

A Little Sneak Peak of the History of Self-Replication

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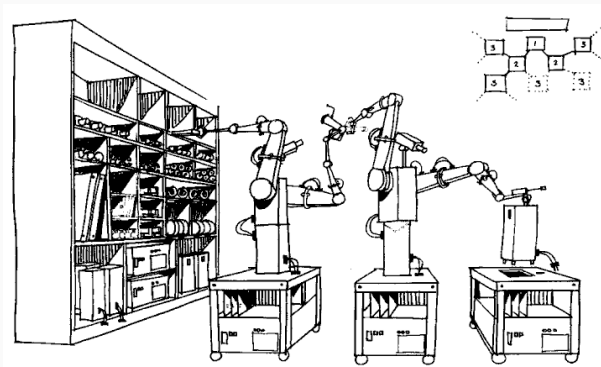


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John von Neumann

- 1903 Budapest - 1957 Washington D.C.
- logical foundations of quantum theory
- co-inventor of game theory
- Manhattan Project
- interest in automatic computing
- ENIAC project, computer architecture
- computing machines and their analogy to complex behaviours of living systems



- Understand the logical principles of self-reproduction independent of their physical realization (advancing our knowledge of biological mechanisms of self-replication)
- Can we construct a self-replicating automaton in some environment?

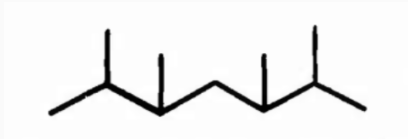
- **Kinematic model**
- **Cellular model**
- **Excitation-threshold-fatigue model** based on cellular model, each cell automaton would be neuron-like structure with a fatigue mechanism and a threshold
- **Continuous model** (based on a system of partial non-linear differential equations governing the diffusion in fluids.)
- **Probabilistic model**

Kinematic Model

Structure elements: computing (and, or, not, delays), kinematic, cutting, fusing, rigid, sensing

Environment: "infinite sea" with infinite supply of randomly distributed basic elements "floating around"

Machine: finite automaton M with a tape containing instructions

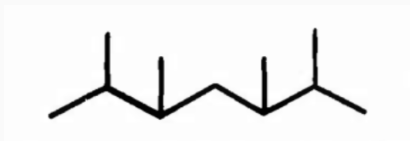


Kinematic Model

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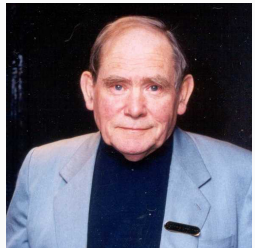
Machine: finite automaton M with a tape containing instructions



Principle: Use description \mathcal{D}_M in two ways: interpret and copy

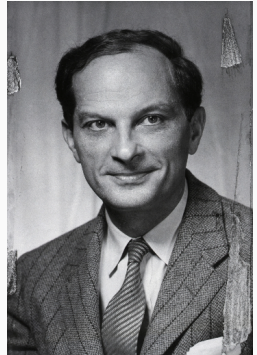
- 2002 Nobel prize in Physiology or Medicine laureate
- one of the first people to see the structure of DNA (1953)

"Von Neumann essentially tells you how its done and then DNA is just one of its implementations."



Stanislaw Ulam

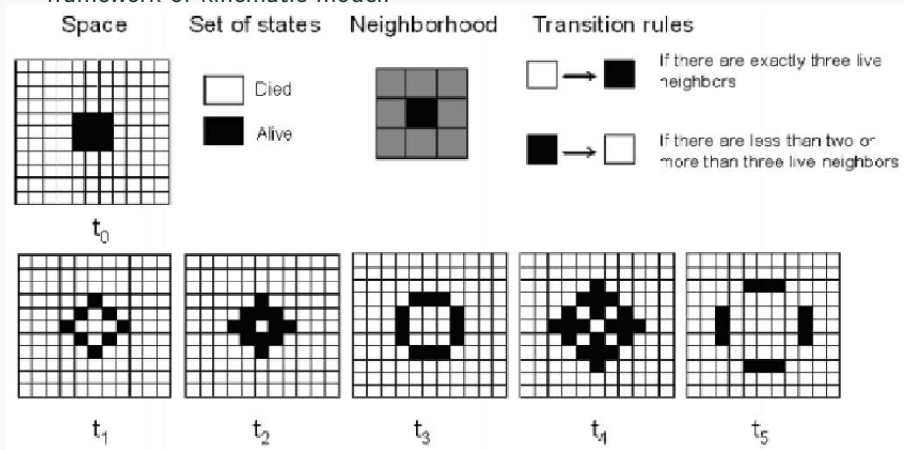
- Polish mathematician
- in 1935 met John von Neumann in Warsaw, invited to come to the Institute for Advanced Study in Princeton, New Jersey
- Manhattan Project, co-inventor of the thermonuclear bomb
- suggested to von Neumann the cellular model



Cellular Automata

Example: Game of Life

More amenable to logical and mathematical treatment than the framework of kinematic model.



Example: Game of Life

Animation.

Properties of Cellular Automata

- Simple - time and space are discrete
- Cell - functional and data storage capabilities
- Nature - parallel

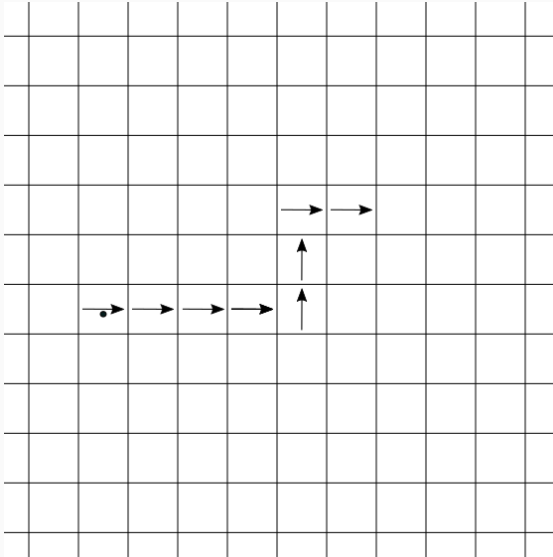
Sufficient Conditions for Self-Replication

What kind of logical organization is sufficient for an automaton to be able to reproduce itself?

- Logical universality.
- Construction capability.
- Constructional universality.

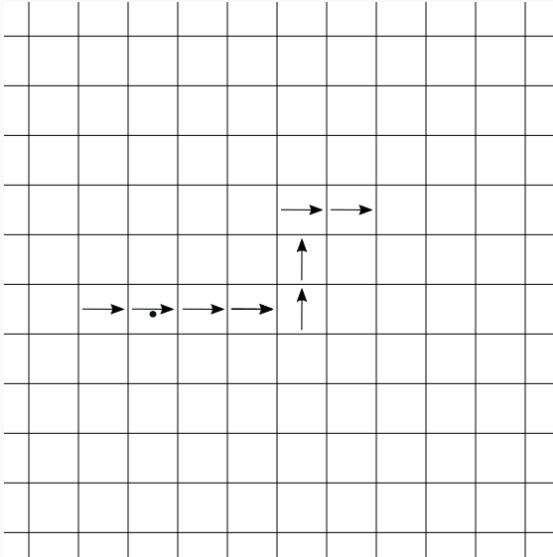
John von Neumann's Construction

Ordinary Transmission Elements



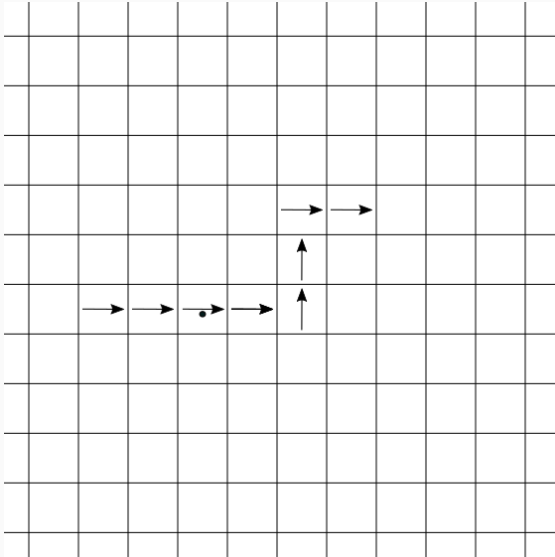
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SPECIAL TRANSMISSION	⇒	⇑	⇐	⇓
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CONFLUENT	C ₀₀	C ₀₁	C ₁₀	C ₁₁
SENSITIZED	S ₀	S ₁	S ₀₀	S ₀₁
	S ₀₁	S ₁₀	S ₁₁	S ₀₀₀

