On the Physical Basics of Information Flow

C.A.Petri

(modified and presented by Rüdiger Valk)

Results obtained in co-operation with
KONRAD ZUSE
1910 - 1995

Communication with Automata

Kommunikation
mit
Automaten

Von der Fakultät für Mathematik und Physik
der Technischen Hochschule Darmstadt

zur Erlangung des Grades eines
Doktors der Naturwissenschaften
(Dr. rer.nat.)

genehmigte
Dissertation

vorgelegt von
Carl Adam Petri
aus Leipzig

Referent: Prof.Dr.rer.techn.A.Walther
Korreferent: Prof.Dr.Ing.H.Unger

Tag der Einreichung: 27.7.1961
Tag der mündlichen Prüfung: 20.6.1962

D 17

Bonn 1962

information & space

concurrency

Petri's general interest:

information processing
&
fundamental laws in Physics

Communication with Automata

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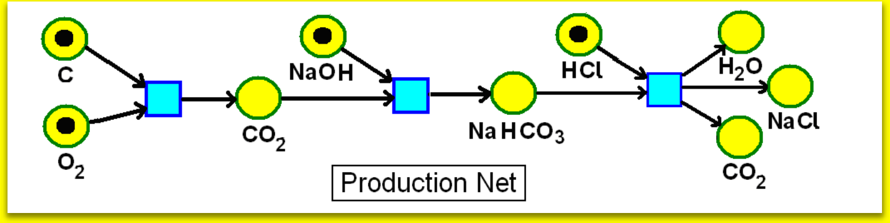
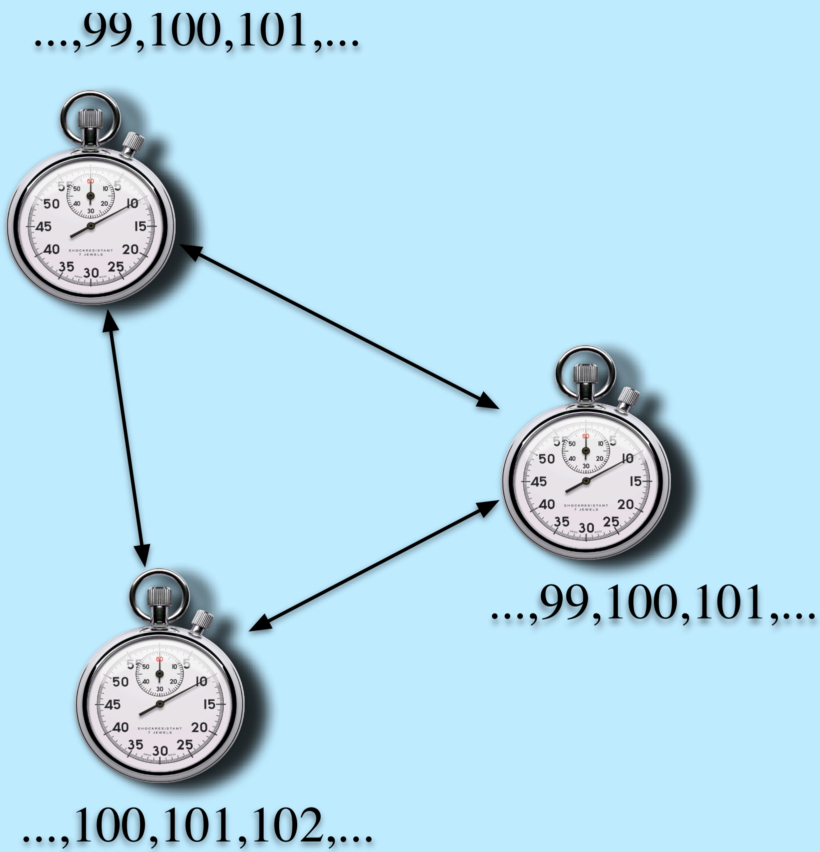
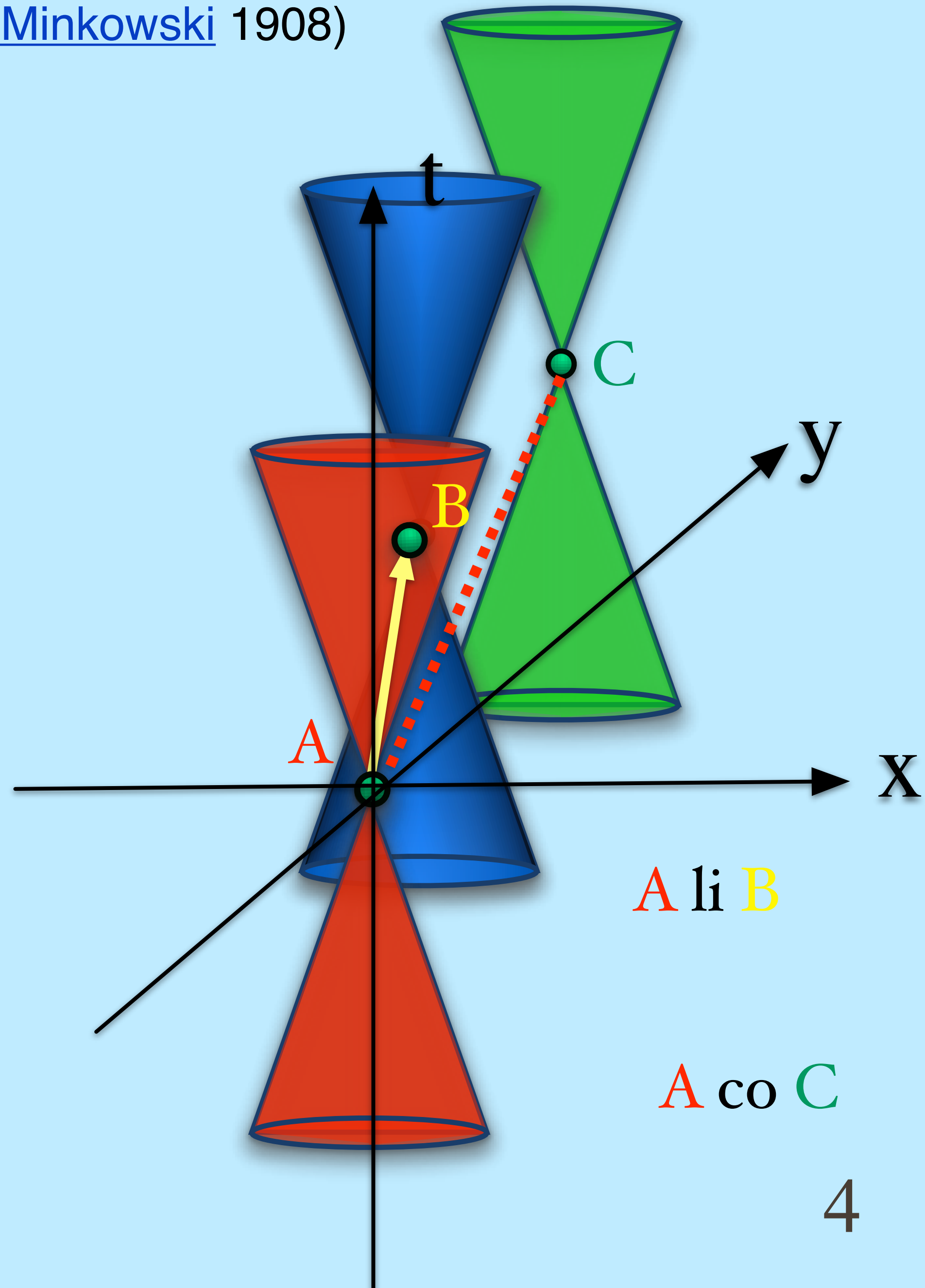
The graphics, together with the rules for their coarsening and refinement, were invented in August 1939 by Carl Adam Petri - at the age of 13 - for the purpose of describing chemical processes,



http://www.scholarpedia.org/article/Petri_net

Minkowski-Diagrams ([Hermann Minkowski]() 1908)





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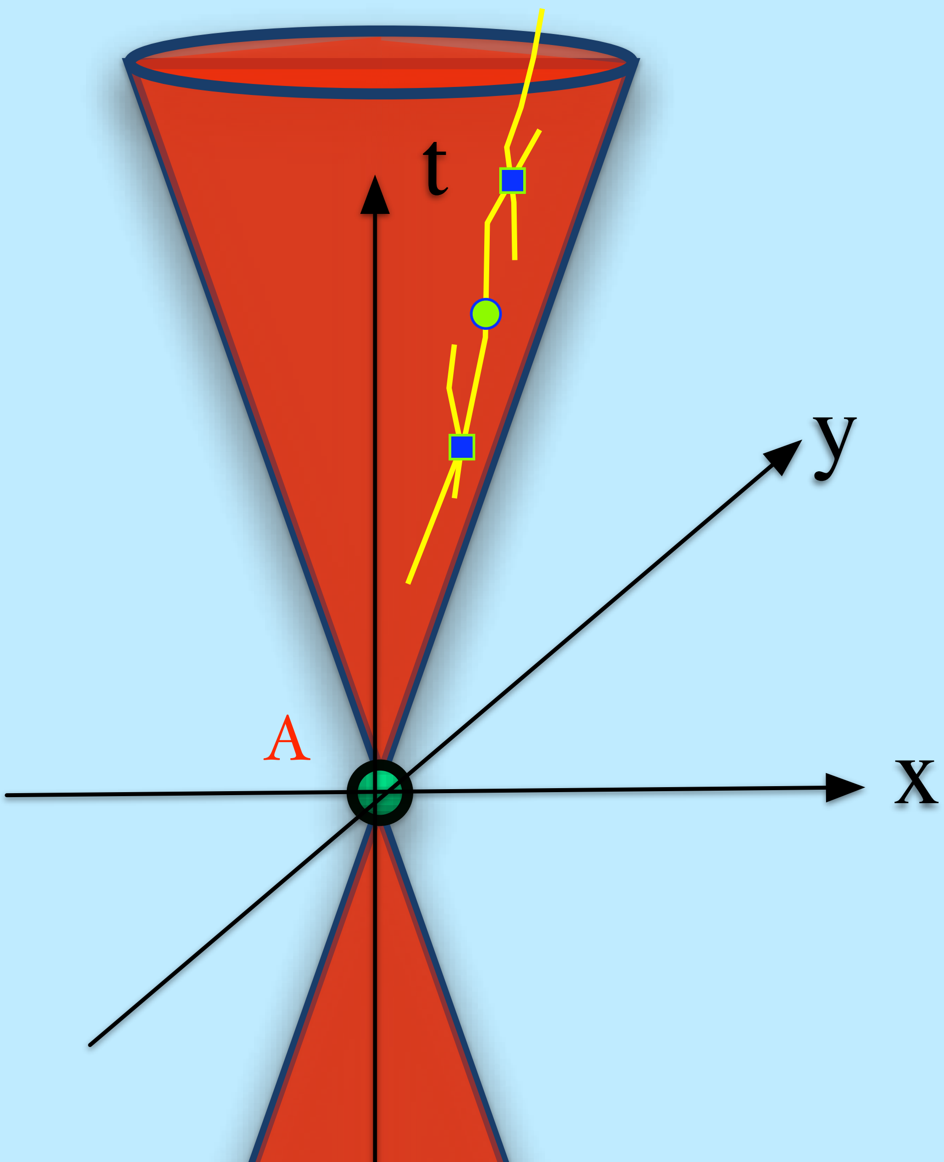

Is the Universe a Computer?

The Universe as a big Net

Das Universum als großes Netz

Die Arbeit von Konrad Zuse wurde in den 1960er Jahren mit der Netztheorie verteilter Systeme weiterentwickelt. Dabei gelang es, einige der Einwände gegen Zuses Konzept auszuräumen.

Von Carl Adam Petri

Wer einen neu konstruierten Computer zum Laufen bringen will, muss eine große Zahl von Einzelteilen zum präzise koordinierten Zusammenspiel bringen – nach dem Vorbild des strengen Wirkens der Naturgesetze. Das hat niemand intensiver erfahren als Konrad Zuse, der Erfinder und Erbauer des weltweit ersten programmgesteuerten Computers.

Der Gedanke liegt nahe, die Naturgesetze direkt für die dauerhafte Stabilität von Computern heranzuziehen. Dann würde der Computer funktionieren, weil er auf Grund der Naturgesetze nicht anders kann. Dazu wäre es freilich notwendig, diese Gesetze in die Sprache des Ingenieurs zu übersetzen. Ist das überhaupt möglich? Wäre es nicht einfacher, die physikalische Natur direkt in der Sprache des Computer-Ingenieurs neu zu beschreiben? Wenn das gelänge, erschiene die Welt als gigantischer Computer.

Seiner Zeit wieder einmal weit voraus, unternahm Zuse ernsthaft diesen Versuch, zum Kopfschütteln der meisten Zeitgenossen. Er begann mit dem damals bereits bekannten Konzept des »zellulären Automaten«: Hier wird der Raum in lauter gleichartige Zellen aufgeteilt, die wie kleine Maschinen nach einem vorgegebenen Verhaltensmuster (»Programm«) mit ihren Nachbarzellen Information austauschen. Es gelang ihm, wenigstens auf dem Papier, die Phänomene »Fortpflanzung« und »Bewegung« von Zustandsmustern zu beschreiben (siehe seinen Artikel auf S. 6). Für eine Nachprüfung durch Computer-Simulation waren die damaligen Maschinen nicht leistungsfähig genug.

Besser ausgerüstet gelang später anderen die Simulation einfacher zellulärer Automaten mit großem rechnerischem Aufwand. Der zelluläre Automat »Spiel des Lebens« von John Horton Conway ist weithin bekannt geworden. Vor allem Stephen Wolfram experimentierte mit vielen verschiedenen Zell-Programmen und stellte der Welt 2002 das Ergebnis seiner Versuche mit einem über 1000-seitigen Buch als »Eine Neue Art von Wissenschaft« vor – gewiss ein vollmundiger Titel.

Eines Tages besuchte mich Konrad Zuse in meinem Arbeitszimmer. Ich war ihm empfohlen worden als erfinderischer Theoretiker mit langjähriger Erfahrung als Leiter eines großen Rechenzentrums. Er bat mich, ihn bei seiner Arbeit zum Rechnenden Raum zu beraten. Ich fühlte mich hoch geehrt und stimmte sofort zu. Es entstand eine äußerst fruchtbare Zusammenarbeit, die sich wider Erwarten über mehr als drei Jahre erstreckte. In ungezählten (Streit-)Gesprächen kamen wir uns wissenschaftlich und persönlich immer näher.

Konrad Zuse vertrat zunächst seinen Ansatz der zellulären Automaten und verteidigte ihn vehement gegen meine Bedenken. Diese bestanden hauptsächlich in Folgendem: Erstens ergibt sich aus der räumlichen Anordnung der Zellen eine Auszeichnung von drei bestimmten Richtungen im Raum, die sich nur durch Einführung zufälliger Prozesse aufheben lässt. (Zuse hielt die Annahme von Zufälligkeit nicht für zielführend.)

Zweitens wandte ich ein, dass sich in diesem Modell die gesamte Physik in den Programmen jeder Zelle verstecke, sozusagen als nicht analysierbare DNA und ohne direkten Bezug zu physikalischen Größen. Ich schlug ihm deshalb eine andere Modellierungstechnik vor: die Netztheorie verteilter Systeme. Heute unter dem Namen »Petri-Netze« bekannt, hatte sie bereits viele erfolgreiche Anwendungen gefunden, so in Bankwesen, Ökonomie, Telekommunikation, Workflow Management, Konfliktlösung, Prozesssteuerung und Biochemie, nur leider noch nicht an ihrem Geburtsort,

Carl Adam Petri (links) im Gespräch mit Konrad Zuse, um 1975

The Universe as a big Net

PETRI-NETZE

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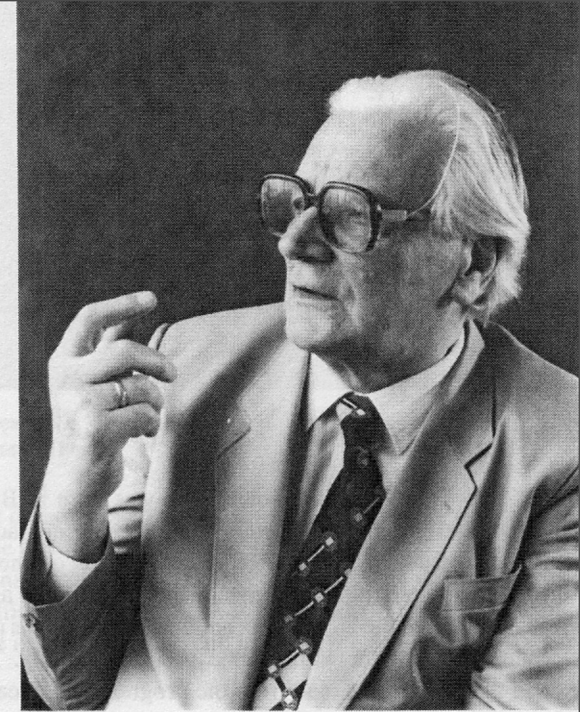


Fig. 2.28 Konrad Zuse
Courtesy of Horst Zuse, Berlin.

Today, in the whole world Konrad Zuse is accepted as the creator / inventor of the first free programmable computer with a binary floating point and switching system, which really worked.

This machine - called Z3 - was completed in his small workshop in Berlin in 1941. First thoughts of Konrad Zuse about the logical and technical principles are even going back to 1934.

