( )) \\ = \end{array}$$

$F[A] = F[B]$   
occlusion twice, identity

*Case analysis:*

$$\begin{array}{c} () ( ) =?= ( ) \\ ( ) =?= ( ) \end{array}$$

$\text{subst}[( ), A, E]$ , arithmetic  
 $\text{subst}[\quad, A, E]$ , identity

*Standard form:*

$$\begin{array}{c} (A ( ) ( )) ((A ( )) (( )) ) \\ ( \quad ) \end{array}$$

$(A B)((A)(B))$   
occlusion, 3 times

$$A ( ) = ( )$$

**Dominion**

# Deep Transformation Example

Minimize:  $((\text{NOT } b) \text{ OR } \text{NOT}(a \text{ OR } (\text{NOT } c))) \text{ AND } ((a \text{ AND } b \text{ AND } c) \text{ OR } \text{NOT}(a \text{ OR } b))$   
 $(\neg b \vee \neg(a \vee \neg c)) \wedge ((a \wedge b \wedge c) \vee \neg(a \vee b))$

Transcribe:  $((b)(a(c)))((a)(b)(c))(a\ b))$

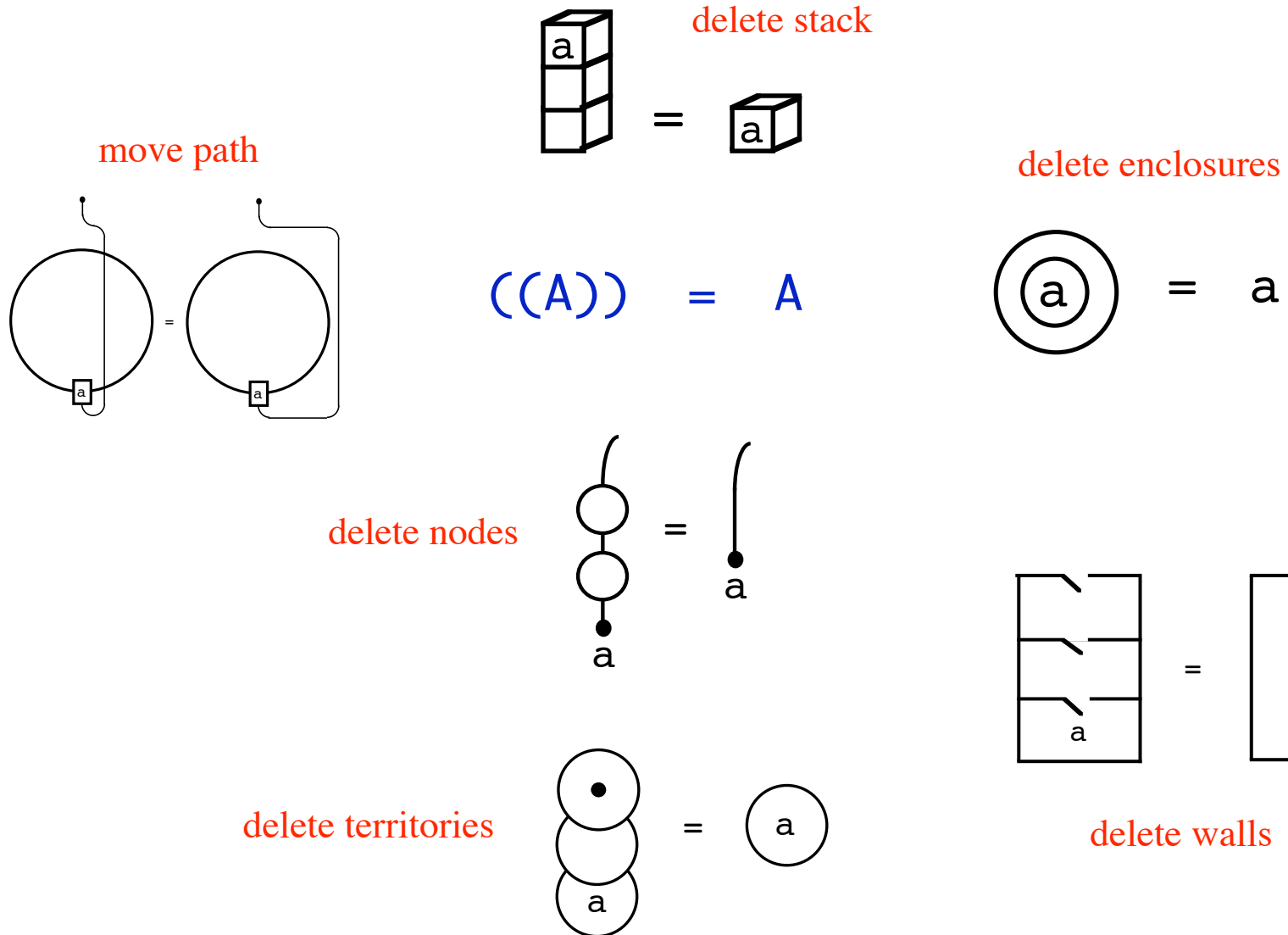
Boundary Reduction:

|   |                                          |           |
|---|------------------------------------------|-----------|
|   | $((b)(a(c)))((a)(b)(c))(a\ b))$          | eg        |
| 1 | $((b)(a(c)))((b)(a(c))(a)(b)(c))(a\ b))$ | per+      |
| 2 | $((b)(a(c)))((a(c))(a)(b)(c))(a\ b))$    | per (b)   |
| 3 | $((b)(a(c)))((a(c))(a)(b)(c))(a\ b))$    | inv       |
| 4 | $((b)(a(c)))((a(c))(b)(c))(a\ b))$       | per a     |
| 5 | $((b)(a(c))((a\ b)))$                    | occ       |
| 6 | $((b)(a(c))a\ b)$                        | inv       |
|   | $((a\ b))$                               | per b     |
|   | $a\ b$                                   | occ       |
|   | $\neg(a \vee b)$                         | interpret |

*What if boundaries were interpreted as functions on their contents?*

1. A **compound function** is added as an argument to an **external boundary function**.
2. An argument to the **compound function** is deleted, changing its arity.
- 3 and 5. **Functional inverses** created by the deleted argument cancel, creating **two new simple arguments**.
4. **One of the simple arguments** voids its **containing function**.
6. **One of the simple arguments** voids **the original compound function** by voiding one of *its* arguments.

# Involution



# Boundary Logic Is Unorthodox

Boundary logic is **not isomorphic** to Boolean logic

- one-to-many map
- absence of relational concepts
- absence of arity and countability
- first class void-equivalence
- one basis constant
- two types of composability
- operational transparency (no function/argument distinction)

Boundary logic is **not group theoretic**

**Identity** for SHARING

$$\begin{array}{rcl} a \diamond i & = & i \diamond a = a \\ a \quad i & = & i \quad a = a \\ a & = & a = a \end{array} \quad \begin{array}{l} \text{identity} \\ \diamond = \text{SHARING} \\ i = \langle \text{void} \rangle \end{array}$$

**Inverse** for SHARING

$$\begin{array}{rcl} a \diamond a^{-1} & = & a^{-1} \diamond a = i^{-1} \\ a \quad (a) & = & (a) \quad a = i^{-1} \\ ( ) & = & ( ) = ( ) \end{array} \quad \begin{array}{l} \text{inverse} \\ \diamond = \text{SHARING} \\ i^{-1} = (i) = ( ) \end{array}$$

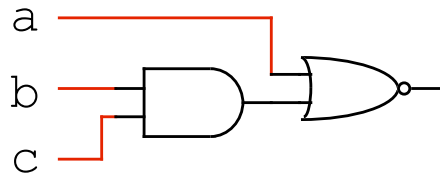
That is, the identity element,  $i$ , defined by the identity equations is the inverse of the identity element,  $i^{-1}$ , defined by the inverse equations.

# Table of Non-Correspondence

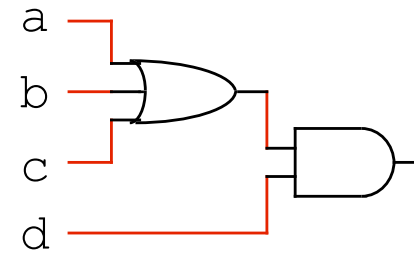
|                        | BOOLEAN       | BOUNDARY                      | DIFFERENCE                 |
|------------------------|---------------|-------------------------------|----------------------------|
| <b>symbols</b>         | tokens        | icons                         | linear vs spatial          |
| <b>constants</b>       | $\{0, 1\}$    | $\{ \bigcirc \}$              | two vs one                 |
| <b>unary operator</b>  | NOT           | BOUNDING                      | delimited collection       |
| <b>binary operator</b> | OR, AND       | SHARING                       | not a function, not binary |
| <b>arity</b>           | specific      | any                           | no concept of argument     |
| <b>mapping</b>         | functional    | structural                    | one-to-many                |
| <b>ordering</b>        | implicative   | bounding                      | spatially explicit         |
| <b>computation</b>     | rearrange     | delete                        | void-equivalence           |
| <b>semigroup</b>       | associative   | no concept                    | boundary structure only    |
| <b>monoid</b>          | identity, $i$ | $\langle \text{void} \rangle$ | existence                  |
| <b>group</b>           | inverse       | $i^{-1}$                      | new structure needed       |
| <b>Abelian group</b>   | commutative   | no concept                    | no spatial metric          |