Ordinary Transmission Elements



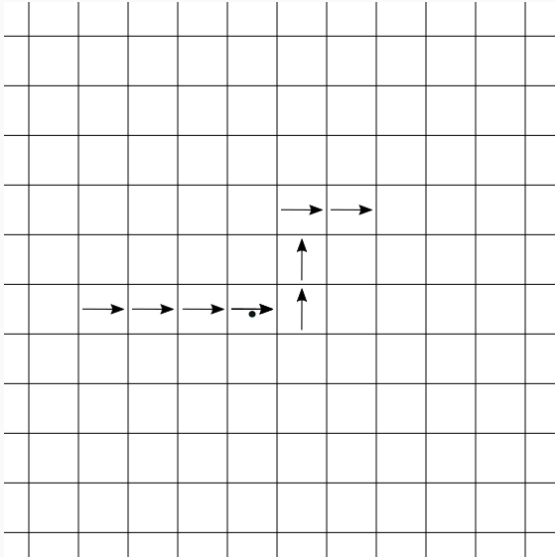
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CONFLUENT	C ₀₀	C ₀₁	C ₁₀	C ₁₁
SENSITIZED	S ₀	S ₀	S ₁	S ₀₀
	S ₀₁	S ₁₀	S ₁₁	S ₀₀₀

Ordinary Transmission Elements



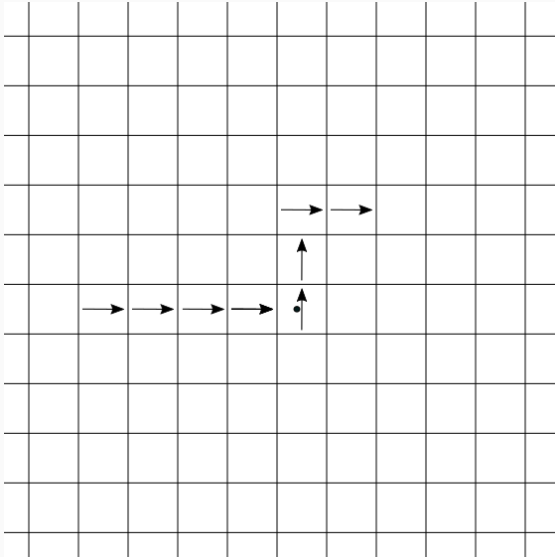
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SPECIAL TRANSMISSION	⇒	⇧	⇨	⇩
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CONFLUENT	C ₀₀	C ₀₁	C ₁₀	C ₁₁
SENSITIZED	S ₀	S ₀	S ₁	S ₀₀
	S ₀₁	S ₁₀	S ₁₁	S ₀₀₀

Ordinary Transmission Elements



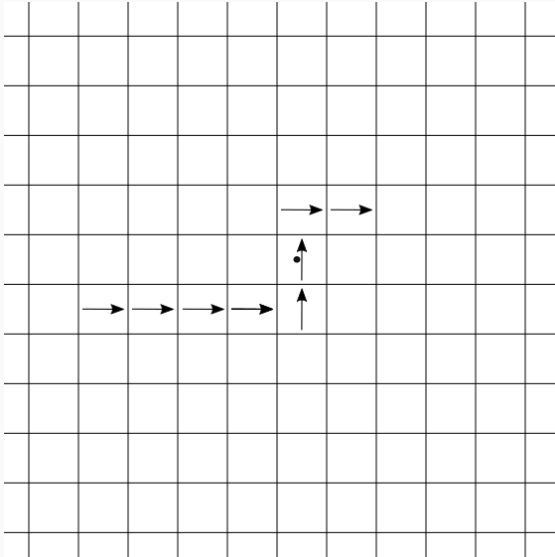
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	→ •	↑ •	← •	↓ •
SPECIAL TRANSMISSION	⇒	⇑	⇐	⇓
	⇒ •	⇑ •	⇐ •	⇓ •
CONFLUENT	C ₀₀	C ₀₁	C ₁₀	C ₁₁
SENSITIZED	S ₀	S ₀	S ₁	S ₀₀
	S ₀₁	S ₁₀	S ₁₁	S ₀₀₀

Ordinary Transmission Elements



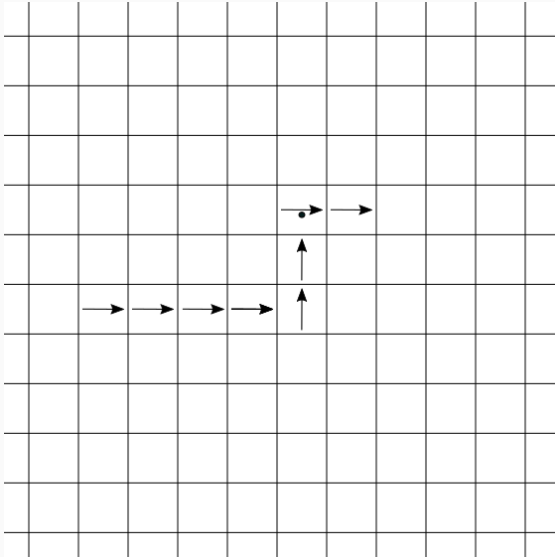
UNEXCITABLE	U			
ORDINARY TRANSMISSION	→	↑	←	↓
	•→	•↑	•←	•↓
SPECIAL TRANSMISSION	⇒	⇧	⇨	⇩
	•⇒	•⇧	•⇨	•⇩
CONFLUENT	C ₀₀	C ₀₁	C ₁₀	C ₁₁
SENSITIZED	S ₀	S ₀	S ₁	S ₀₀
	S ₀₁	S ₁₀	S ₁₁	S ₀₀₀

Ordinary Transmission Elements



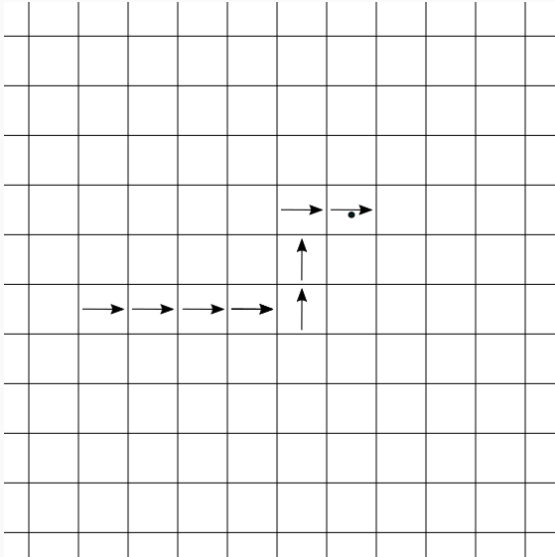
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ORDINARY TRANSMISSION	→	↑	←	↓
	•→	•↑	•←	•↓
SPECIAL TRANSMISSION	⇒	⤴	⇐	⤵
	•⇒	•⤴	•⇐	•⤵
CONFLUENT	C ₀₀	C ₀₁	C ₁₀	C ₁₁
SENSITIZED	S ₀	S ₀	S ₁	S ₀₀
	S ₀₁	S ₁₀	S ₁₁	S ₀₀₀