Konrad Zuse, also created the first programming language of the world, called the Plankalkül. (1942-1945)
F. L. Bauer (University of München)

Meetings with Zuse

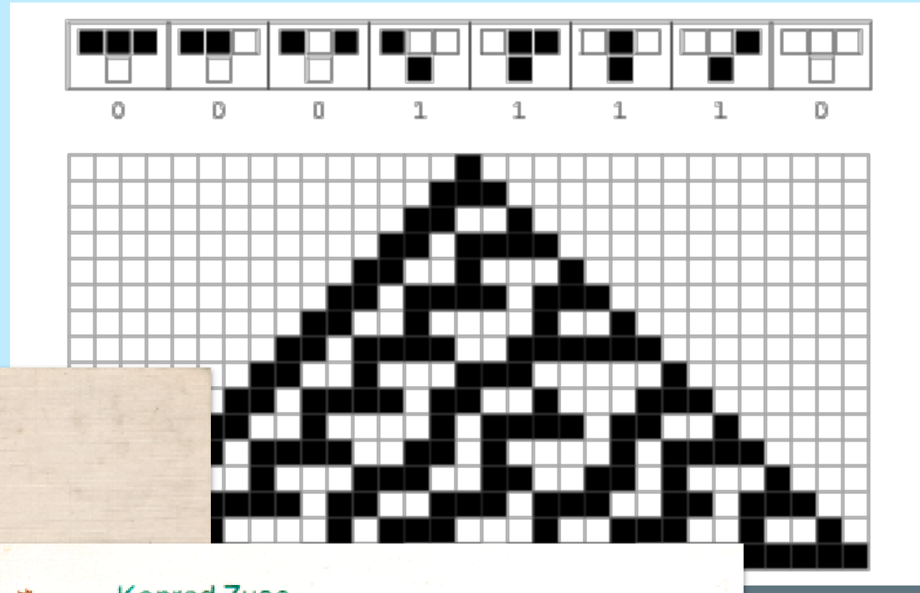
about 1970 - 80

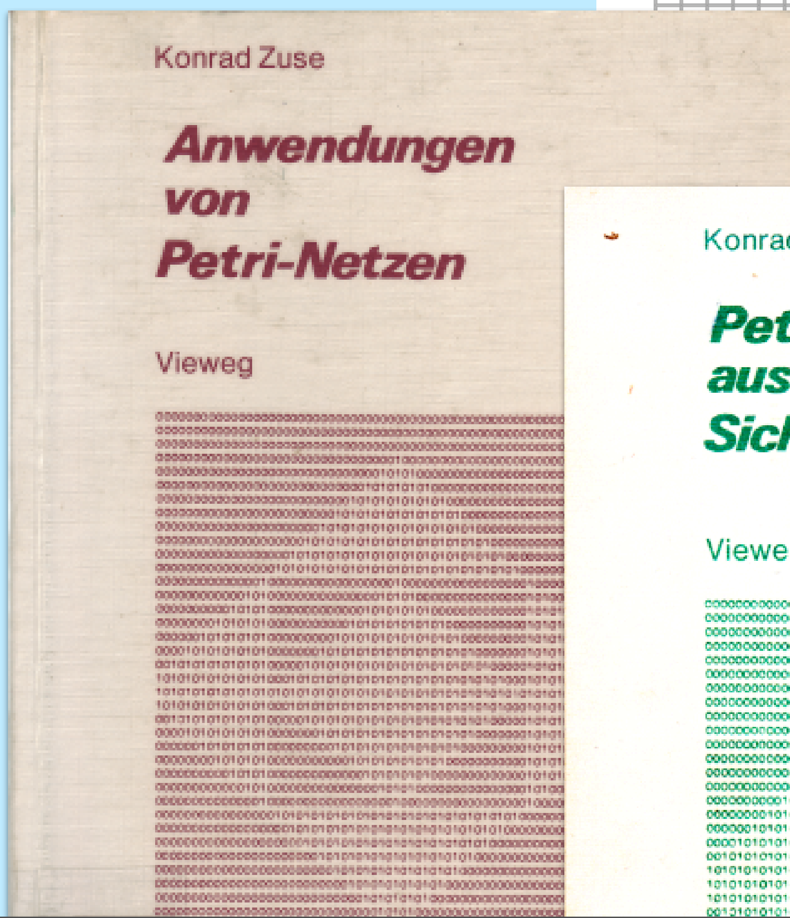
Which tenets?

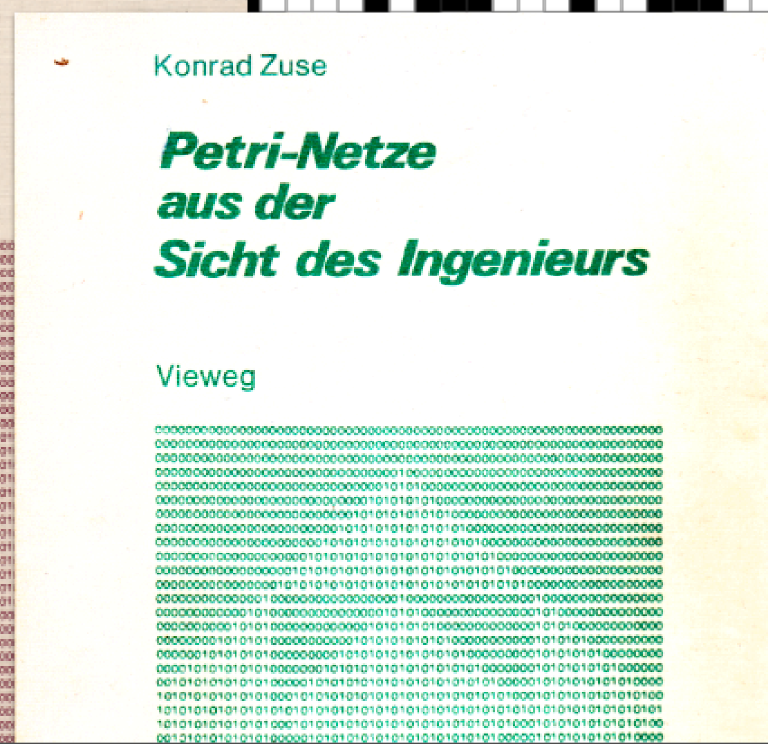
Zuse: "Those which can be understood by an Engineer".

Is the universe a gigantic computer?

Meetings with Zuse







Which tenets?

Zuse: “Those which can be understood by an Engineer“.

But many years passed before the deterministic approach of Gerard ‘t Hooft (2002) made a complete elaboration of the originally conceived ideas possible, namely that of

Combinatorial Modelling

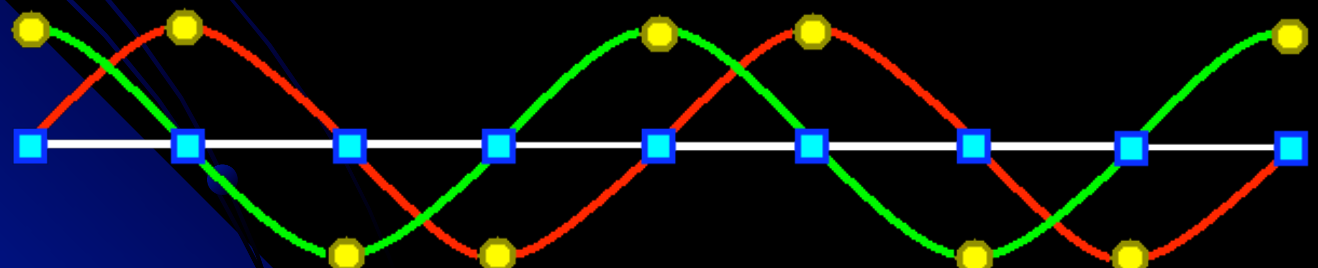
INNOVATIONS

- Revised Order Axioms for Measurement
- Synthesis of „Discrete“ and „Continuous“
- Derivation of Computing Primitives from smallest closed Signal Spaces

Procedure

By means of NET modelling, we translate the main tenets of modern Physics into their combinatorial form.

In that form, they are independent of scale, and relate to direct experience as well as to the sub-microscopic level of quantum foam.



Essentials of Net Theory

1. TWO kinds of world points:

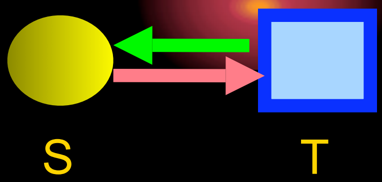
elements: STATES   and   TRANSITIONS

e.g.   Substances   and   Reactions

2. TWO relations between world points:

arcs: GIVE   and   TAKE

e.g.   Creation   and   Annihilation



3. TWO kinds of **continuity** expressible:

Mathematical continuity (“connected and compact”)

Experienced continuity (“connected indifference”)

The Framework for Axioms

nets

$S \cup T \neq 0$	$S \cap T = 0$
${}^{\bullet}x \cup x^{\bullet} \neq 0$	${}^{\bullet}x \cap x^{\bullet} = 0$

occurrence

$E \neq 0$	Sep2 E
${}^{\bullet}E = M - M'$	$E^{\bullet} = M' - M$

net morphism

$f : A \longrightarrow A' \cup id$
$f : F \longrightarrow F' \cup id$

piles

$T(n+1) = S(n)$
$C(n+1) \, . \, C(n) = 0$

Net - Topology

transition bordered

=

closed set

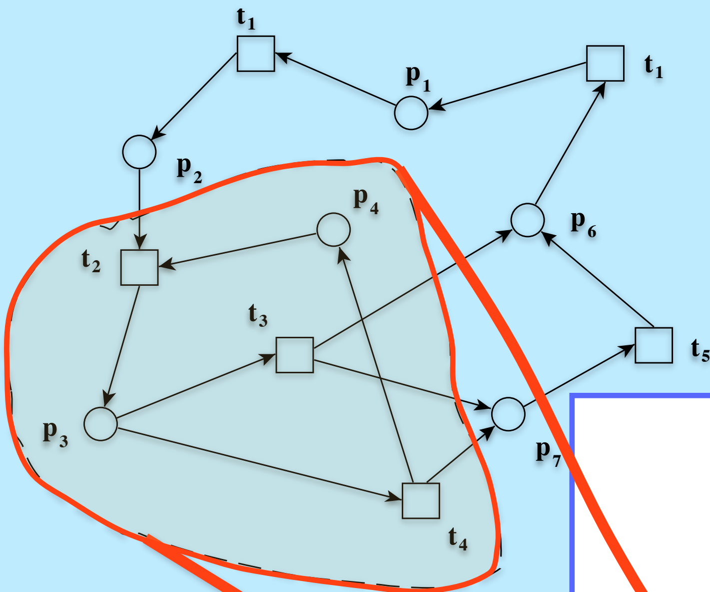


Fig. 2.11. A transition-bordered set

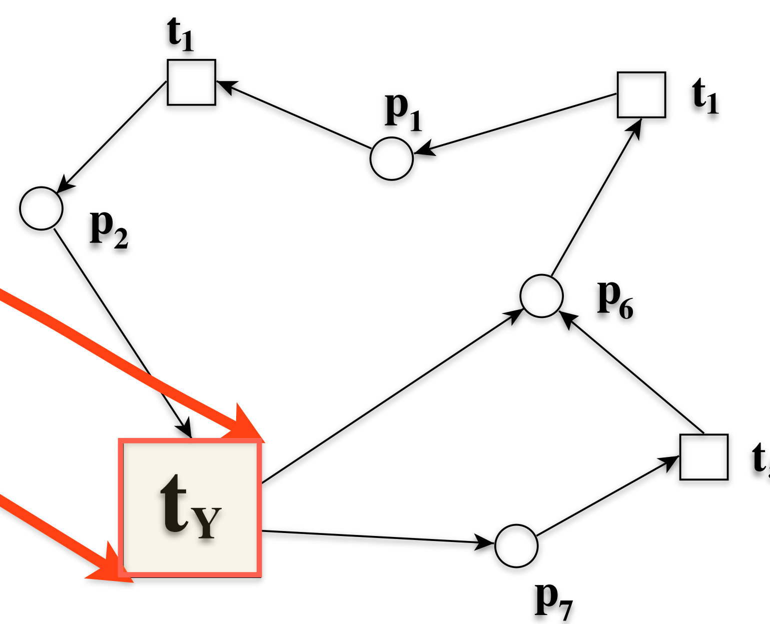
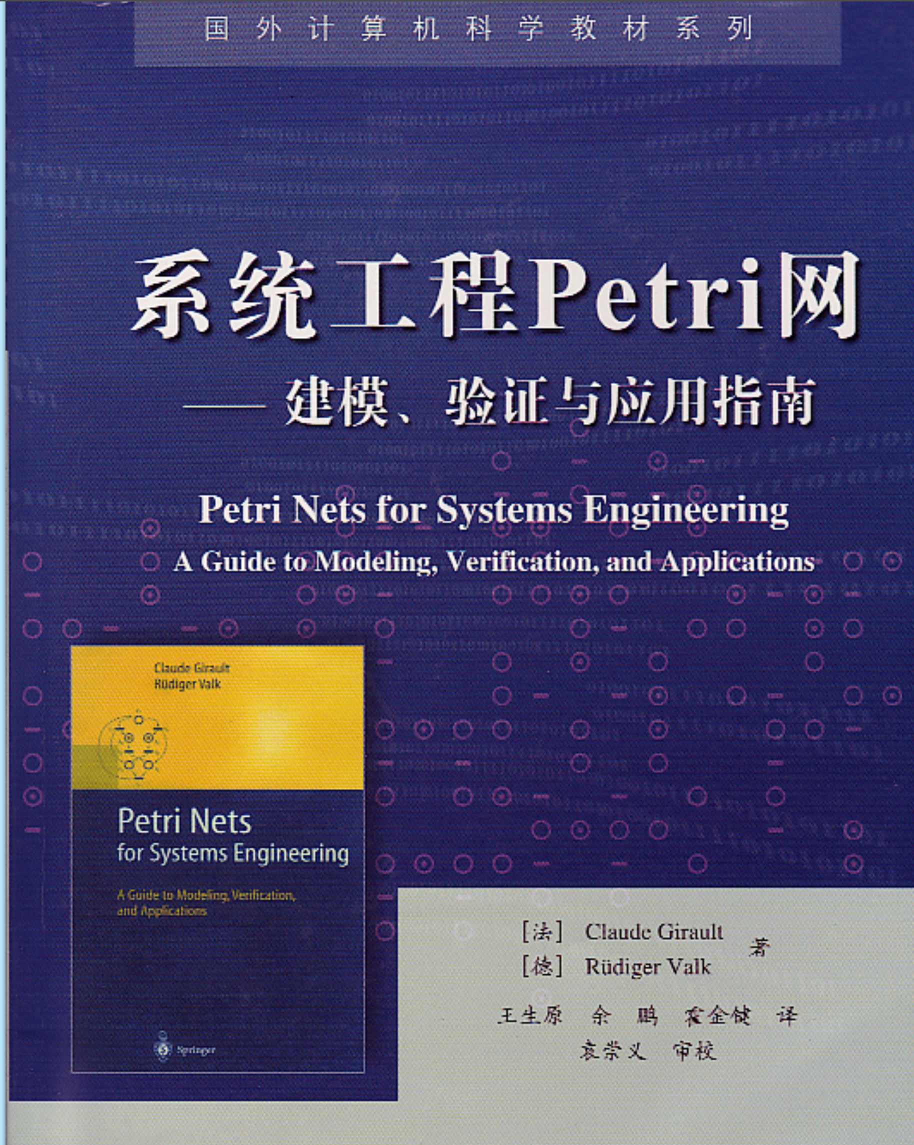


Fig. 2.12. Abstraction from the net of Figure 2.11



是开集又是闭集，例如令 $Y := P \cup T$。在这种情况下，Y 到底是被替换为一个库所还是变迁，则是由应用系统的上下文决定的。

在图 2.11 所示的网系统中，集合 $Y = \{p_3, p_4, t_2, t_3, t_4\}$ 是一个变迁边界集合，可以将其抽象为一个变迁 t_Y，从而得到一个新的网系统，如图 2.12 所示。下面我们给出这个抽象操作的形式化定义。

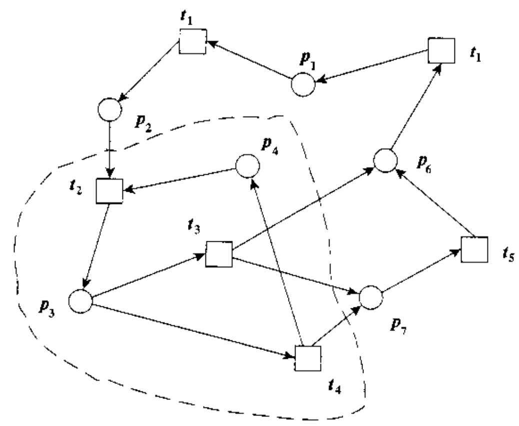


图 2.11　变迁边界集合示例

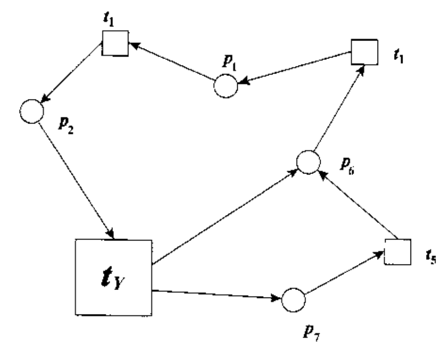
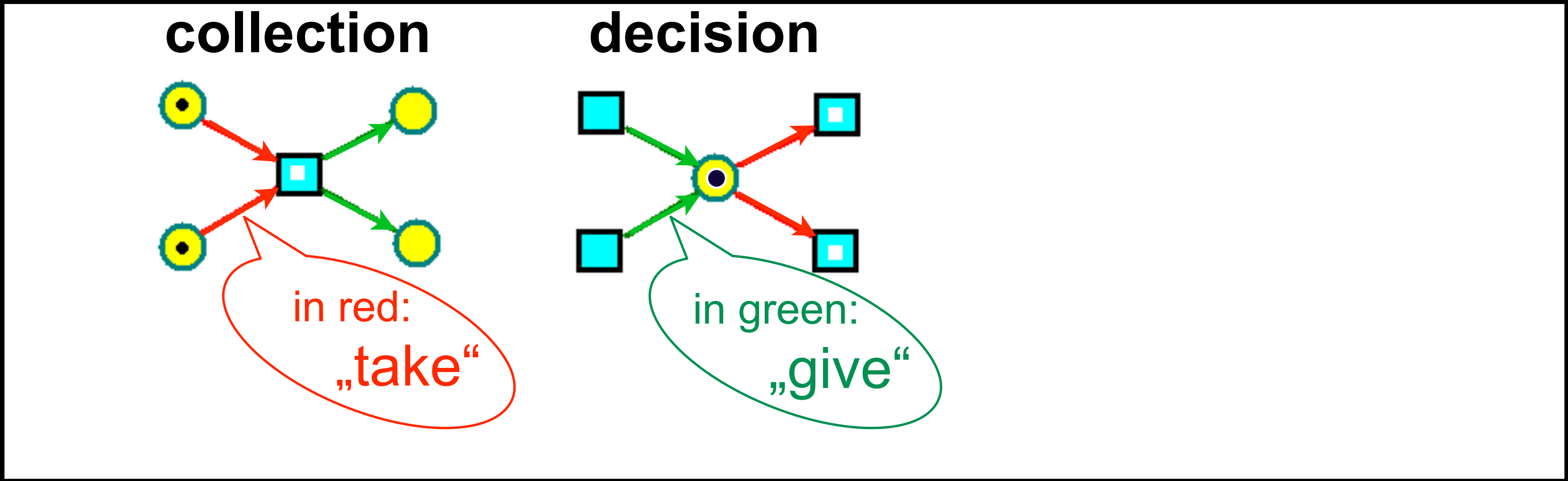


图 2.12　抽象之后的网模型

1 开集和闭集定义了网的拓扑，其中表示了元素和其相邻元素的图形化结构。

1 Open and closed sets define a topology for a net, which formalises the notion of vicinity of elements with respect to the graphical structure.