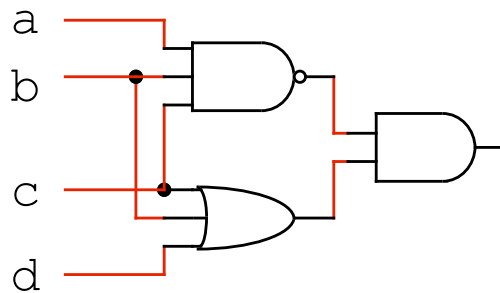
# Circuit Structures in Boundary Logic



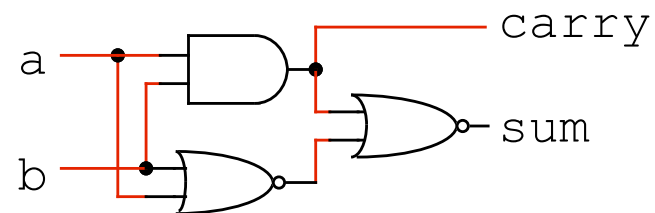
$(a ((b)(c)))$



$((d)(a b c))$



$((b c d) ((a)(b)(c)))$



$\text{sum} = (\text{carry} (a b))$   
 $\text{carry} = ((a)(b))$

# Fully Nested Containment Graph

The containment graph representation is in **Implicate Normal Form** when there is no internal fanout (no structure sharing).

## Implicate Normal Form

*deepest nesting*

fewest literal references

no internal pins

*shortest wires*

unique up to form distribution

finesses intractability

## Conjunctive Normal Form (PoS)

shallowest nesting (2 levels)

most literal references

most internal pins

longest wires

unique up to variable labeling

grows exponentially large

## 4-bit Magnitude Comparator

((eq 1) (gt 2) (lt 3))

((1 ((j) (a (b)) (b (a)) (c (d)) (d (c)) (e (f)) (f (e)) (g (h)) (h (g))))))

(2 ((i ((j) ((g (h)) ((h (g)) ((e (f)) ((f (e)) ((c (d)) (a (b) (d (c))))))))))

(3 ((k ((j) ((h (g)) ((g (h)) ((f (e)) ((e (f)) ((d (c)) (b (a) (c (d))))))))))

# Abstraction and Management of Complexity

*Design abstractions can be constructed bottom-up  
by using **parens pattern templates**.*

## **Abstraction types**

Functional modules, library cells  
Structural modules, library macros  
Dataflow modules, serial/parallel decomposition  
Input symmetries  
Parametric generation  
Bit-width vector abstraction  
Specialized technology maps (LUTs, FPGA cells)

Boundary logic transformations apply equal well to

- simple inputs (signals)
- compound boundary forms (subnets)
- modules and vectors (black-box abstractions)

# Prototype Software Implementation

## *Software capabilities*

- fully functional **boundary logic reduction engines** (logic, area, delay)
- functional tools for high-quality **interactive netlist restructuring**
- HDL language netlist parsers
- TSMC logic library mapping for delay and area models
- **design exploration** tools, including area/delay trade-offs

## *Software limitations*

- prototype software implementation is **proof-of-concept**
- current LISP implementation is somewhat brittle
- delay modeling is based on weak physical models
- not an entire synthesis package
- not yet optimized for performance efficiency
- some functionality is designed but not yet implemented
- **no user interface** as yet

## *Conceptual limitations*

- no personal HDL or layout design experience
- work has not been published, no peer review

# Computational Pragmatism

*Constructing a novel mathematical system is easy.  
What differentiates good ones from bad ones is their **utility**.*

Logic problems to **calibrate computational utility**:

Almost all problems found  
in logic textbooks are  
computationally trivial.

- simple tautology -- syllogistic dilemma

$$((a \rightarrow b) \wedge (c \rightarrow d) \wedge (a \vee c)) \rightarrow (b \vee d)$$

- simple minimization -- absorption

$$a \wedge (a \vee b)$$

- simple challenging tautology -- distribution of if-then-else (**ite**)

$$\text{ite}[\text{ite}[a, b, c], d, e] = \text{ite}[a, \text{ite}[b, d, e], \text{ite}[c, d, e]]$$

- simple challenging minimization -- factor forms with a dozen variables

Reduce from 12 to 8 variable occurrences:

$$(\neg a \wedge (\neg(g \vee (b \wedge c)) \vee \neg(f \vee (d \wedge e \wedge g)))) \vee \neg((b \wedge c) \vee (d \wedge e))$$

- commercial tautology

c5315 -- 178 inputs, 123 outputs, 1300 logic gates

80386core -- 36 inputs, 70 outputs, 20000 logic gates

- commercial minimization

minimal area and delay for above circuits

- huge randomly constructed SAT problems

10,000s of variables, millions of clauses