Ordinary Transmission Elements



UNEXCITABLE	U			
ORDINARY TRANSMISSION	→	↑	←	↓
	•→	•↑	•←	•↓
SPECIAL TRANSMISSION	⇒	⇑	⇐	⇓
	•⇒	•⇑	•⇐	•⇓
CONFLUENT	C ₀₀	C ₀₁	C ₁₀	C ₁₁
SENSITIZED	S ₀	S ₀	S ₁	S ₀₀
	S ₀₁	S ₁₀	S ₁₁	S ₀₀₀

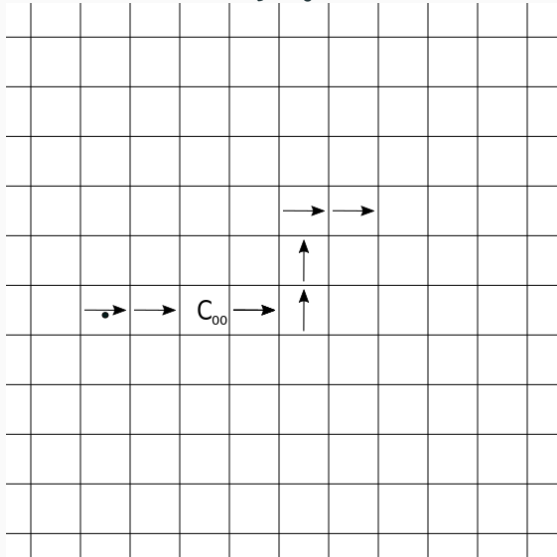
Ordinary Transmission Elements



UNEXCITABLE	U			
ORDINARY TRANSMISSION	→	↑	←	↓
	•→	•↑	•←	•↓
SPECIAL TRANSMISSION	⇒	⇑	⇐	⇓
	•⇒	•⇑	•⇐	•⇓
CONFLUENT	C ₀₀	C ₀₁	C ₁₀	C ₁₁
SENSITIZED	S ₀	S ₀	S ₁	S ₀₀
	S ₀₁	S ₁₀	S ₁₁	S ₀₀₀

Confluent Elements

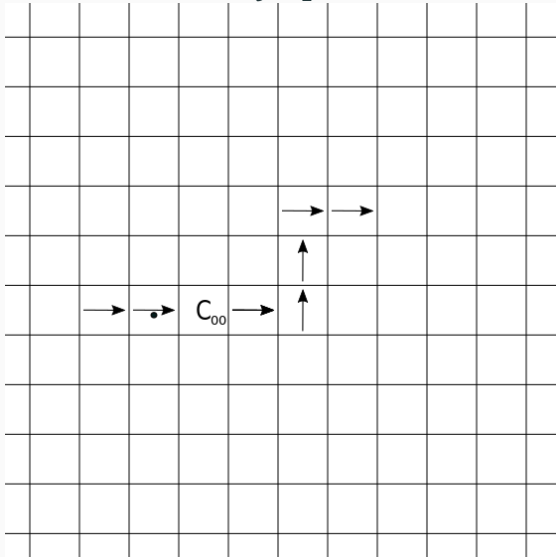
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UNEXCITABLE	U
ORDINARY TRANSMISSION	$\rightarrow \uparrow$
	$\leftarrow \downarrow$
SPECIAL TRANSMISSION	$\Rightarrow \Uparrow$
	$\Leftarrow \Downarrow$
CONFLUENT	$C_{00} C_{01} C_{10} C_{11}$
SENSITIZED	$S_0 S_1 S_{00}$
	$S_{01} S_{10} S_{11} S_{000}$

Confluent Elements

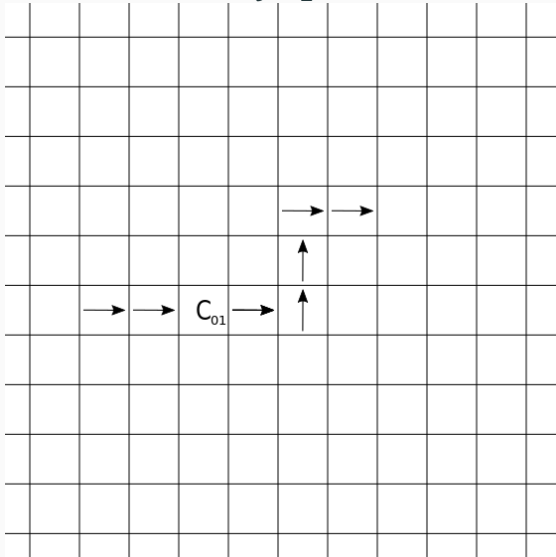
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ORDINARY TRANSMISSION	→ ↑ ← ↓
	•→ •↑ •← •↓
SPECIAL TRANSMISSION	⇒ ⇑ ⇐ ⇓
	•⇒ •⇑ •⇐ •⇓
CONFLUENT	c_{00} c_{01} c_{10} c_{11}
SENSITIZED	s_0 s_1 s_{00} s_{01}
	s_{10} s_{11} s_{000}

Confluent Elements

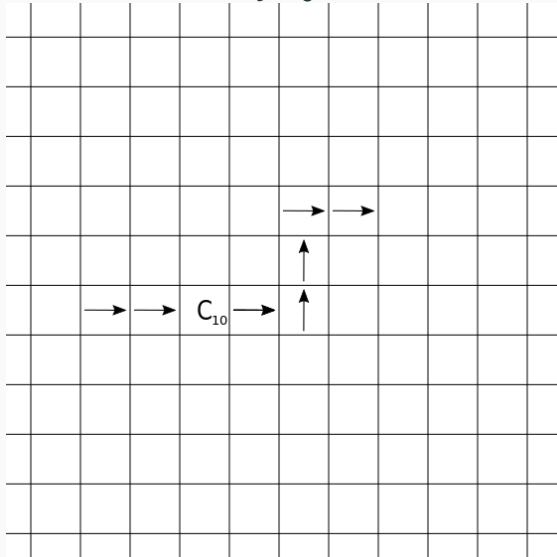
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UNEXCITABLE	U
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	•↑ •← •↓
SPECIAL TRANSMISSION	⇒ ⇑ ⇐ ⇓
	•⇑ •⇑ •⇓ •⇓
CONFLUENT	c_{00} c_{01} c_{10} c_{11}
SENSITIZED	s_{0j} s_0 s_1 s_{00}
	s_{01} s_{10} s_{11} s_{000}

Confluent Elements

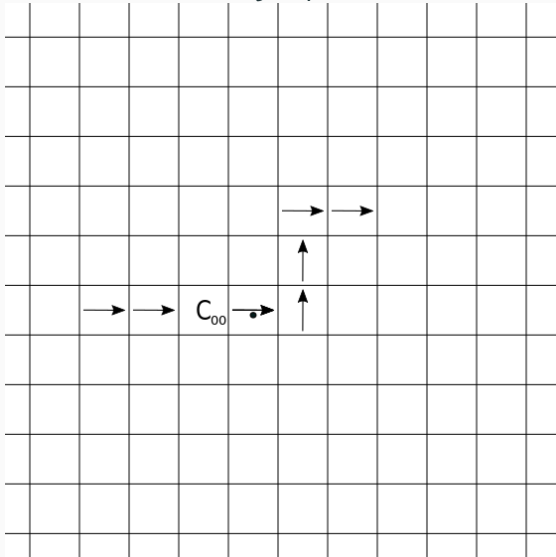
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UNEXCITABLE	U
ORDINARY TRANSMISSION	→ ↑ ← ↓
	•↑ •↓
SPECIAL TRANSMISSION	⇒ ⇑ ⇐ ⇓
	•⇑ •⇓
CONFLUENT	c_{00} c_{01} c_{10} c_{11}
SENSITIZED	s_0 s_1 s_{00} s_{01}
	s_{10} s_{11} s_{000}