The Elements Used in Construction



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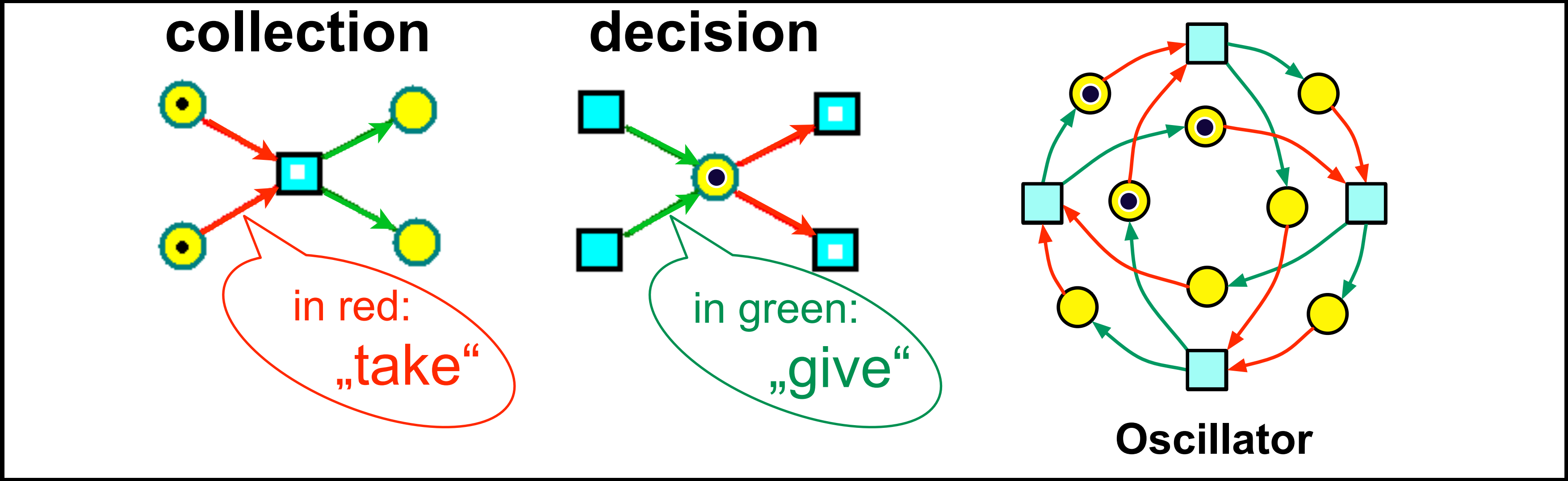
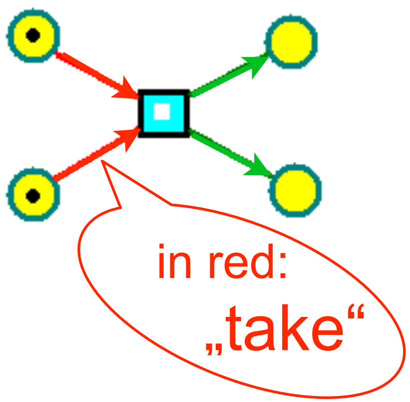
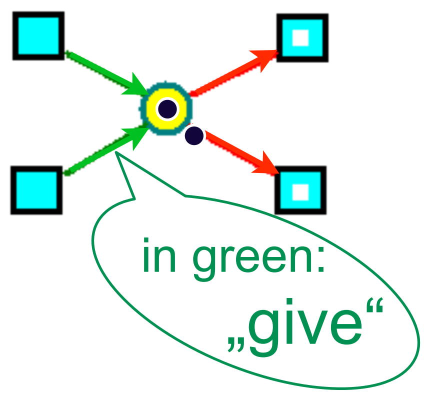


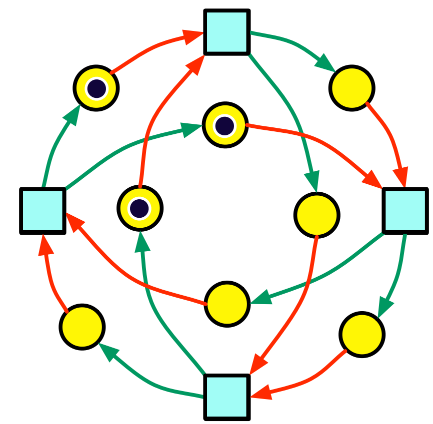
The Elements Used in Construction

collection



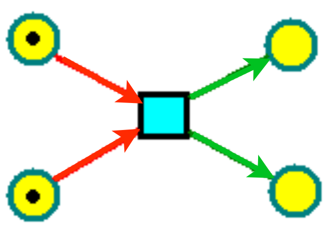
decision





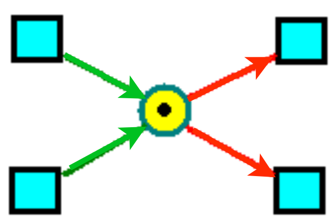
Oscillator

NET TOPOLOGY



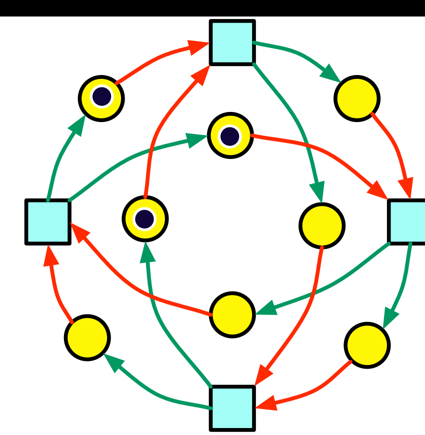
open subnet

The transition is completed by four states



closed subnet

The state is completed by four transitions

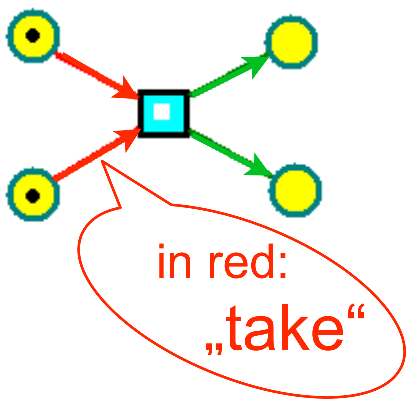


open subnet

The eight uncompleted states form the border

The Elements Used in Construction

collection



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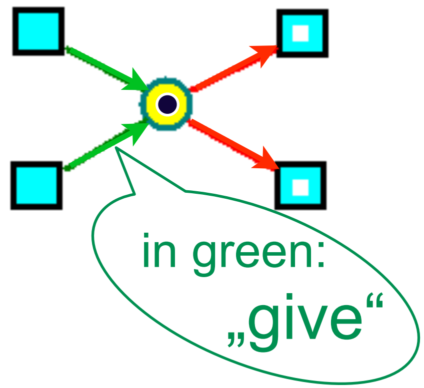

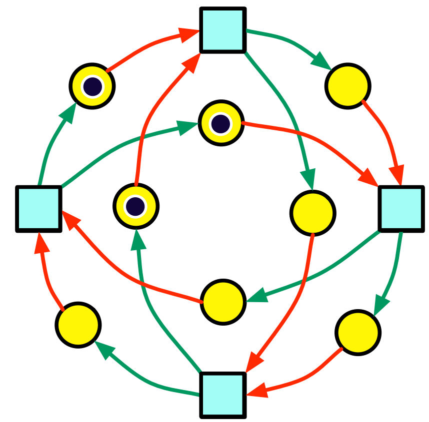

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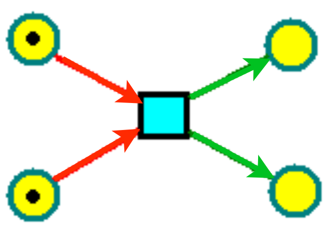

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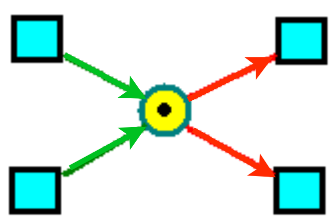

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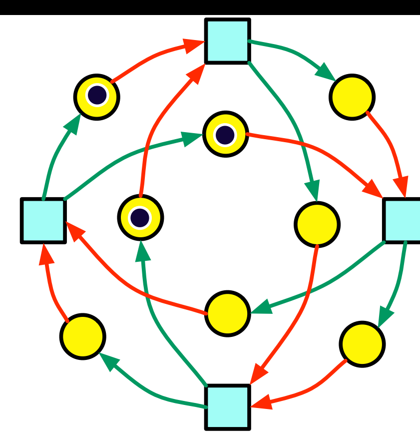


open subnet

The eight uncompleted states form the border

Measurement

in the classical sense

as related to

the Uncertainty Principle

Four Theses on Measurement

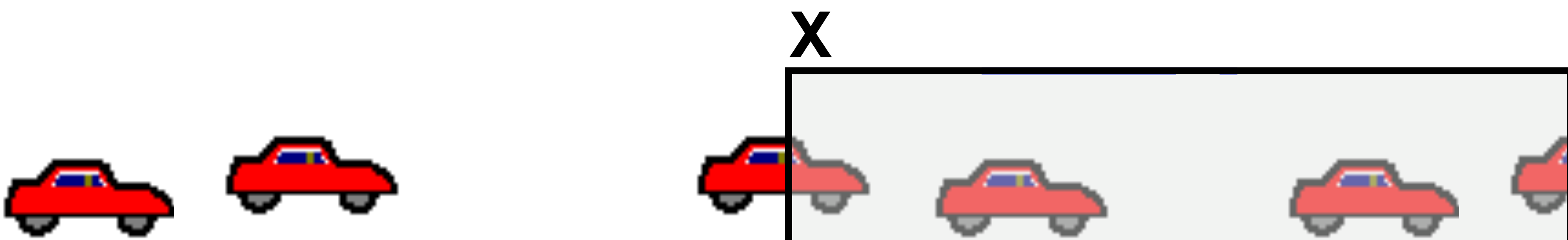
- Every act of Measurement occurs in a Time Window.
- Measurement is, in essence, equivalent to Counting. *)
- Continuous change (e.g. motion) goes unnoticed if not articulated by perceptible non-zero changes.
- Counting leads to a unique result only if the set of objects to be counted and the Time Window are under complete control.

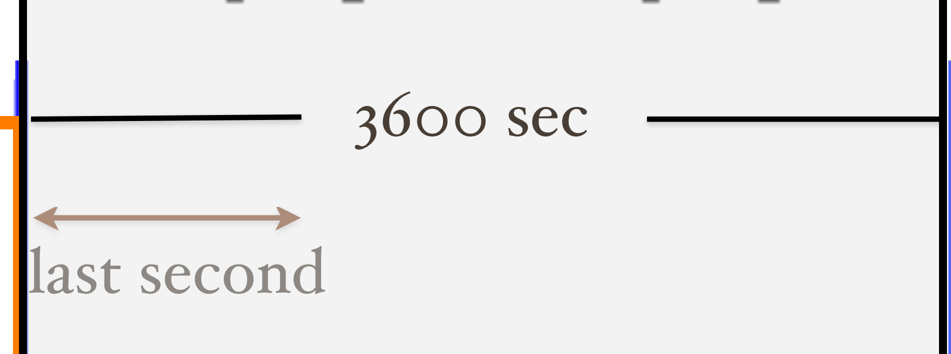
*) SI: 1 second := 9 192 631 770 periods (^{133}Cs line)

Law of Uncertainty of Counting

of independent events: $\boxed{\Delta n \geqq 1}$

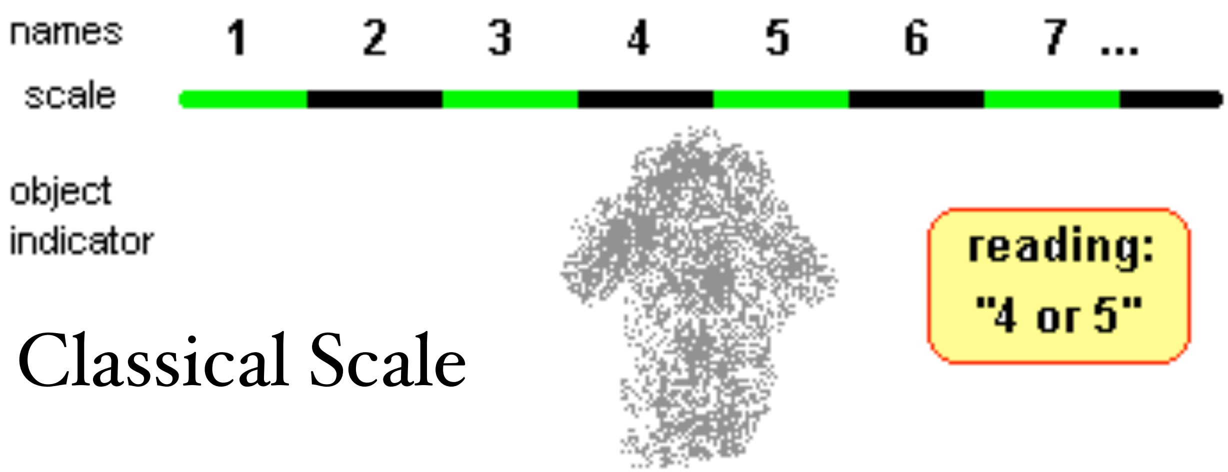
Traffic Statistics: How many cars pass point X in one hour?