Confluent Elements

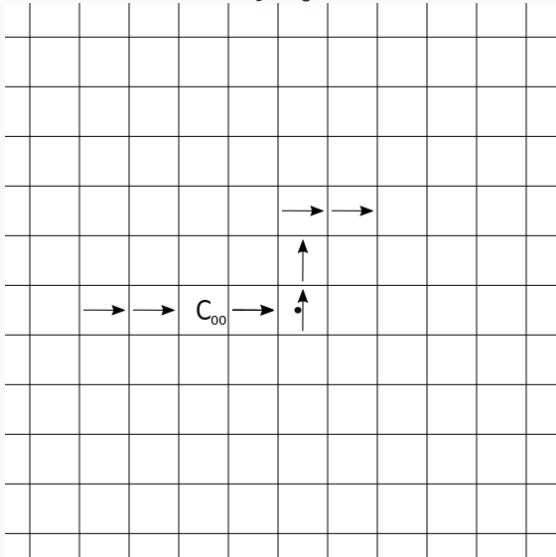
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UNEXCITABLE	U
ORDINARY TRANSMISSION	→ ↑ ← ↓
	•↑ •↓
SPECIAL TRANSMISSION	⇒ ⇑ ⇐ ⇓
	•⇑ •⇓
CONFLUENT	C_{00} C_{01} C_{10} C_{11}
SENSITIZED	S_0 S_1 S_{00}
	S_{01} S_{10} S_{11} S_{000}

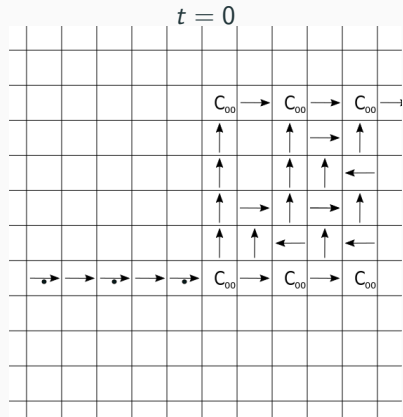
Confluent Elements

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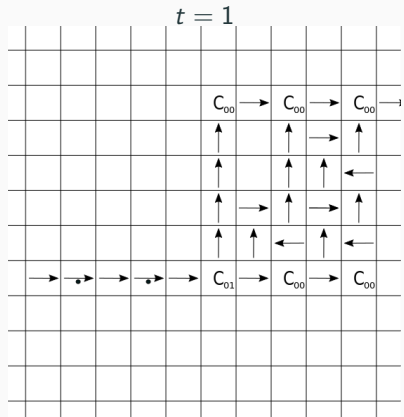
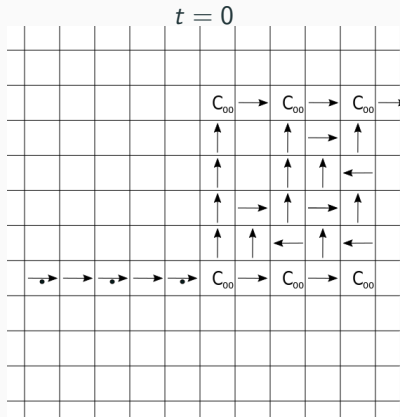


UNEXCITABLE	U
ORDINARY TRANSMISSION	→ ↑ ← ↓
	•↑ •↓
SPECIAL TRANSMISSION	⇒ ⇑ ⇐ ⇓
	•⇑ •⇓
CONFLUENT	C ₀₀ C ₀₁ C ₁₀ C ₁₁
SENSITIZED	S ₀ S ₁ S ₀₀ S ₀₀₀
	S ₀₁ S ₁₀ S ₁₁ S ₀₀₀

Decoder 10101

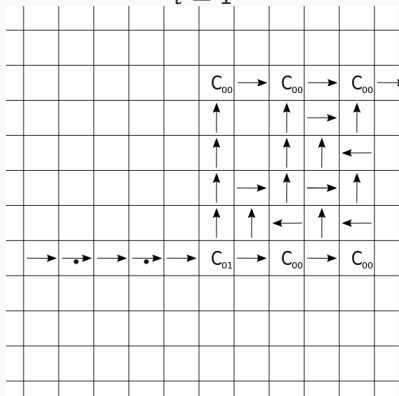


Decoder 10101

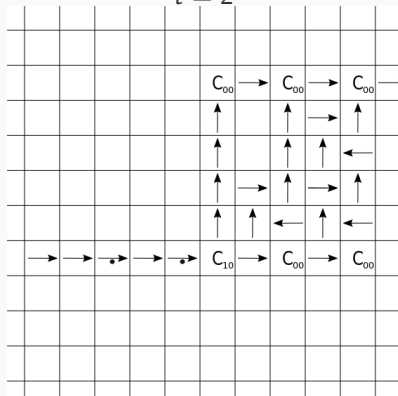


Decoder 10101

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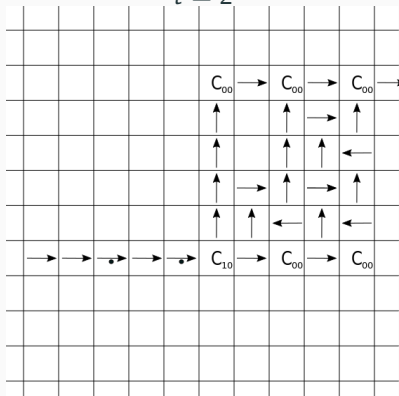


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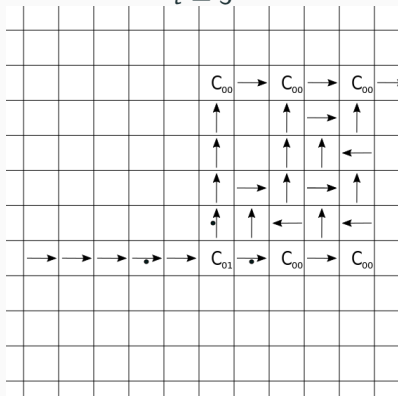


Decoder 10101

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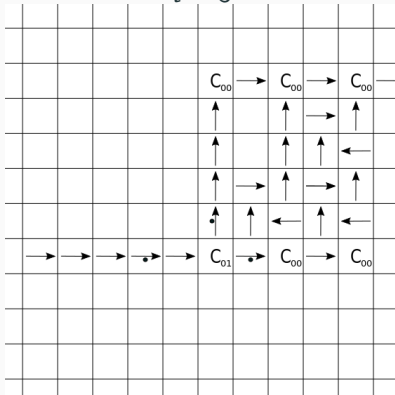


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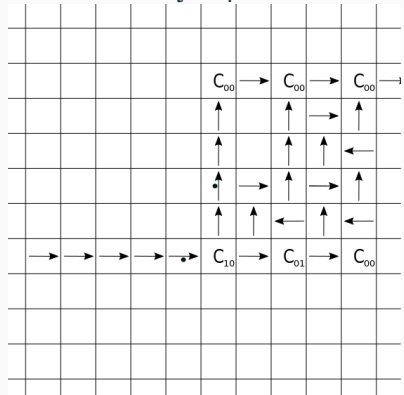