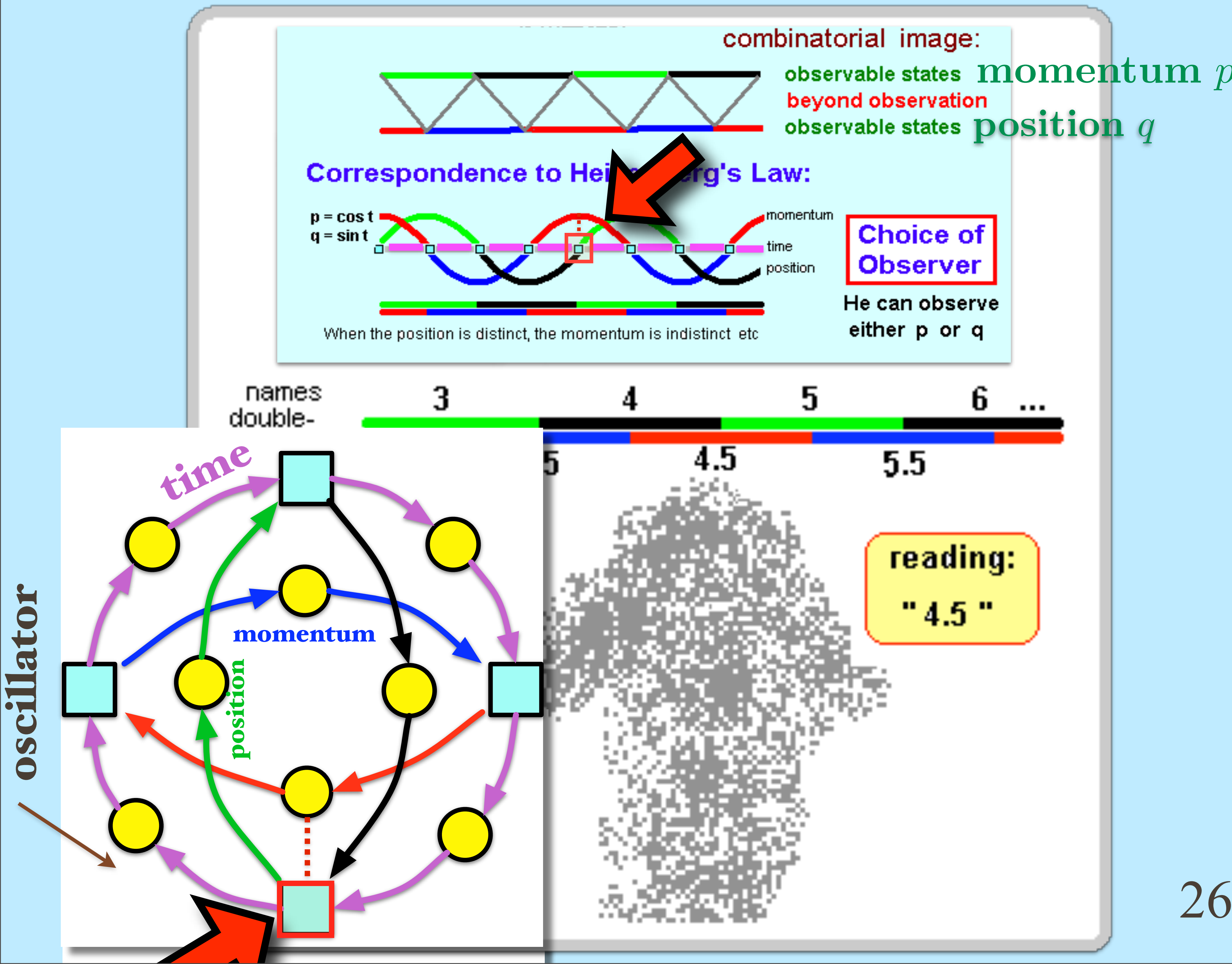




Δn is the unavoidable possible miscount

Classical Scale




combinatorial image:
observable states
beyond observation
observable states
momentum p
position q
Correspondence to Heisenberg's Law:
p = cos t
q = sin t
momentum
time
position
When the position is distinct, the momentum is indistinct etc
Choice of Observer
He can observe either p or q
names
double-
3
4
5
6 ...
5
4.5
5.5
reading:
" 4.5 "
time
momentum
position
oscillator

The Main Principles of Modern Physics

$$c = c'$$

Invariance Speed of Light

$$\Delta p \cdot \Delta x \geqslant h/4\pi$$

Uncertainty Relation

$$E = mc^2$$

Equivalence of Energy and Mass

$$E = h\nu$$

Quantization of Energy

Relativity

Quantum Physics

$$x' = \frac{(x - vt)}{\sqrt{1 - \frac{v^2}{c^2}}} \qquad y' = y \qquad z' = z \qquad t' = \frac{(t - \frac{vx}{c^2})}{\sqrt{1 - \frac{v^2}{c^2}}}$$

n

$$x' = L(x - vt)$$
$$t' = L(t - wx)$$

Invariance Speed of Light

no mention of c !

$$L = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

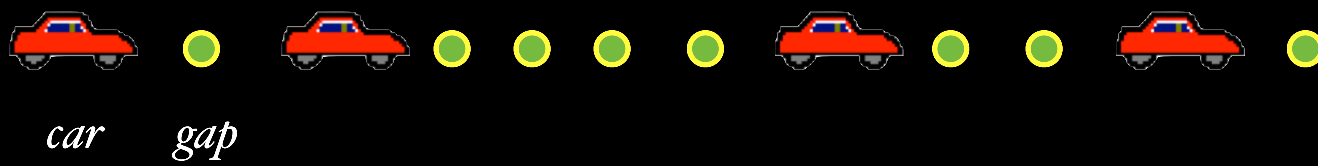
$$w := \frac{v}{c^2}$$

slowness

$$[\frac{sec}{m}]$$

These results pertain also to macroscopic levels!

Slowness Effects



This motion proceeds fastest if there is just one gap in front.

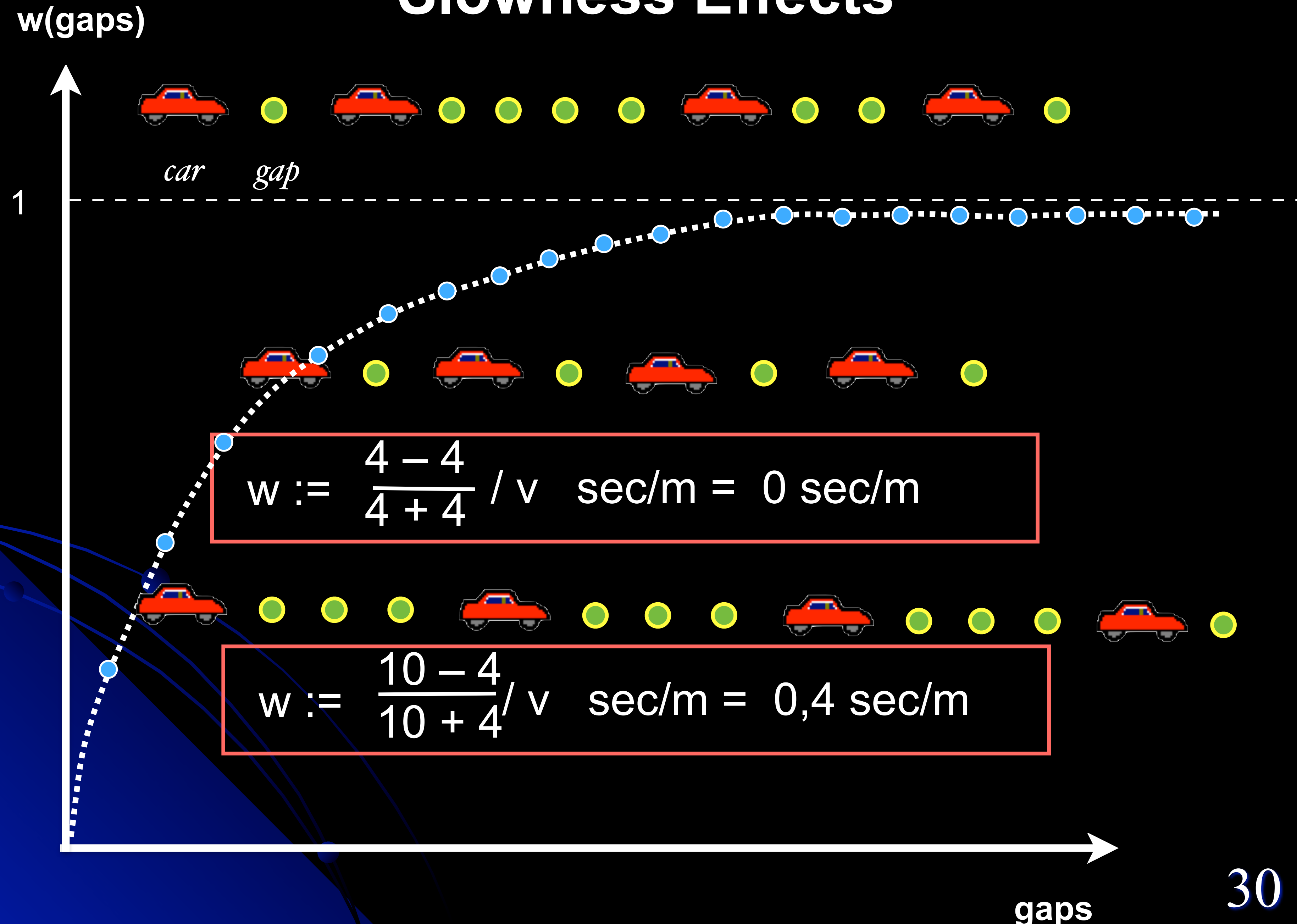
Otherwise, we define SLOWNESS w as the quotient

$$w := \frac{\text{gaps} - \text{cars}}{\text{gaps} + \text{cars}} \;/\; v \text{ (cars)} \qquad \text{sec/m}$$

$$w := \frac{8 - 4}{8 + 4} \;/\; v \quad \text{sec/m} = 1/3 \text{ sec/m}$$

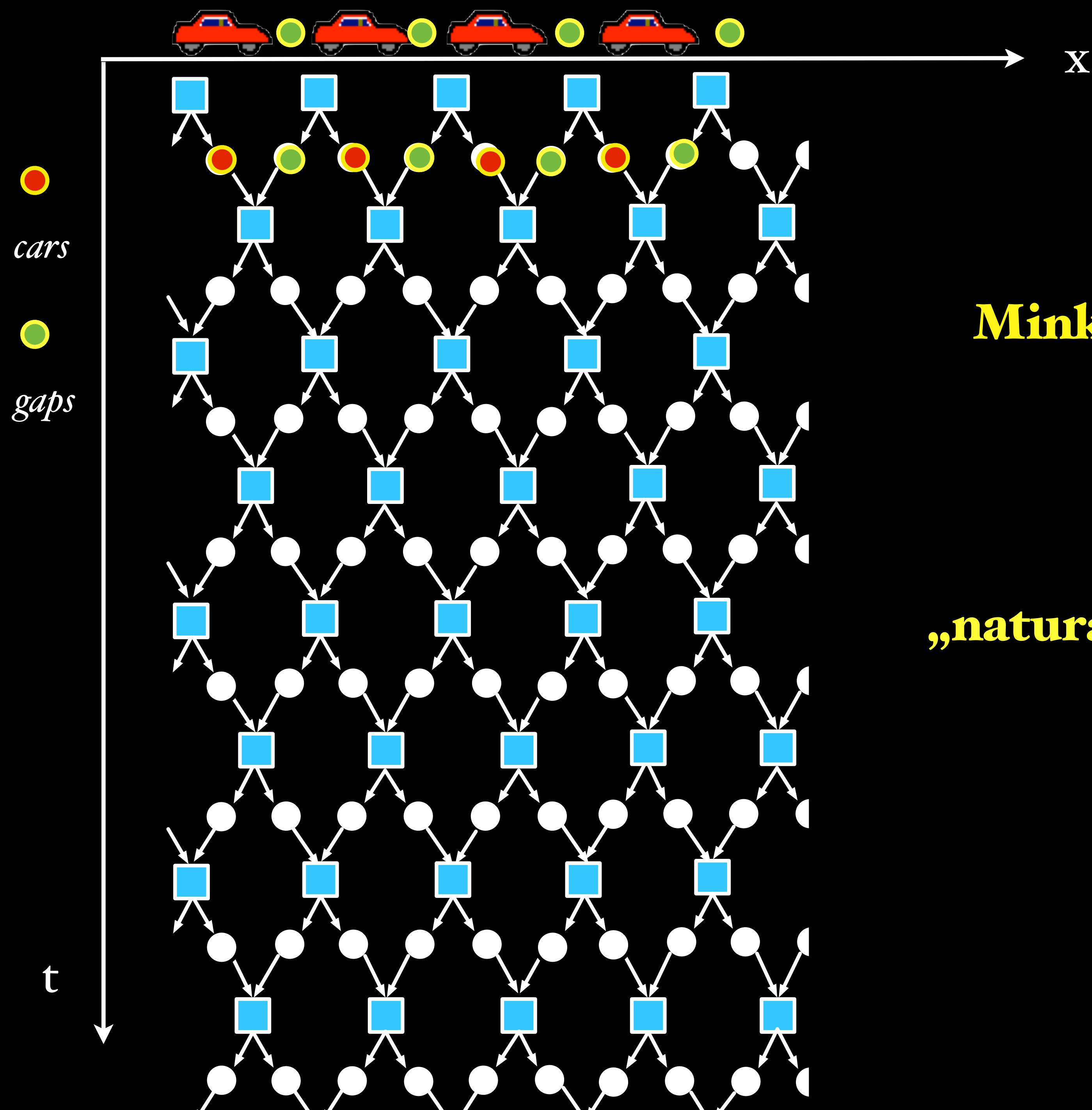
The concept of slowness is a key to understanding repetitive GROUP behaviour. It can be applied to Organization, to Work Flow (**Just-in-time Production**), and to Physical Systems.

Slowness Effects



$$w := \frac{4-4}{4+4} / v \quad sec/m = 0 \; sec/m$$

$$w := \frac{10-4}{10+4} / v \quad sec/m = 0{,}4 \; sec/m$$



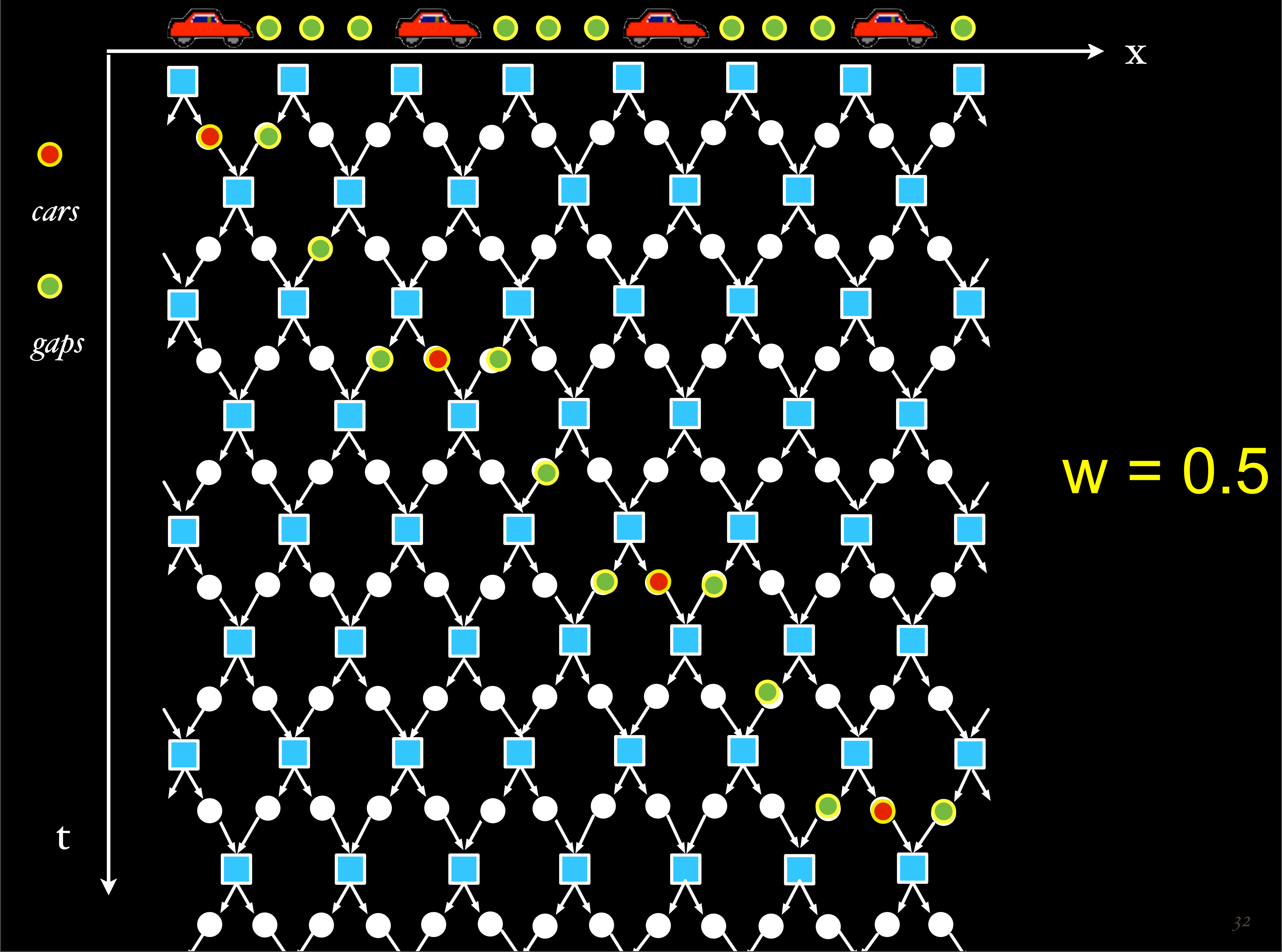
from

Minkowski Space

to

Petri‘s „natural coordinates“

$w = 0$



x
cars
gaps
t
w = 0.5

We saw:

The concept of SLOWNESS has its origin in Physics:

It appears in the symmetrical Lorentz Transformation

$$x' := L\,(x - v\,t)\,;\quad t' := L\,(t - w\,x)\,;\quad w := v / c^2$$

w is measured in seconds (lost) per meter

v is measured in meters (gained) per second

It is the inverse **$w = 1 / u$** of the superluminal phase velocity **u** of material waves, and it is relevant to the movement of electrons in a semiconductor as they interchange places with gaps.

Hence, we saw an example of translation to macroscopic level .

Determinism

Petri and Zuse saw no chance to implement their deterministic approach to Information on the level of Quantum Mechanics, because Observation and Measurement have unpredictable outcomes there.

Therefore, they ended the co-operation.

Re-started in 2002:

Petri saw a new chance for completing their work by following the guidelines of Nobel Laureate Gerard `t Hooft who proposes a deterministic model on an essentially finer scale.

Gerard 't Hooft

writes in „Determinism beneath Quantum Mechanics" (2002):

"Contrary to common belief, it is not difficult to construct deterministic models where stochastic behaviour is correctly described by quantum mechanical amplitudes, in precise accordance with the Copenhagen-Bohr-Bohm doctrine. ......

Gerard 't Hooft

writes in „Determinism beneath Quantum Mechanics“ (2002):

“Theories of this kind would not only be appealing from a philosophical point of view,

but may also be essential for understanding causality at Planckian distance scales.

Conclusions of Gerard 't Hooft:

Our view towards the quantum mechanical nature of the world can be summarized as follows:

Nature's fundamental laws are defined at the Planck scale.

At that scale, all we have is bits of information.