Decoder 10101

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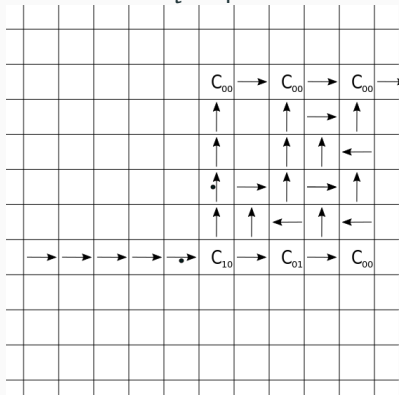


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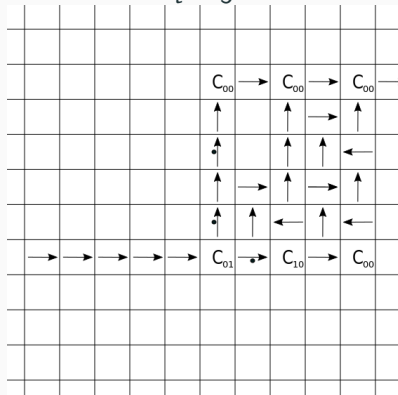


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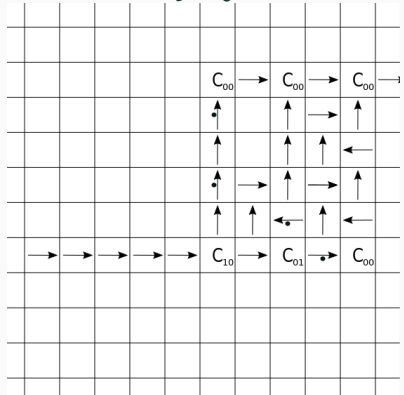
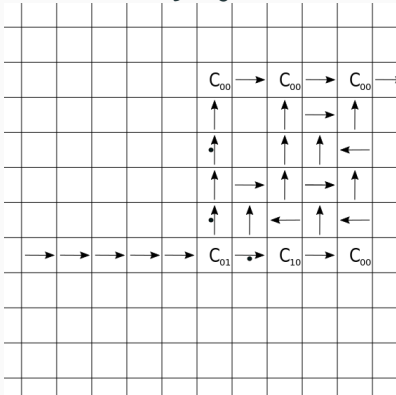
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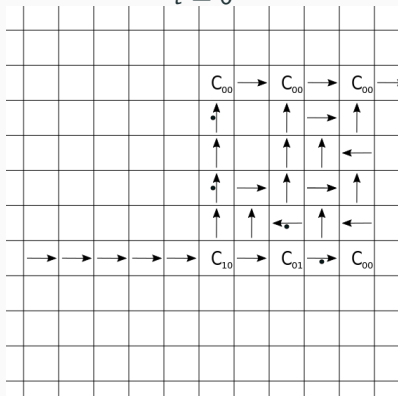


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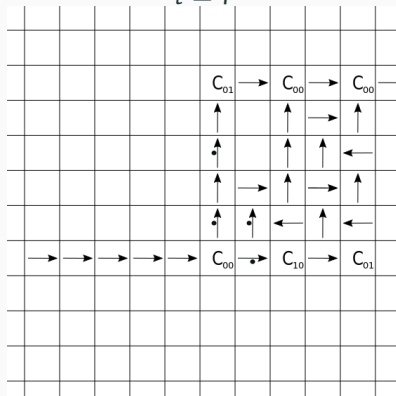


Decoder 10101

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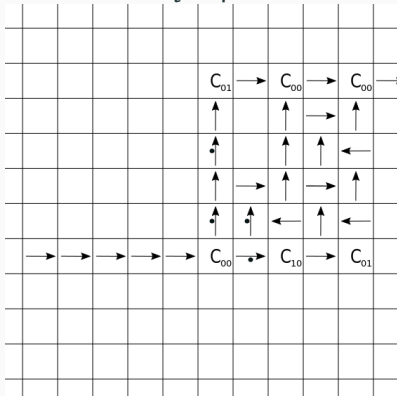


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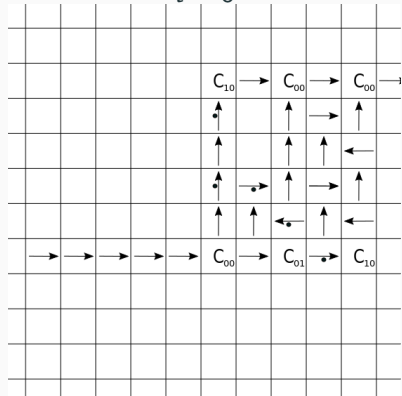


Decoder 10101

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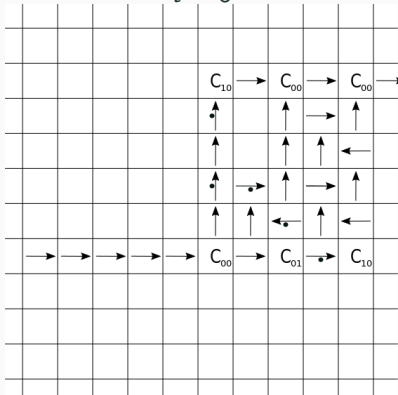


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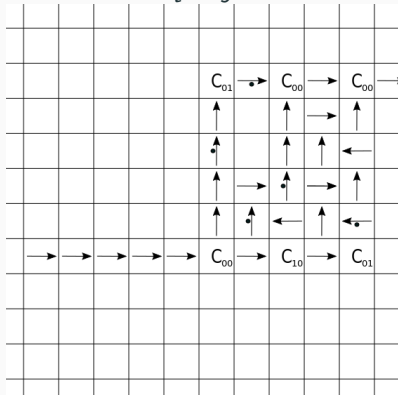


Decoder 10101

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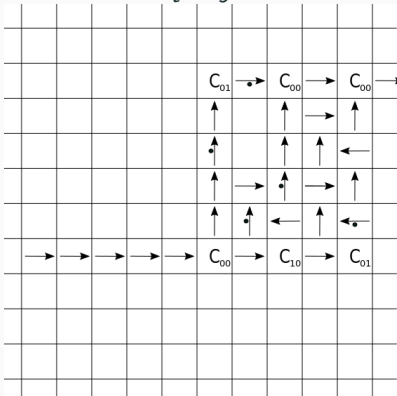


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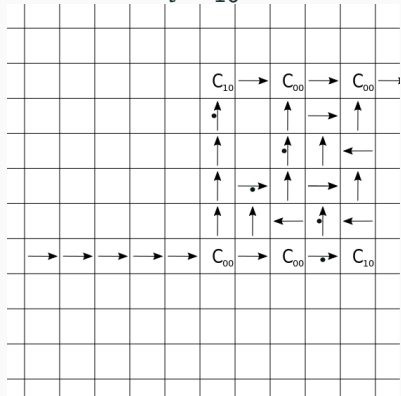


Decoder 10101

$t = 9$



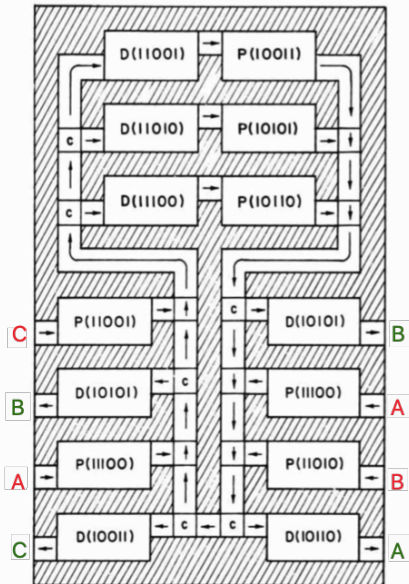
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Decoder 10101

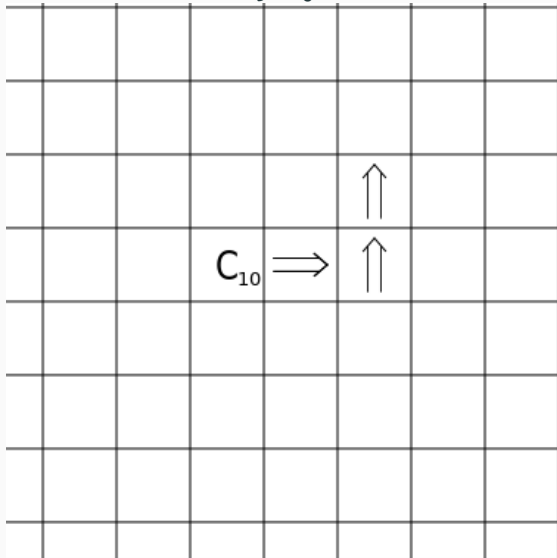


Coded Channel



Special Transmission Elements

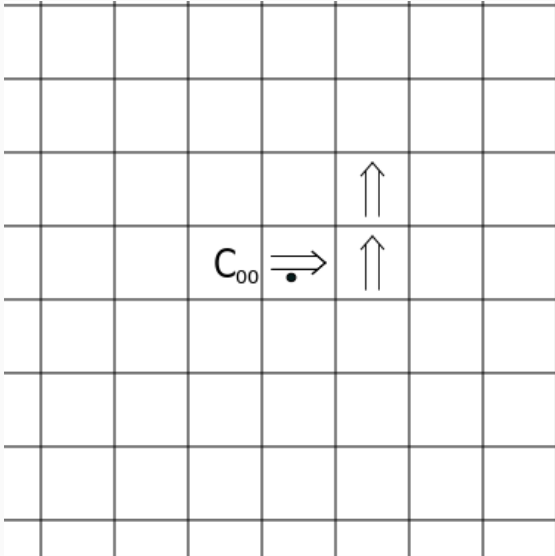
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UNEXCITABLE	U			
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	•→	•↑	•←	•↓
SPECIAL TRANSMISSION	⇒	⇑	⇐	⇓
	•⇒	•⇑	•⇐	•⇓
CONFLUENT	C_{00}	C_{01}	C_{10}	C_{11}
SENSITIZED	S_0	S_1	S_2	S_3
	S_{01}	S_{10}	S_{11}	S_{000}

Special Transmission Elements

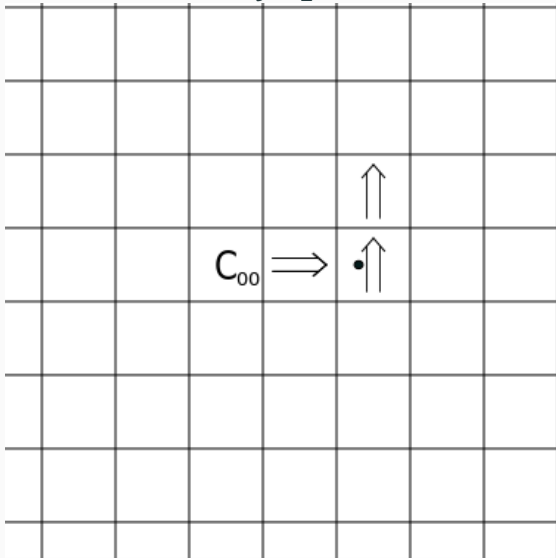
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UNEXCITABLE	U			
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	→•	•↑	←•	•↓
SPECIAL TRANSMISSION	⇒	⤴	⇐	⤵
	⇒•	•⤴	⇐•	•⤵
CONFLUENT	C_{00}	C_{01}	C_{10}	C_{11}
SENSITIZED	S_0	S_0	S_1	S_{00}
	S_{01}	S_{10}	S_{11}	S_{000}

Special Transmission Elements

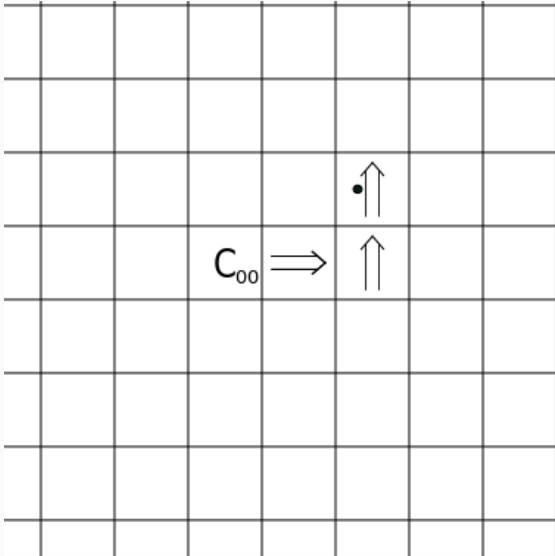
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UNEXCITABLE	U			
ORDINARY TRANSMISSION	→	↑	←	↓
	•→	•↑	•←	•↓
SPECIAL TRANSMISSION	⇒	⇑	⇐	⇓
	•⇒	•⇑	•⇐	•⇓
CONFLUENT	C_{00}	C_{01}	C_{10}	C_{11}
SENSITIZED	S_0	S_0	S_1	S_{00}
	S_{01}	S_{10}	S_{11}	S_{000}

Special Transmission Elements

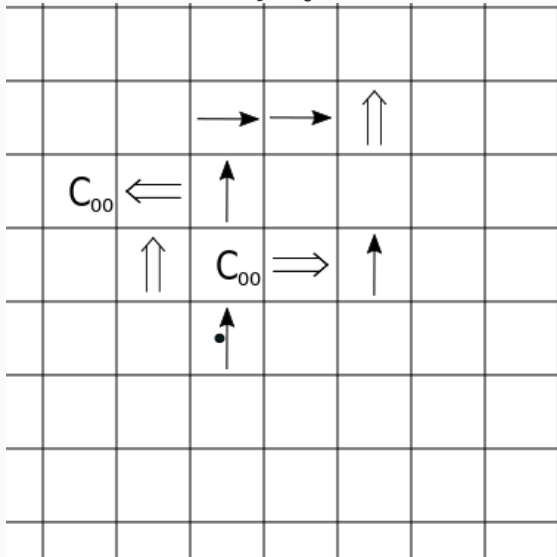
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UNEXCITABLE	U			
ORDINARY TRANSMISSION	→	↑	←	↓
	•→	•↑	•←	•↓
SPECIAL TRANSMISSION	⇒	⇑	⇐	⇓
	•⇒	•⇑	•⇐	•⇓
CONFLUENT	C_{00}	C_{01}	C_{10}	C_{11}
SENSITIZED	S_0	S_1	S_2	S_3
	S_{01}	S_{10}	S_{11}	S_{000}