Determinism excludes the **Creation** of Information.

We (Petri) go one **tentative** step further and forbid **the Destruction** of Information, in order to establish a

Law of Conservation of Information

as a prototype of Conservation Laws in general.

Accordingly, we describe the physical Universe in terms of

Signal Flow and – equivalently – of **Information Flow.**

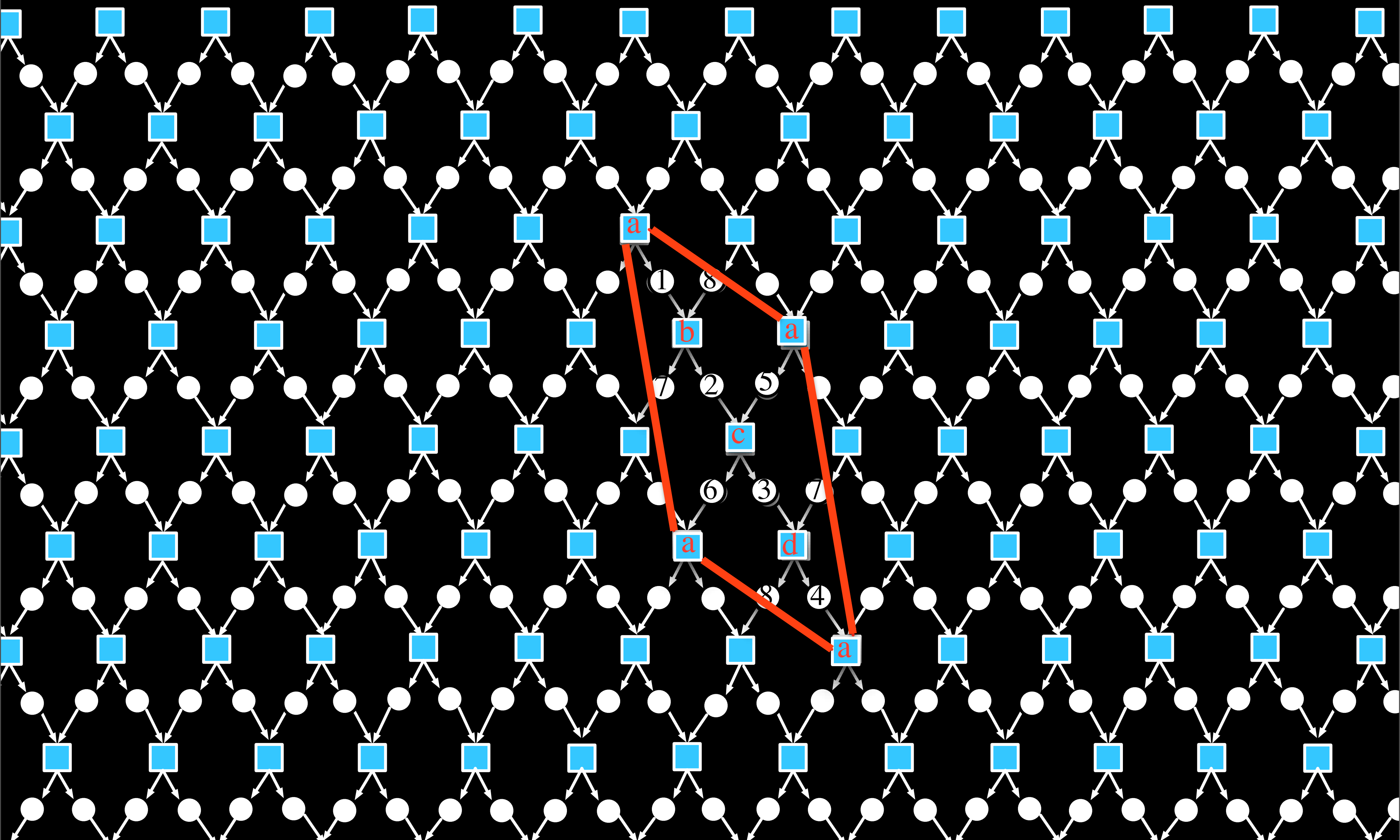
We derive the **Information Operators** from the idea

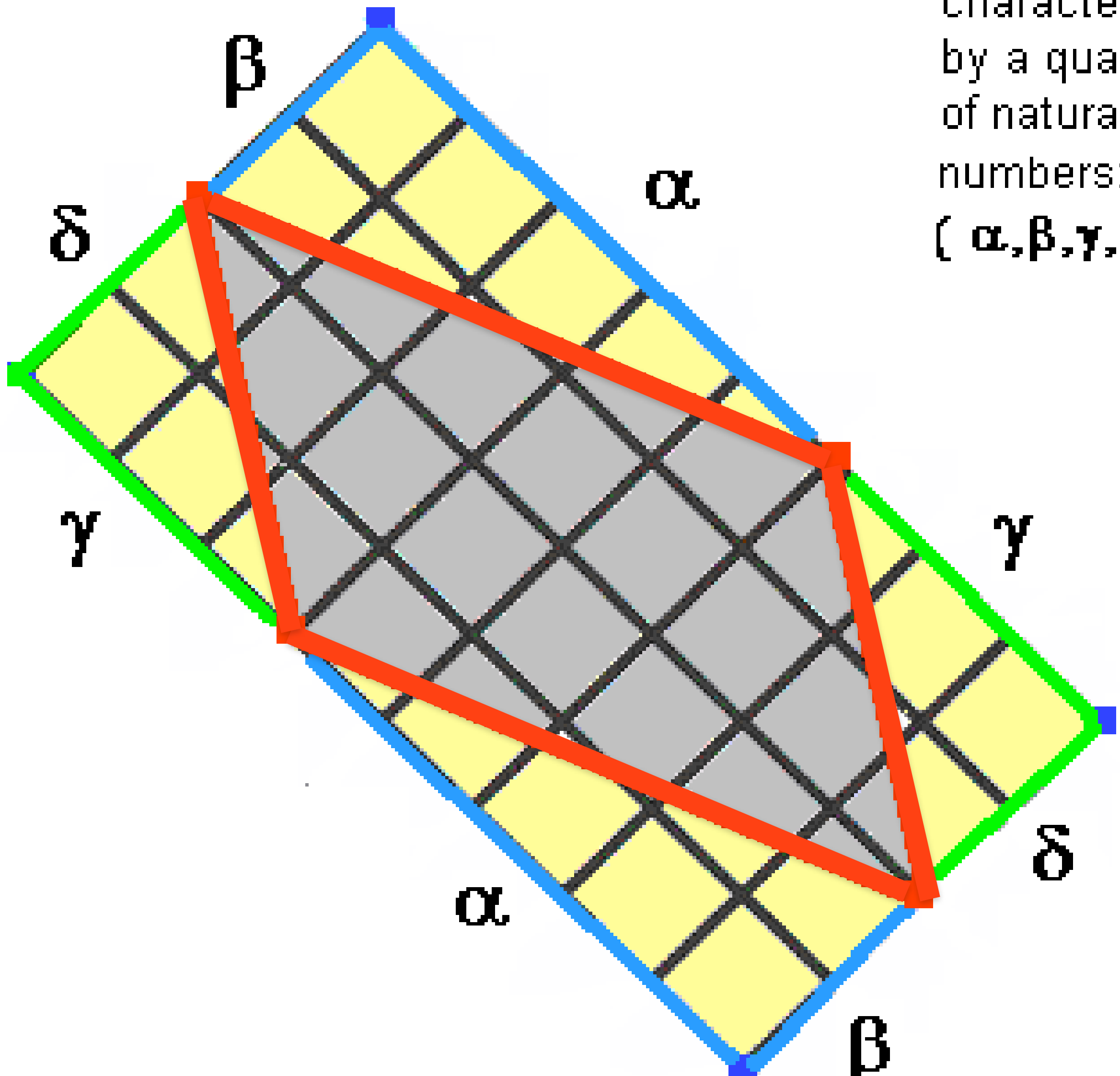
of space-time periodic movement of Signals in an

INTEGER MINKOWSKI SPACE

Petri's „natural coordinates"

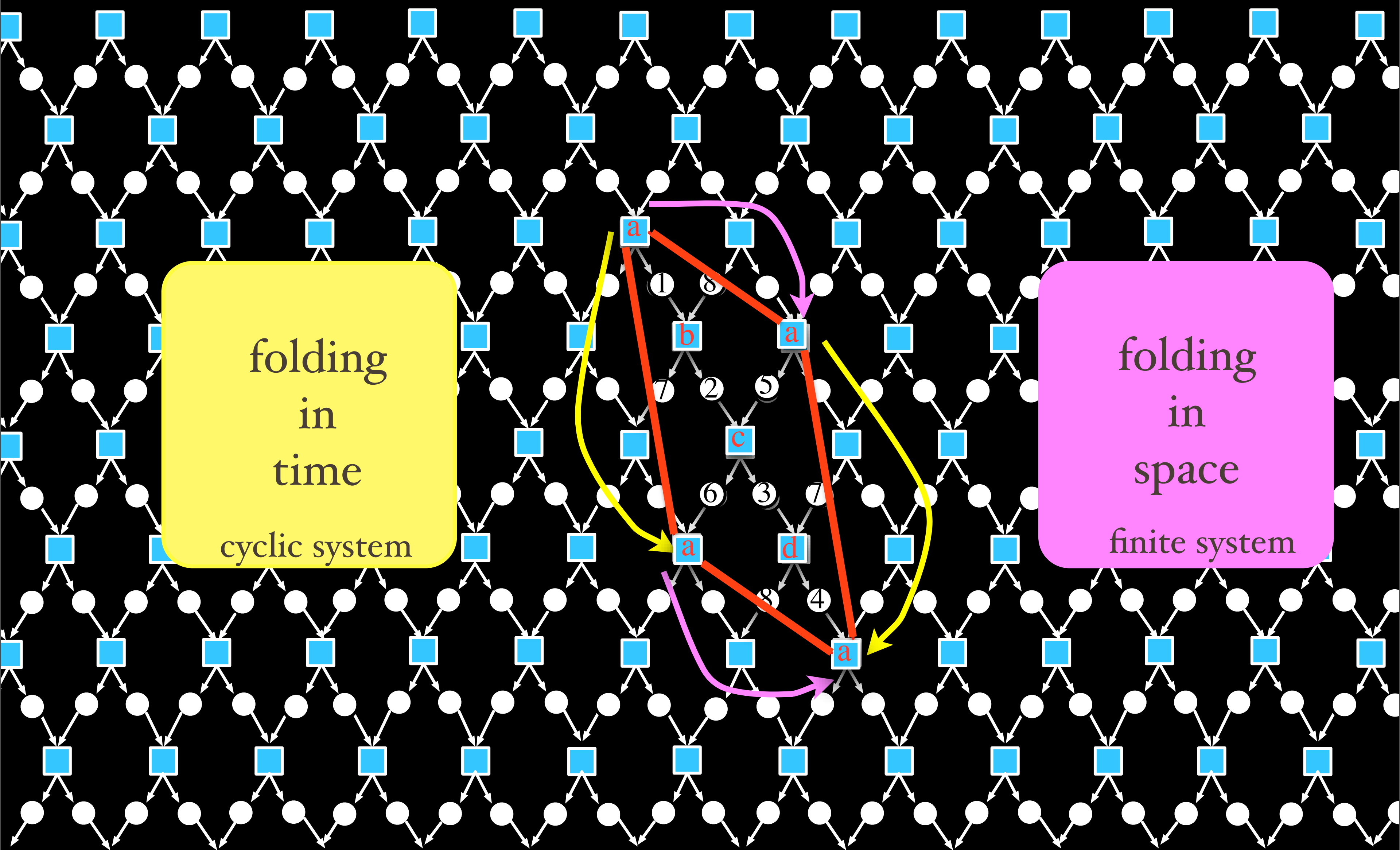
Petri's „natural coordinates"





Repetitive behaviour is characterized by a quadruple of natural numbers:
(α,β,γ,δ)

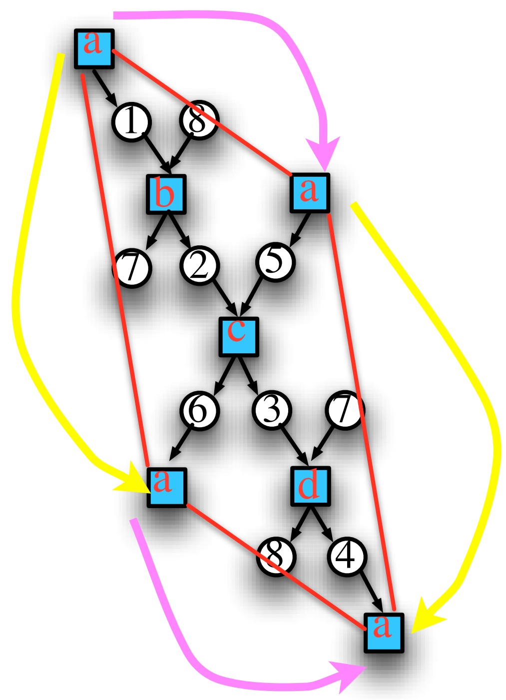
Petri‘s „natural coordinates“



Petri‘s „natural coordinates“

folding
in
time

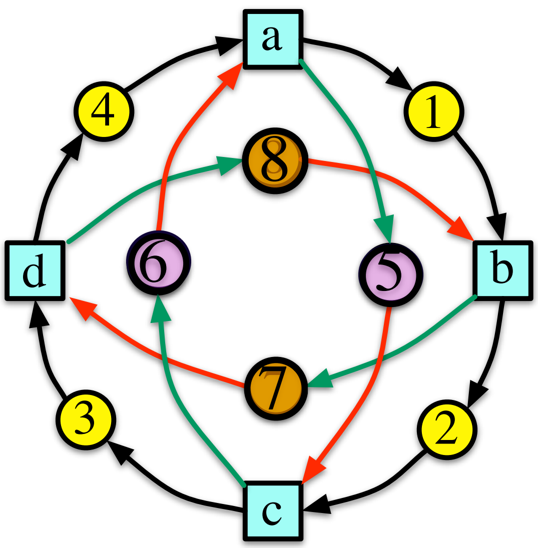
cyclic system



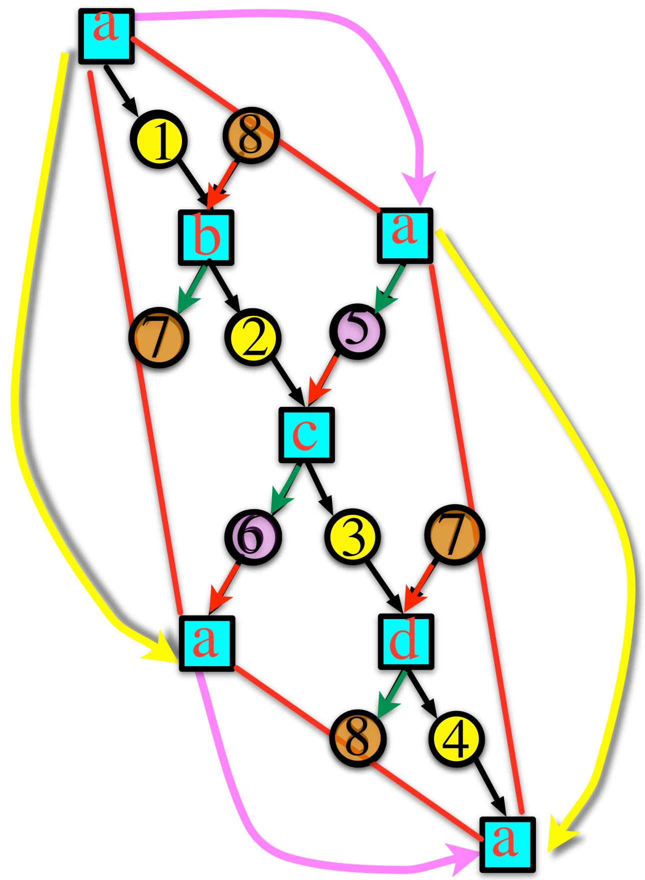
folding
in
space

finite system

Petri's „natural coordinates"



Oscillator !



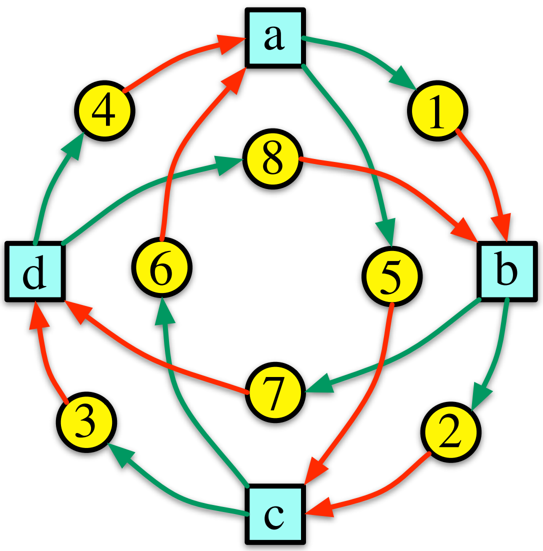
Folding the Space-Time image of a parallelogram to a „Cycloid" represents signal movement periodic in space and time.

New orientation of arrows!

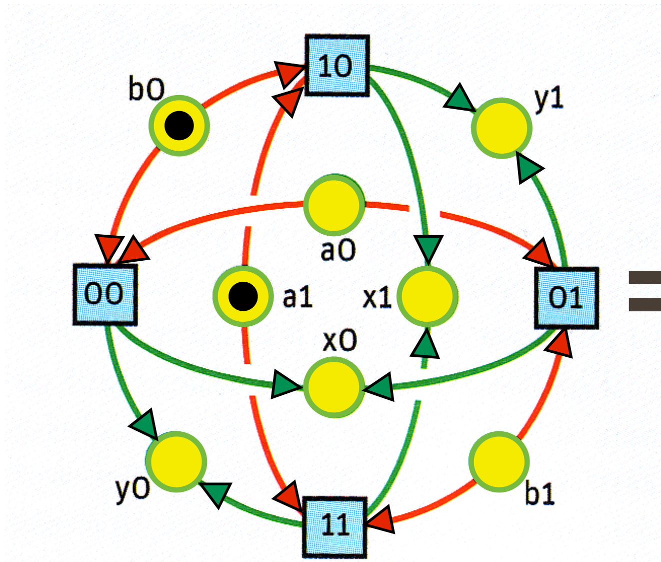
x = a

y = a XOR b

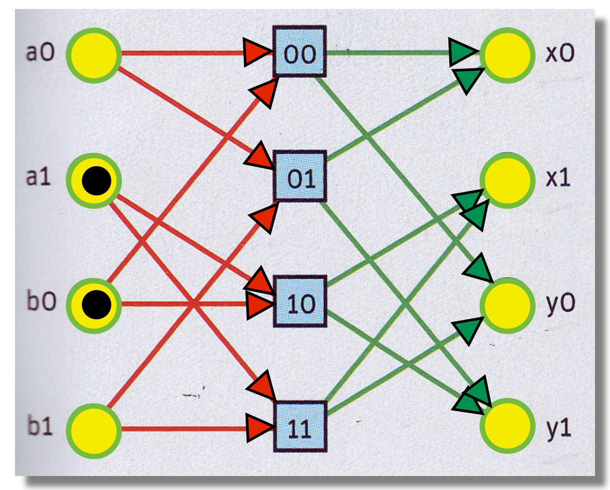
Exclusive OR



oscillator



=



isomorphic graph

We derive the **Information Operators** from the idea of space-time periodic movement of Signals in an INTEGER MINKOWSKI SPACE

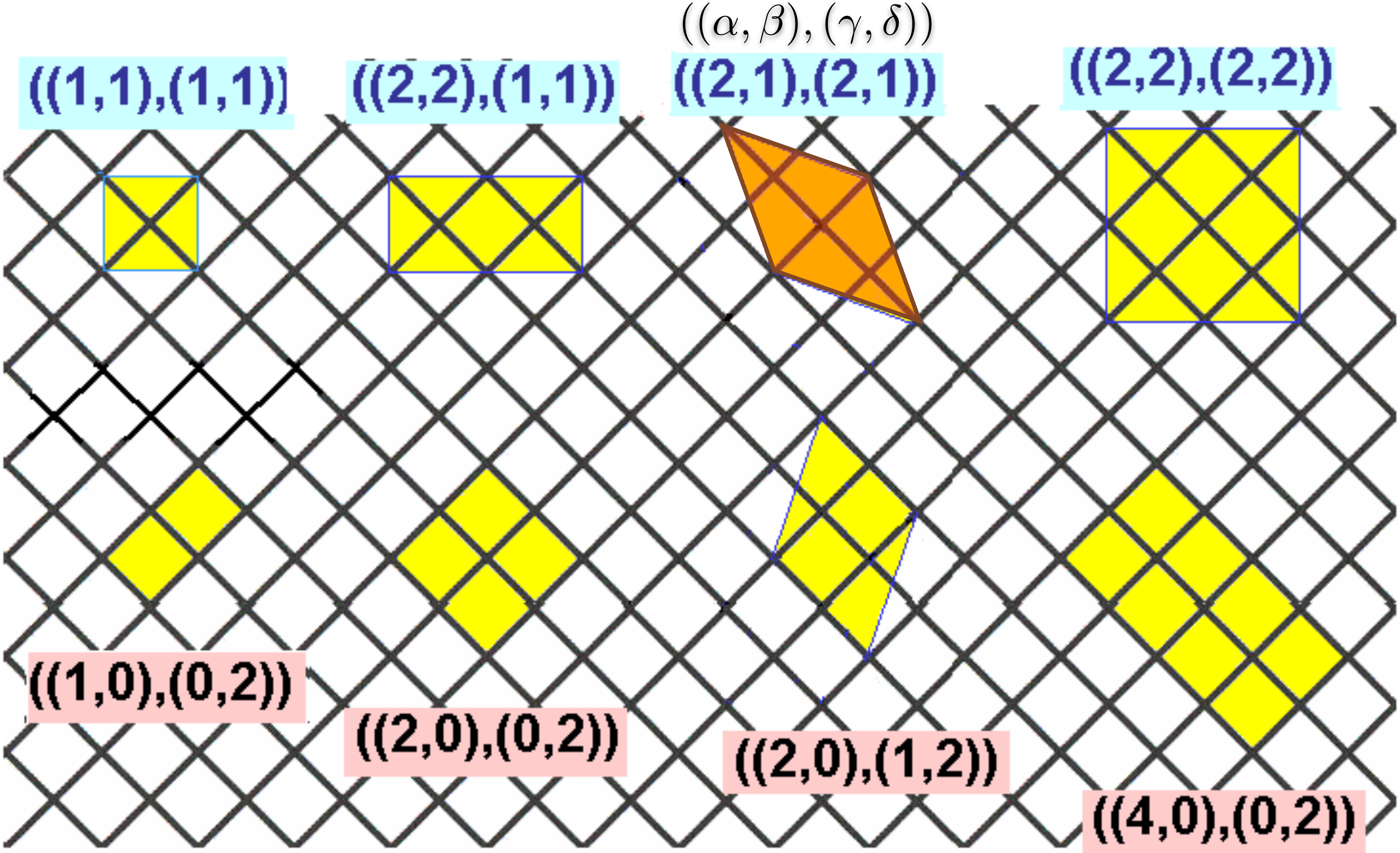
Petri‘s „natural coordinates“

A central idea of Combinatorial Modelling:

We use the Trajectories of Particles

as NATURAL COORDINATES

The smallest regular patterns of behavior



LT-compatible and degenerate Cycloids

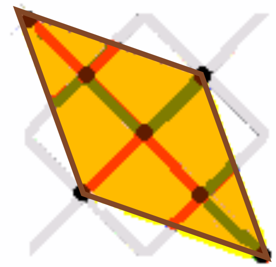
The smallest lossfree Boolean Transfe

Bit-pair-Equality

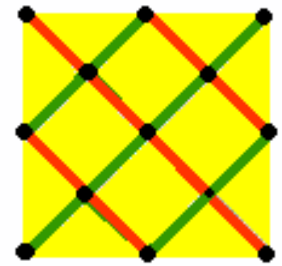
Synchronizer, Bit Exchange

$((\alpha,\beta),(\gamma,\delta))$

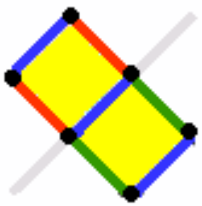
XOR-Transfer



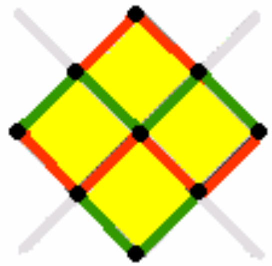
Majority Transfer



$((4,0),(0,2))$

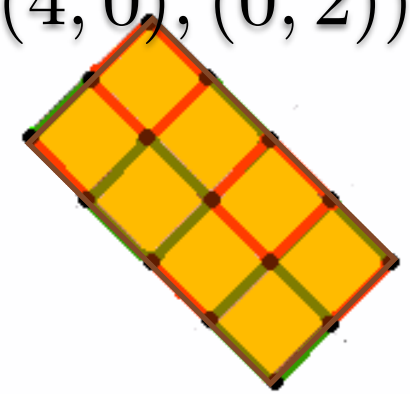


Dual of the two-state Automaton (not a net!)

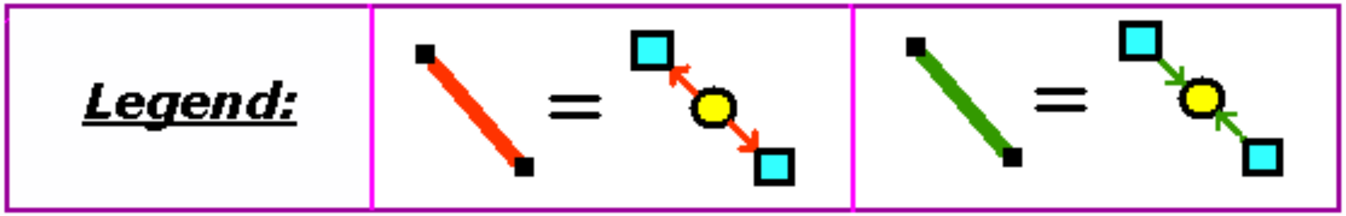


Synchronizer, Bit Exchange

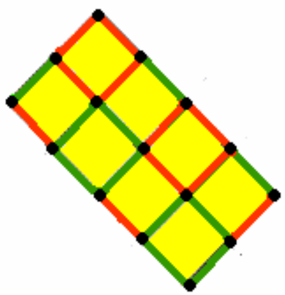
XOR-Transfer



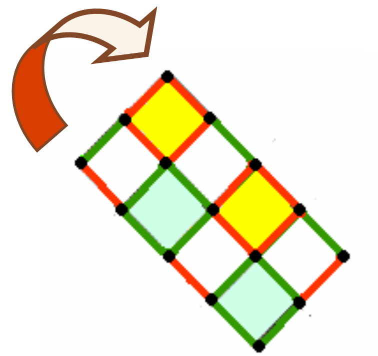
Quine Transfer = conditional Bit Exchange



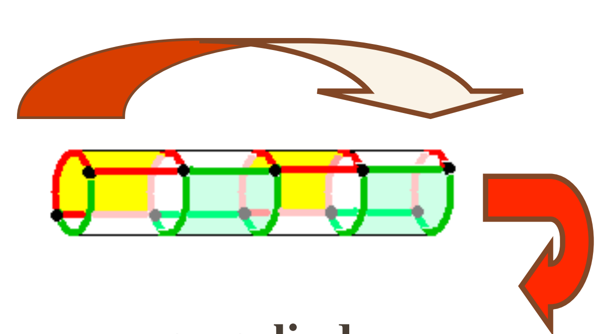
How the Net constructs can be generated from the rough images



Quine Transfer
= conditional
Bit Exchange

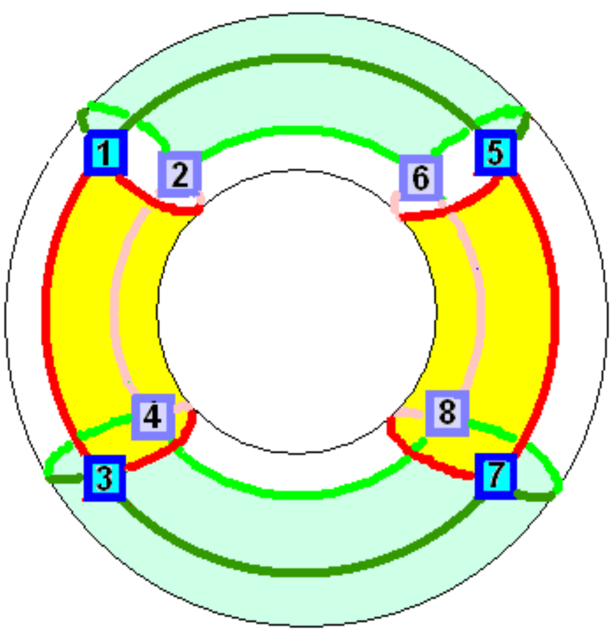


input- and output squares

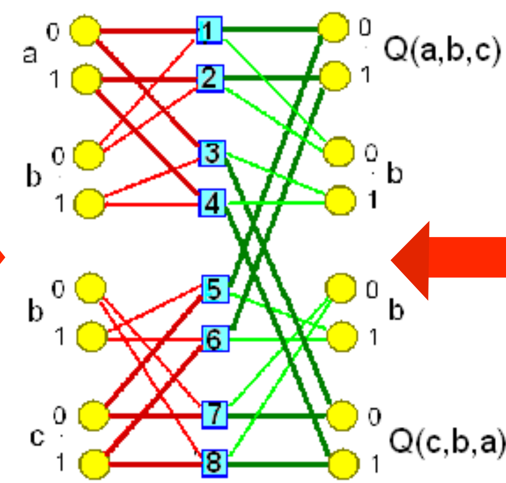


on cylinder

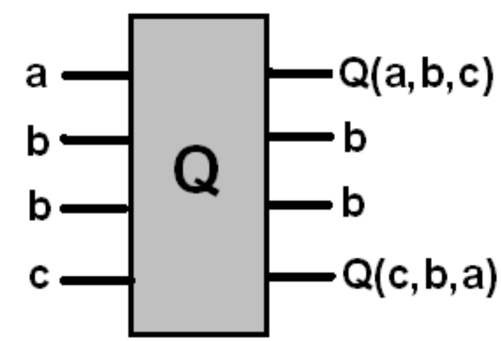
Quine's Function Q(a,b,c)
means
if b = 0 **then** a **else** c



on torus



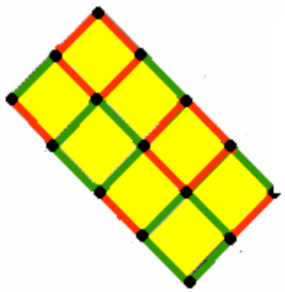
apply legend and unfold define usage



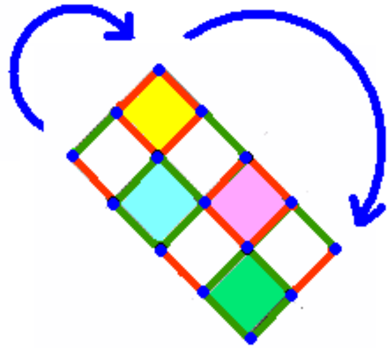
block image

Information Flow Graph

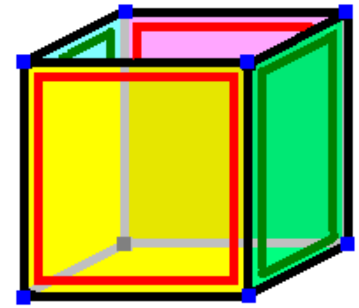
How the Net constructs can be generated from the rough images



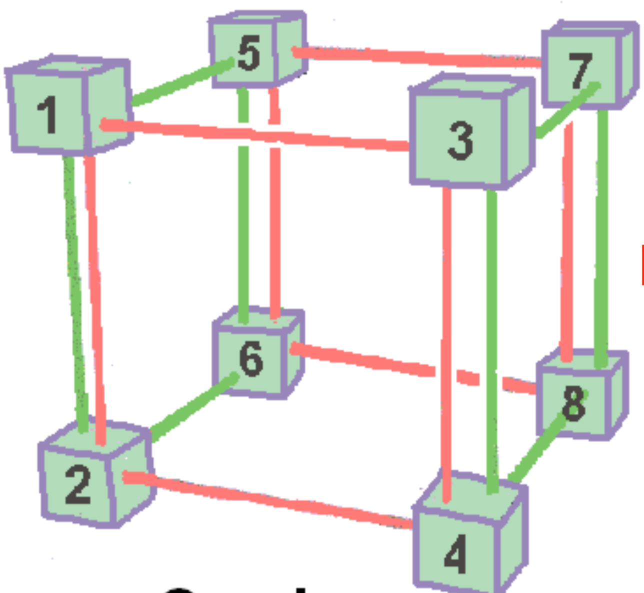
Quine Transfer
= conditional
Bit Exchange