Destruction

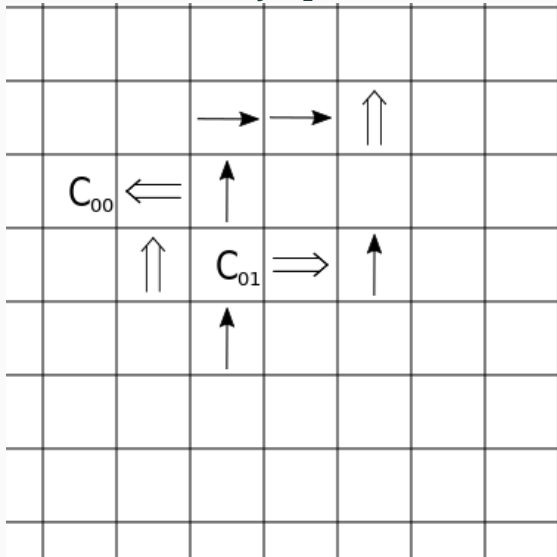
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UNEXCITABLE	U			
ORDINARY TRANSMISSION	→	↑	←	↓
	→•	•↑	←•	•↓
SPECIAL TRANSMISSION	⇒	⇧	⇨	⇩
	⇒•	•⇧	⇨•	•⇩
CONFLUENT	C_{00}	C_{01}	C_{10}	C_{11}
SENSITIZED	S_0	S_1	S_2	S_3
	S_{01}	S_{10}	S_{11}	S_{000}

Destruction

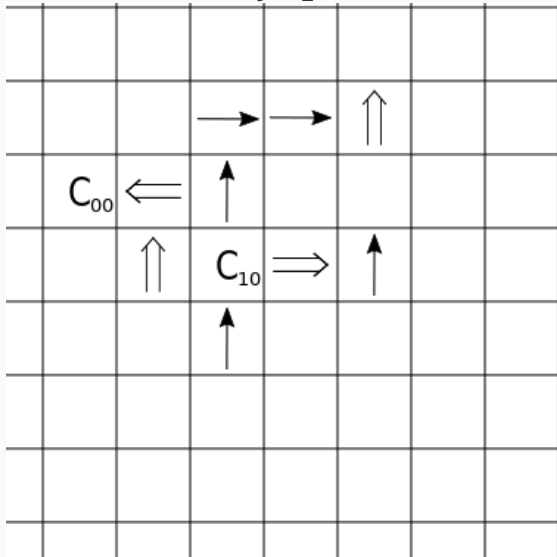
$t = 1$



UNEXCITABLE	U
ORDINARY TRANSMISSION	→ ↑ ← ↓
	•↑ •← •↓
SPECIAL TRANSMISSION	⇒ ⇑ ⇐ ⇓
	•⇑ •⇑ •⇓ •⇓
CONFLUENT	C_{00} C_{01} C_{10} C_{11}
SENSITIZED	S_0 S_0 S_1 S_{00}
	S_{01} S_{10} S_{11} S_{000}

Destruction

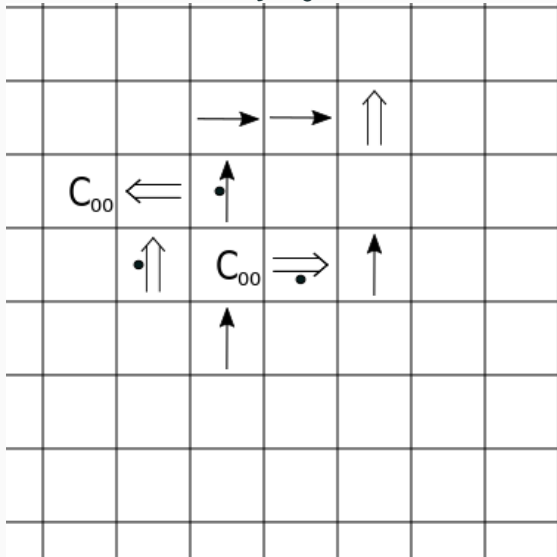
$t = 2$



UNEXCITABLE	U								
ORDINARY TRANSMISSION	<table><tr><td>→</td><td>↑</td><td>←</td><td>↓</td></tr><tr><td>→•</td><td>•↑</td><td>←•</td><td>•↓</td></tr></table>	→	↑	←	↓	→•	•↑	←•	•↓
→	↑	←	↓						
→•	•↑	←•	•↓						
SPECIAL TRANSMISSION	<table><tr><td>⇒</td><td>⤴</td><td>⇐</td><td>⤵</td></tr><tr><td>⇒•</td><td>•⤴</td><td>⇐•</td><td>•⤵</td></tr></table>	⇒	⤴	⇐	⤵	⇒•	•⤴	⇐•	•⤵
⇒	⤴	⇐	⤵						
⇒•	•⤴	⇐•	•⤵						
CONFLUENT	<table><tr><td>C_{00}</td><td>C_{01}</td><td>C_{10}</td><td>C_{11}</td></tr></table>	C_{00}	C_{01}	C_{10}	C_{11}				
C_{00}	C_{01}	C_{10}	C_{11}						
SENSITIZED	<table><tr><td>S_0</td><td>S_1</td><td>S_{00}</td><td>S_{01}</td></tr><tr><td>S_{10}</td><td>S_{11}</td><td>S_{000}</td><td>S_{001}</td></tr></table>	S_0	S_1	S_{00}	S_{01}	S_{10}	S_{11}	S_{000}	S_{001}
S_0	S_1	S_{00}	S_{01}						
S_{10}	S_{11}	S_{000}	S_{001}						

Destruction

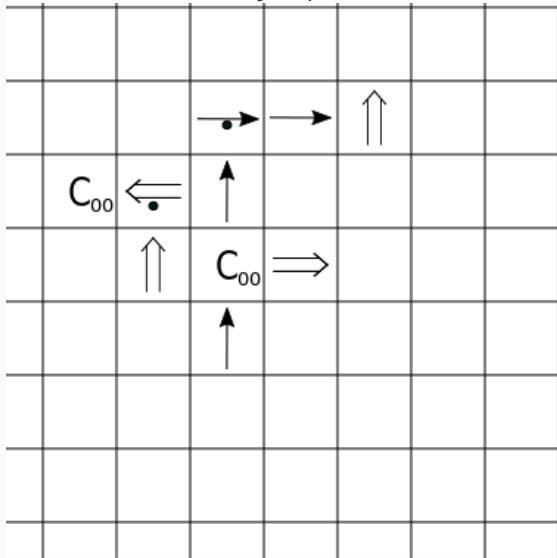
$t = 3$



UNEXCITABLE	U
ORDINARY TRANSMISSION	→ ↑ ← ↓
	•→ •↑ •← •↓
SPECIAL TRANSMISSION	⇒ ⇑ ⇐ ⇓
	•⇒ •⇑ •⇐ •⇓
CONFLUENT	C_{00} C_{01} C_{10} C_{11}
SENSITIZED	S_0 S_1 S_2 S_3
	S_{01} S_{10} S_{11} S_{000}

Destruction

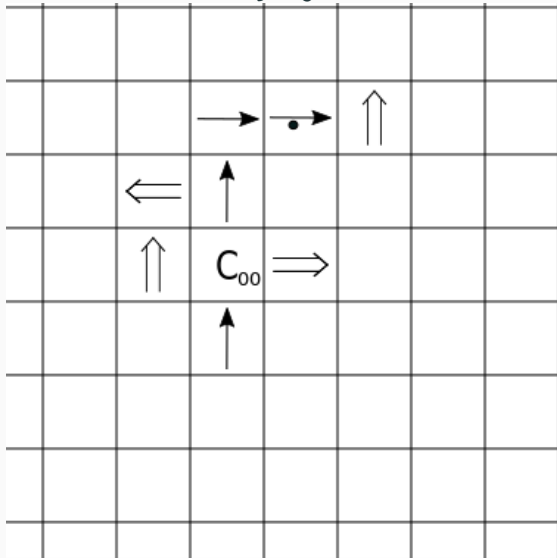
$t = 4$



UNEXCITABLE	U
ORDINARY TRANSMISSION	→ ↑ ← ↓
	••••
SPECIAL TRANSMISSION	⇒ ⇑ ⇐ ⇓
	••••
CONFLUENT	C ₀₀ C ₀₁ C ₁₀ C ₁₁
SENSITIZED	S ₀ S ₁ S ₀₀ S ₀₀₀
	S ₀₁ S ₁₀ S ₁₁ S ₀₀₀