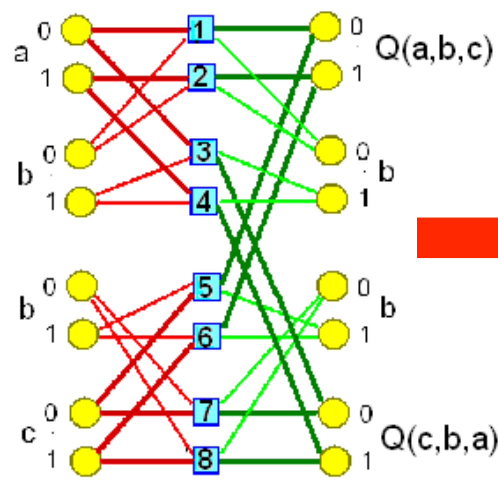
input- and output
squares



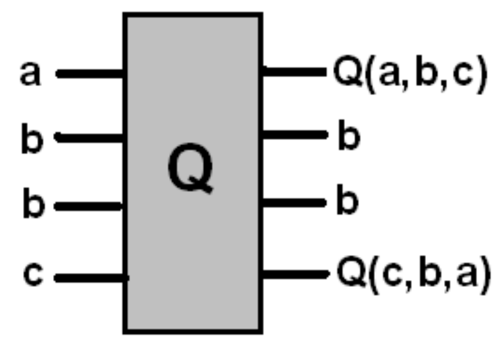
on a cube



Q cube

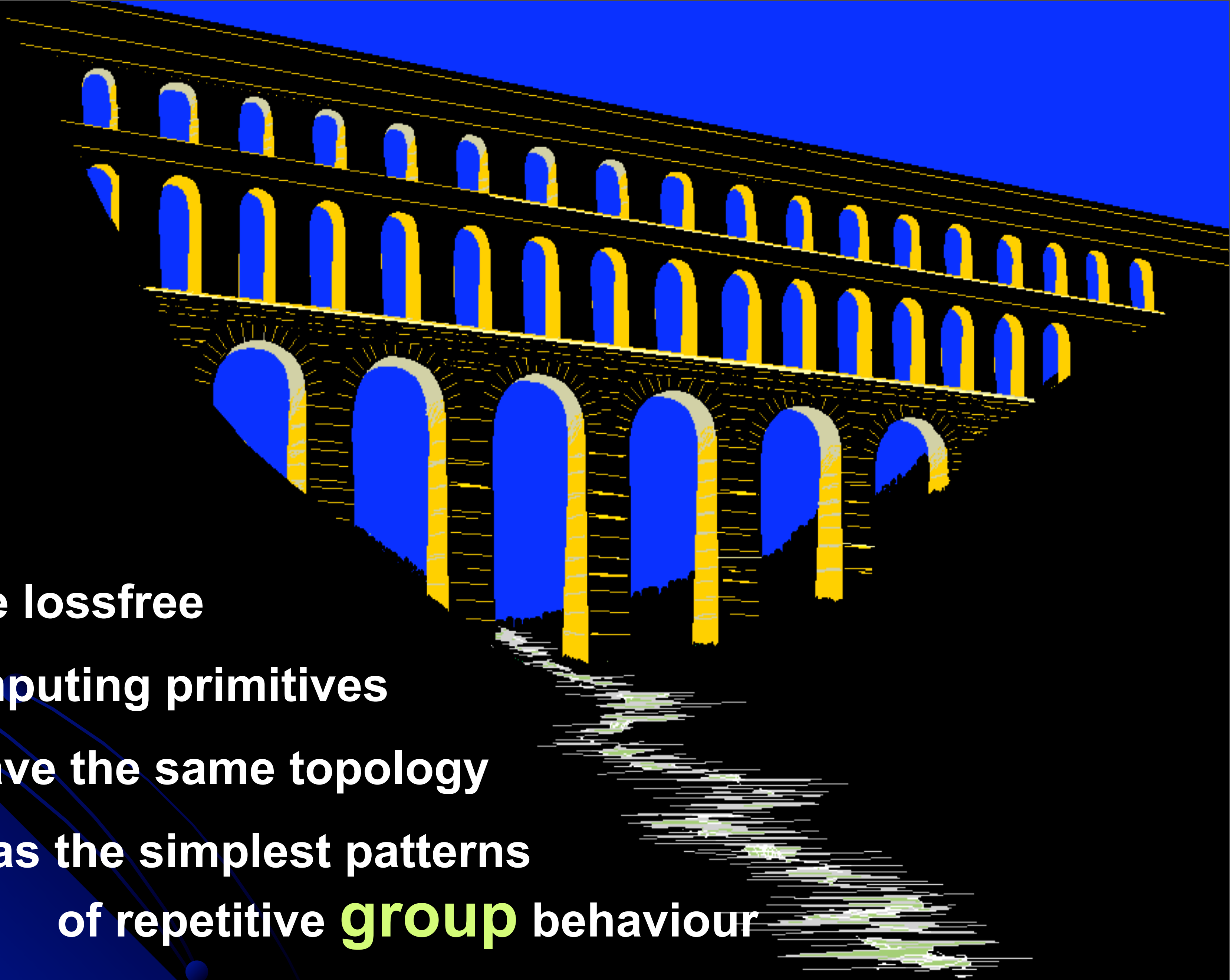


apply legend
and unfold
define usage



block image

Information
Flow Graph



Those lossfree

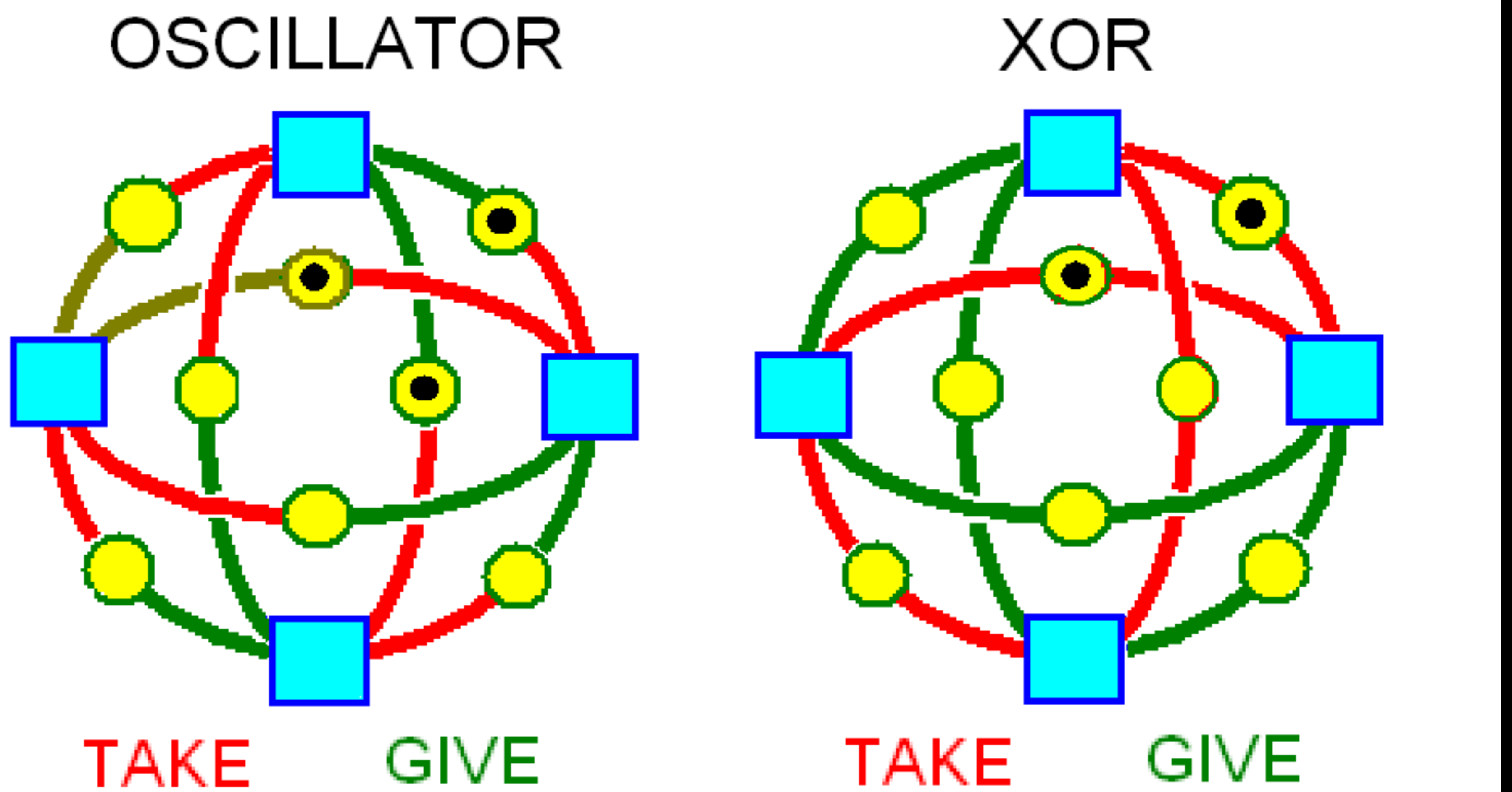
computing primitives

have the same topology

as the simplest patterns

of repetitive **group** behaviour

Different structures - same topology:



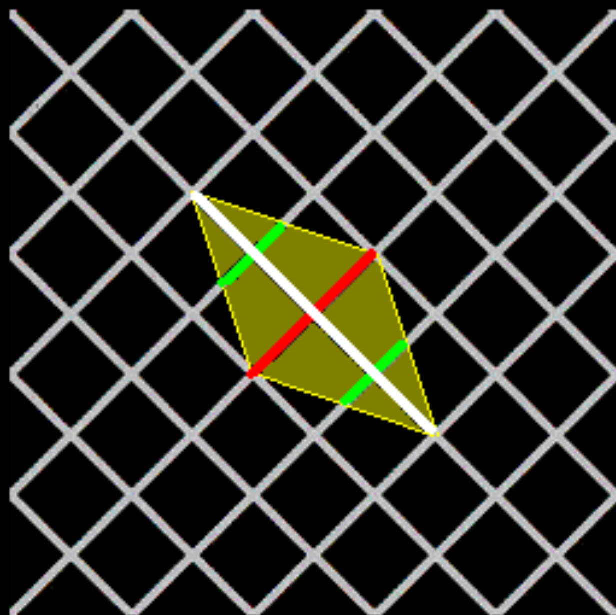
T-input T-output T-input T-output

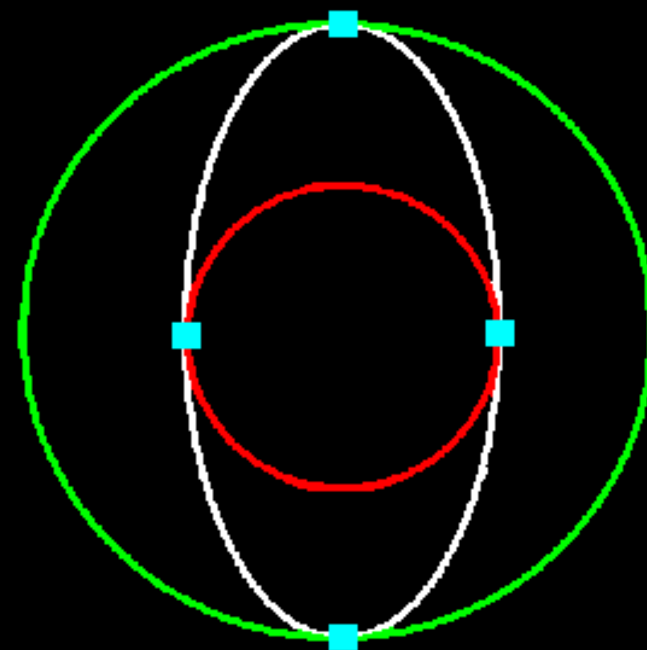
CONTINUOUS SPACES

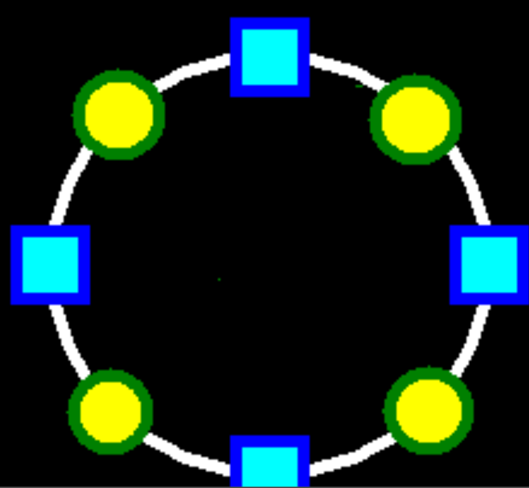
continuous := connected and compact

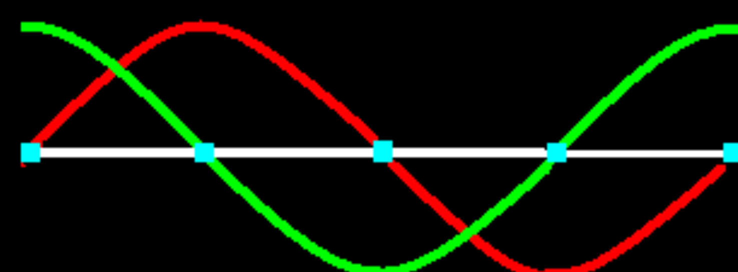
Structure	infinite	finite
$(\mathbb{R},<)$ Real Numbers	Not Contin.	Not Contin.
$[0,1] \subset \mathbb{R}$ "Continuum"	Continuous	Not Contin.
$\mathbb{R} \cup \{\infty\}$ compactified	Continuous	Not Contin.
(S,T,F) Nets	Not Contin.	Continuous

Typical patterns we have considered:

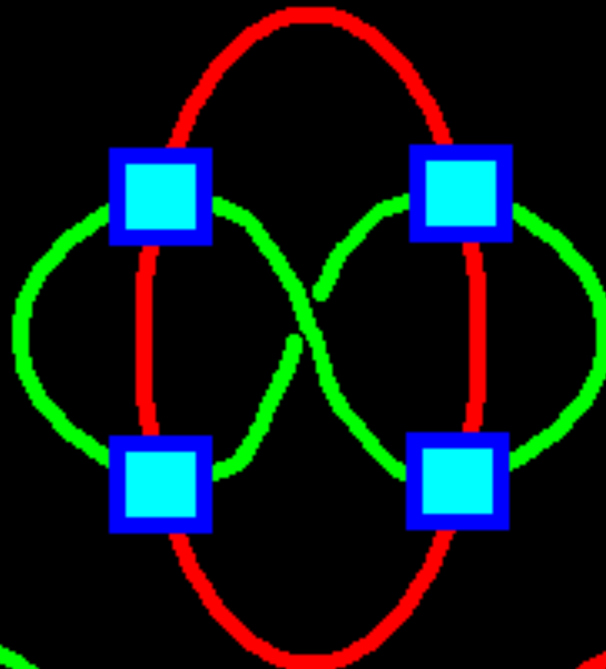




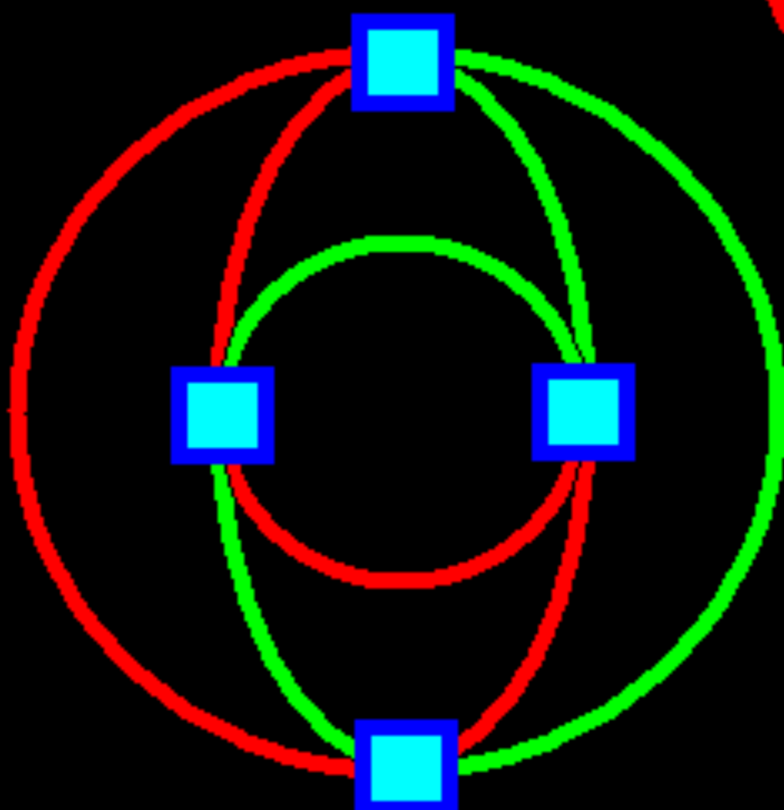


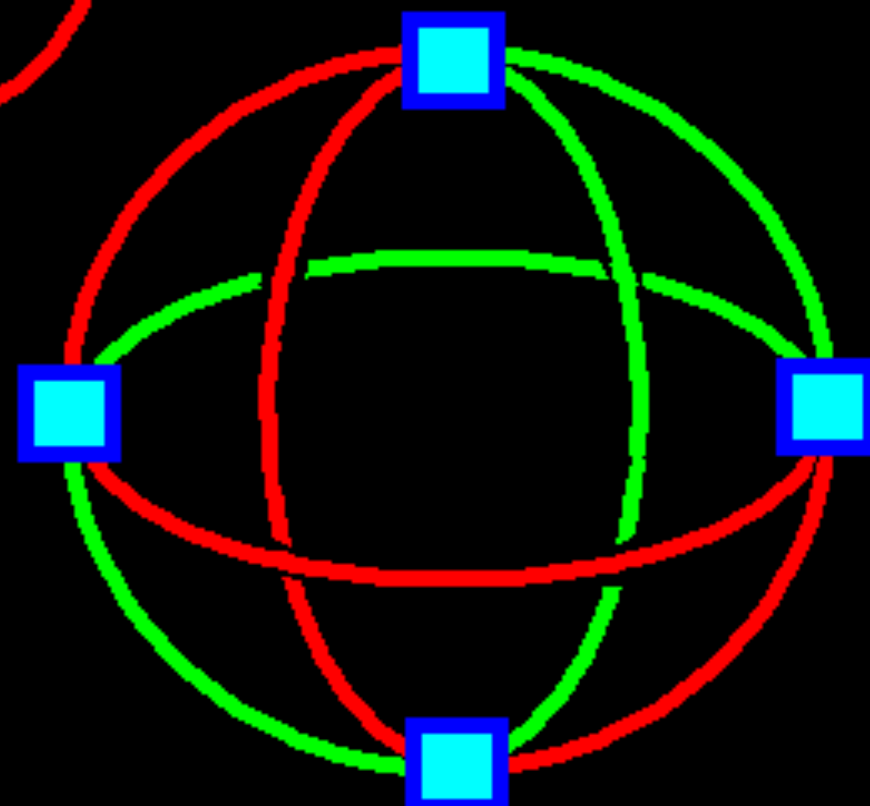


Three Presentations

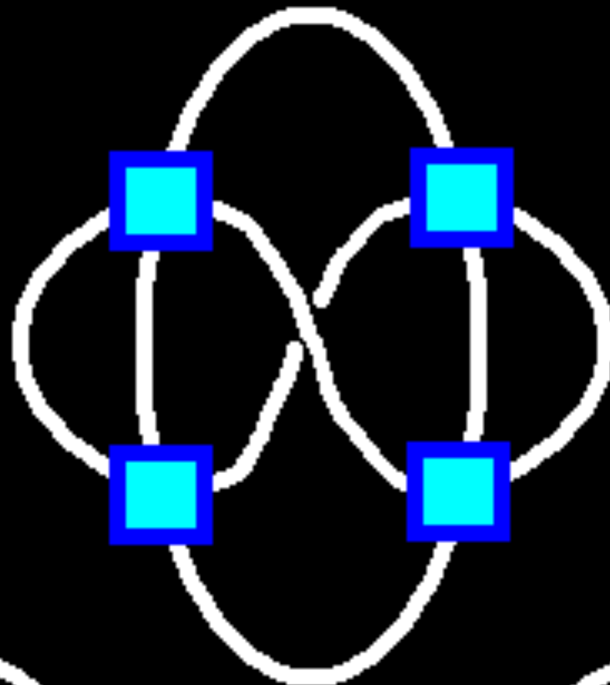


of the same NET

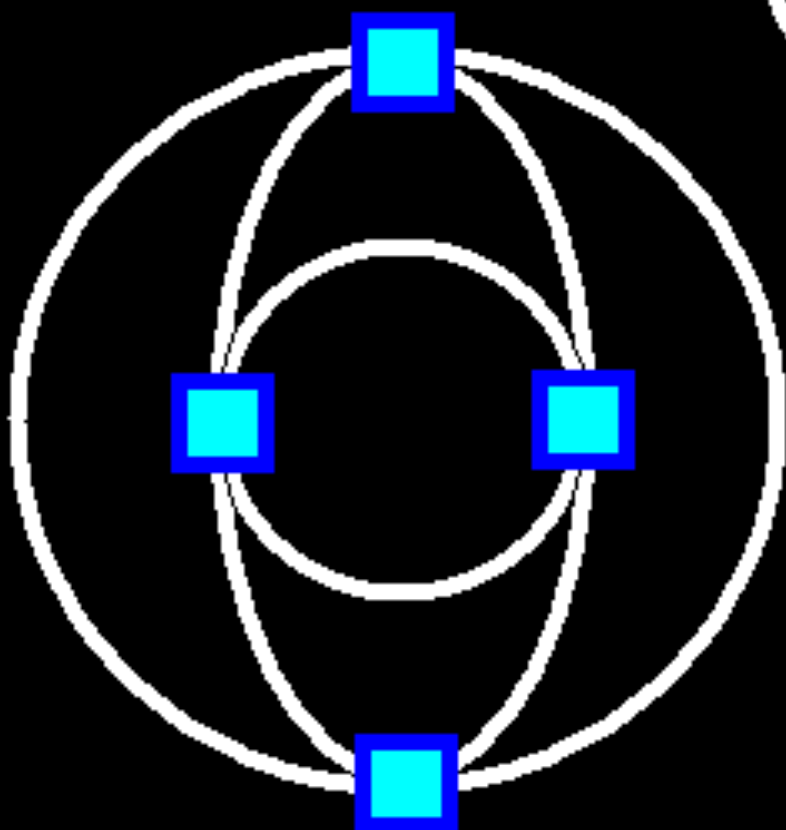


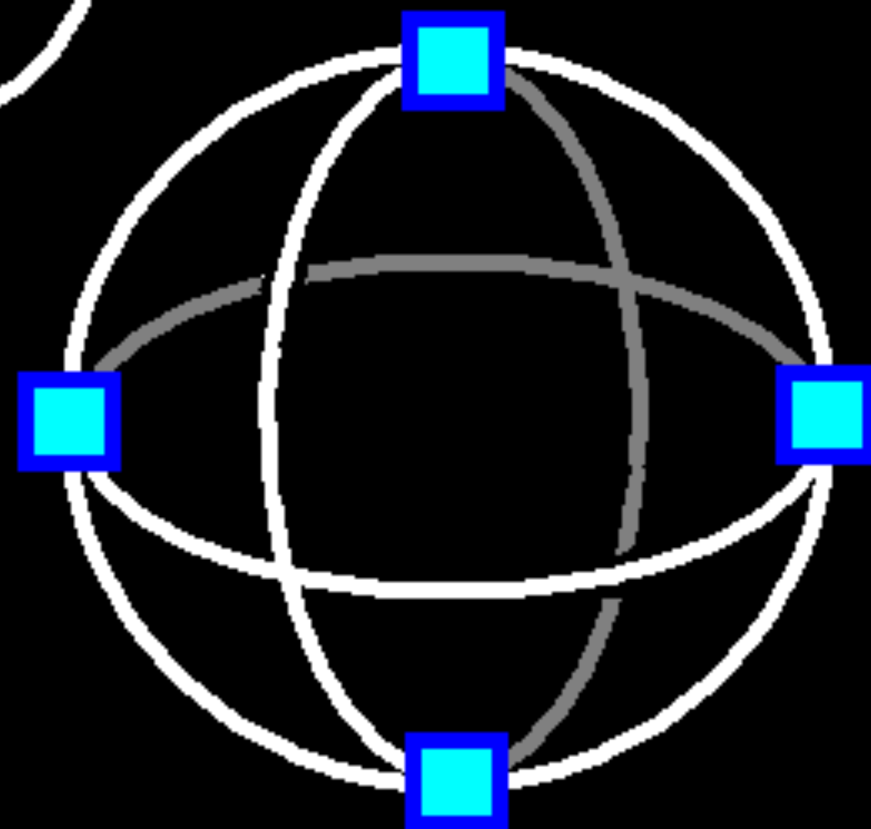


Three Presentations



of the same Topology





Combinatorial Topologies

(such as connected Nets and Net Piles)

are Continuous Spaces
if and only if they are **Finite.**

that is, they share the properties
„connected“ and „compact“
with the Continuum of Real Numbers [0,1]

What follows from this main result ?

It follows that, if we base our models on the combinatorial concepts of signal flow suggested by Informatics, and insist on continuity (as Zuse did), we end up inevitably with a model of a Finite Universe.

Albert Einstein uttered the suspicion that the use of Real Numbers in general might **rest on an illusion**.

Many years later, Stephen Hawking adduced very strong reasons to confirm Einstein's doubt.

Today, there is a growing number of authors argueing in the direction of finite models of the univers!

What follows from this main result ?

In a finite world, can we use Analysis with a clean conscience?

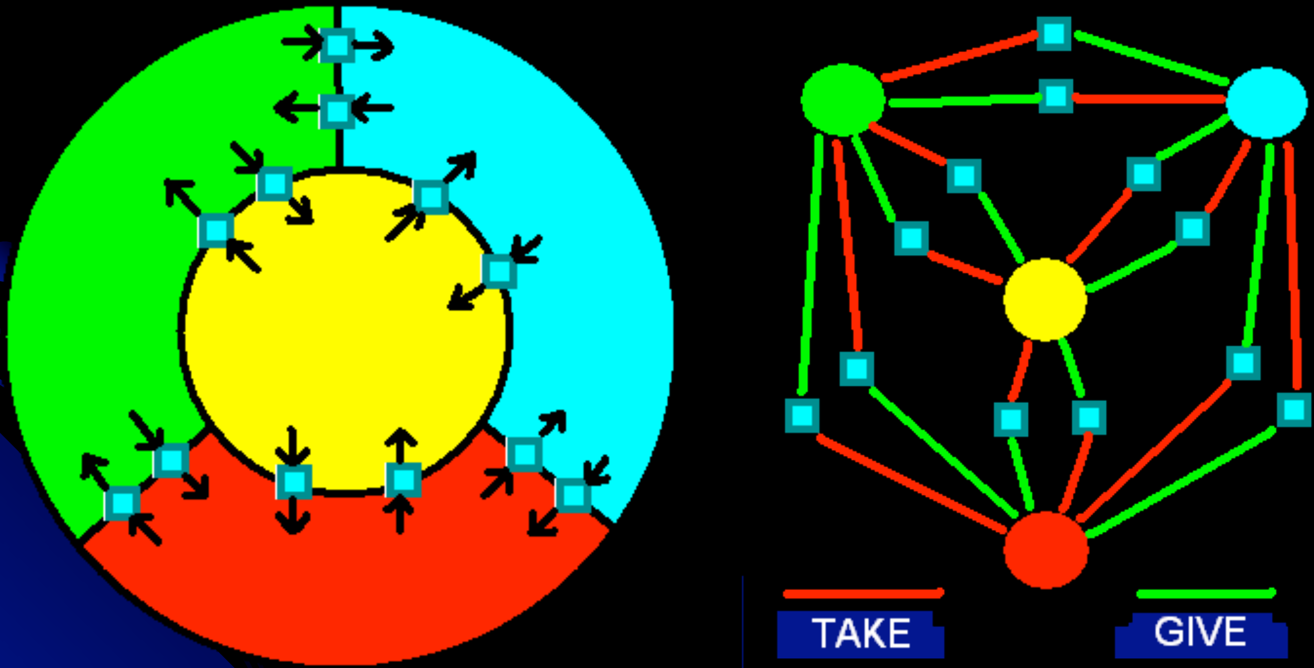
Definitely yes, if we do not forget that it is an extrapolation of what can be experienced.

We must not believe that we have „Command and Control of the Infinite“.

We have to reject infinite results, and to consider the results of Analysis as good approximations of reality and not – contrary to widespread opinion – as more precise than observed reality.

Continuity in Finite Structures

Contrary to widespread opinion, Infinity is not a prerequisite for Continuity. E.g. a political map is a continuous structure: Each state begins/ends **at** its borders, just as a Net state **at** the neighbouring transitions. The map gives rise to a special type of Net, and each piece of borderline to **two** transitions:



Any FINITE refinement can be applied to each map.

Continuity in Finite Structures

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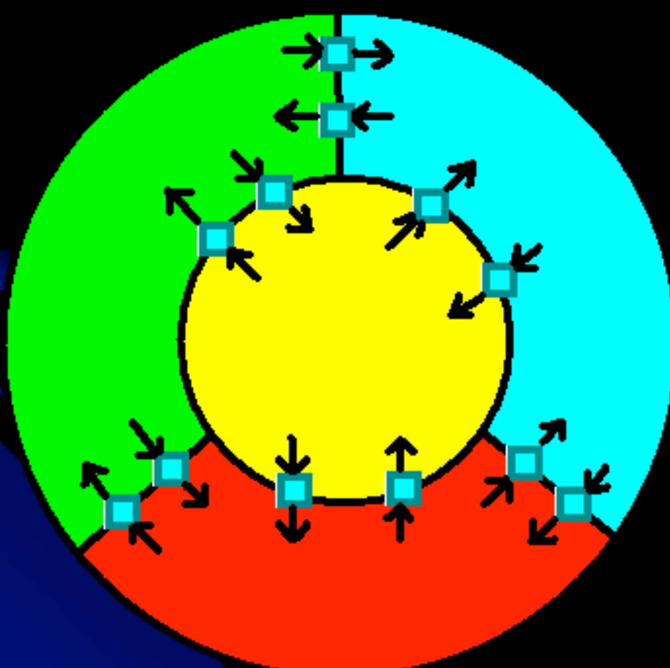
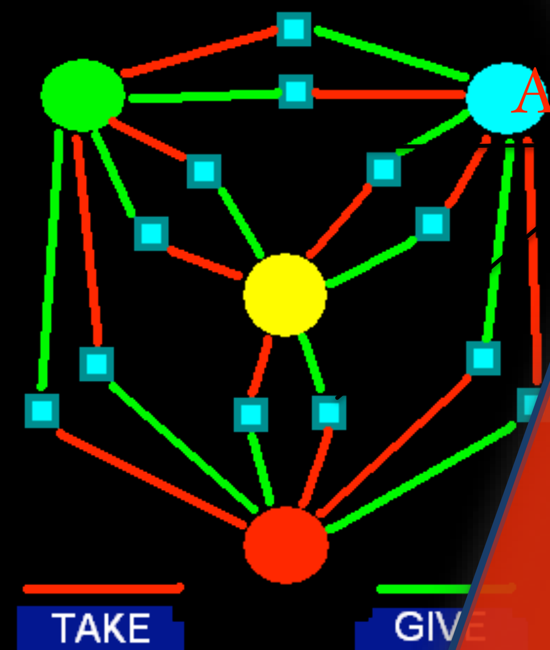
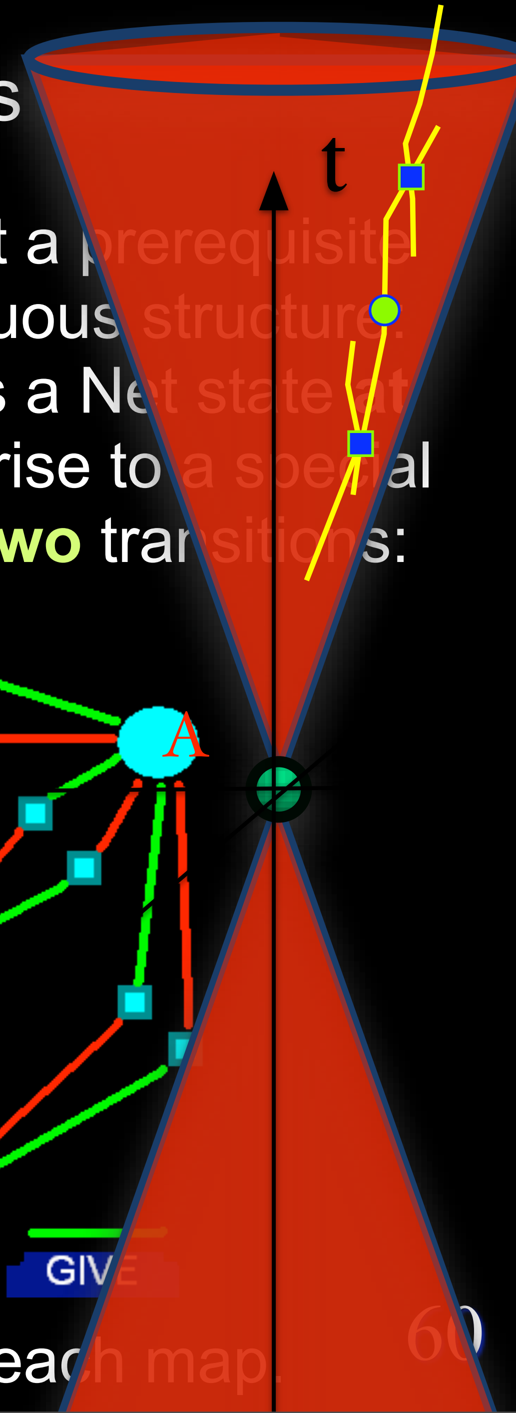






Any FINITE refinement can be applied to each map.

For Zuse's „Computing Universe",
this result suggests to assume a **Finite Continuous Space without Boundary**

The Signal Flow Image is a 2-in 2-out Net of size **2^2^2^2^2 < 10^20000**

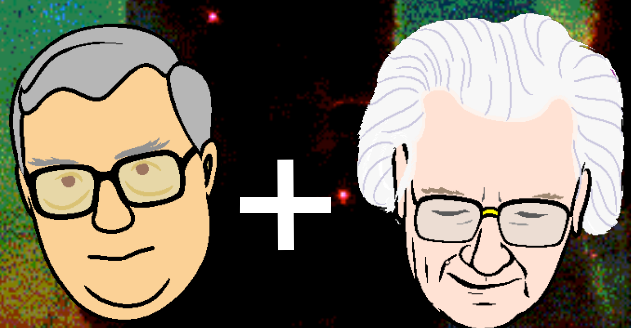
„without Boundary"
means
open *and* closed

for once, not digital.

For Zuse's „Computing Universe", this result suggests to assume a **Finite Continuous Space without Boundary**.

The Information Flow Image is a smaller Net: an S-arc graph of size < **2^2^2^2^2**

„without Boundary"
means
open *and* closed



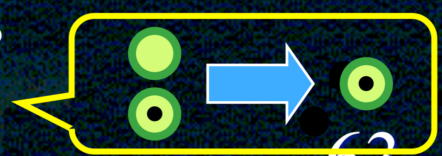
1985

The Behaviour Net of this „Universe“ is **periodic** because of the finiteness of that Universe. Its size can be estimated as **2^2^2^2^2^2** .

It consists of cyclic
Signal Histories
over all time

If Information loss occurs, the Behaviour Net is not periodic, nor are the Signal Paths cyclic. Determinism is still holding.

`t Hooft likes that better ... And you ?
It is easy to merge some state pairs !



Konrad Zuse disputing with Carl Adam Petri

about 1975

Sceptical audience inspecting Universe

Tobias Petri

This lecture was based on the article

„Das Universum als großes Netz“

(in German) published in

SPEKTRUM DER WISSENSCHAFT

Special issue on the topic

„Ist das Universum ein Computer?“

SPEZIAL 3/07 (Nov. 2007)

Copies of full text of Petri‘s original lecture and

of a original much extending

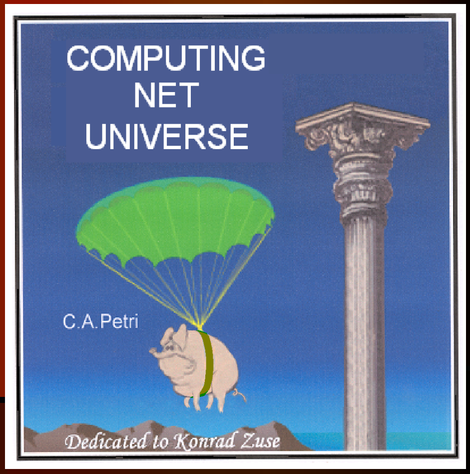
presentation (in English)

„COMPUTING NET UNIVERSE“-

A continuation of the work of Konrad Zuse

available on CD

after this Lecture



THANK YOU !