Destruction

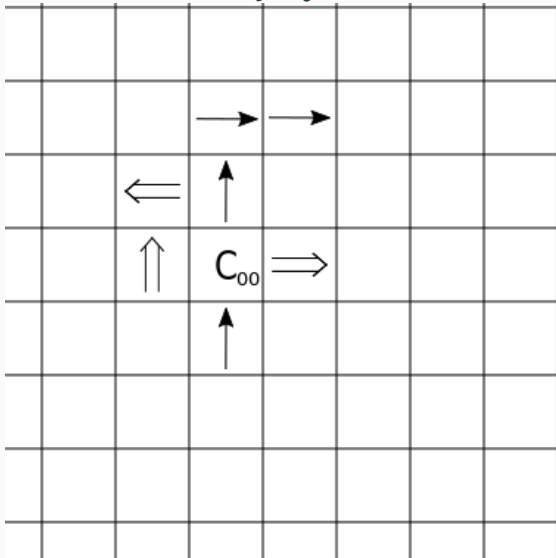
$t = 5$



UNEXCITABLE	U			
ORDINARY TRANSMISSION	→	↑	←	↓
	→•	•↑	←•	•↓
SPECIAL TRANSMISSION	⇒	⤴	⇐	⤵
	⇒•	•⤴	⇐•	•⤵
CONFLUENT	C_{00}	C_{01}	C_{10}	C_{11}
SENSITIZED	S_0	S_1	S_2	S_3
	S_{01}	S_{10}	S_{11}	S_{000}

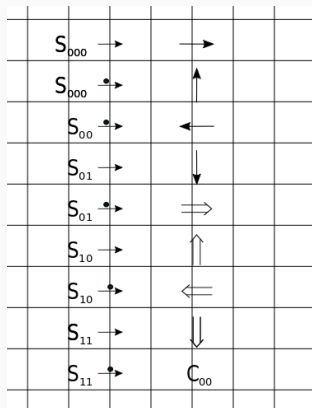
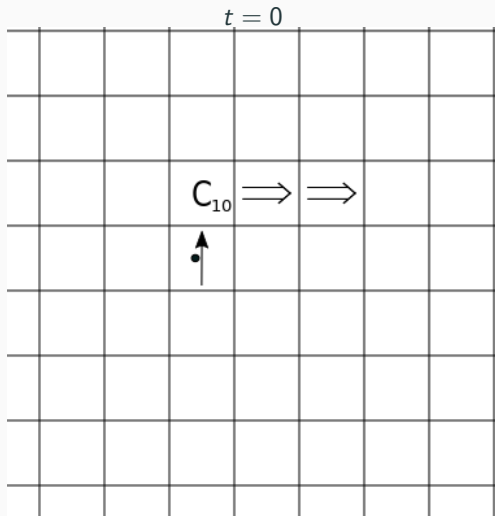
Destruction

$t = 6$

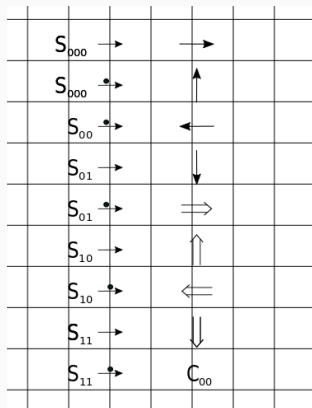
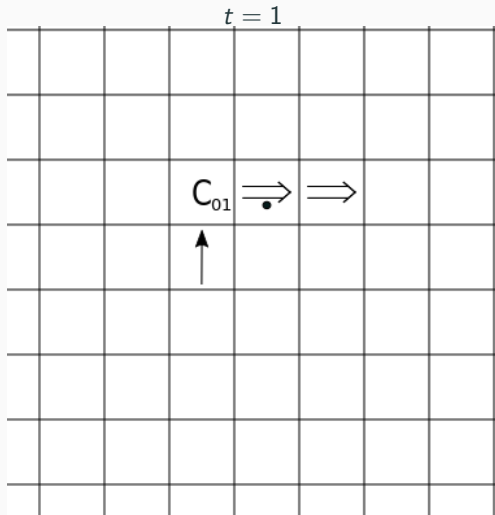


UNEXCITABLE	U			
ORDINARY TRANSMISSION	→	↑	←	↓
	•→	•↑	•←	•↓
SPECIAL TRANSMISSION	⇒	⇑	⇐	⇓
	•⇒	•⇑	•⇐	•⇓
CONFLUENT	C_{00}	C_{01}	C_{10}	C_{11}
SENSITIZED	S_0	S_1	S_2	S_3
	S_{01}	S_{10}	S_{11}	S_{000}

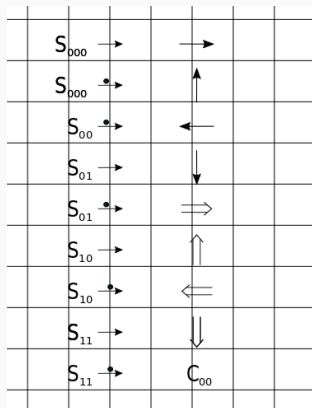
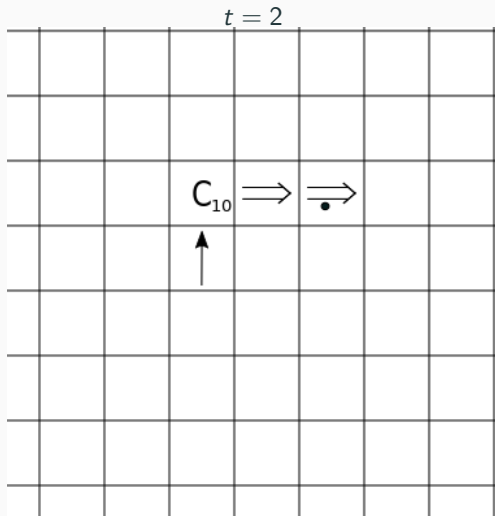
Construction



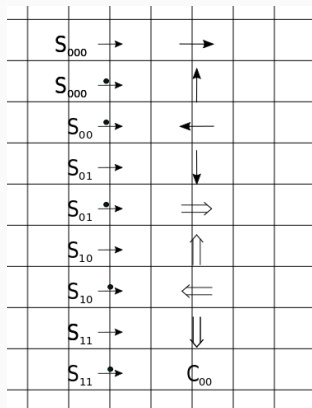
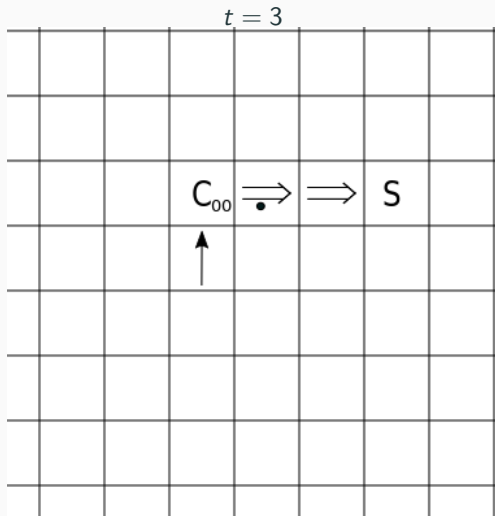
Construction



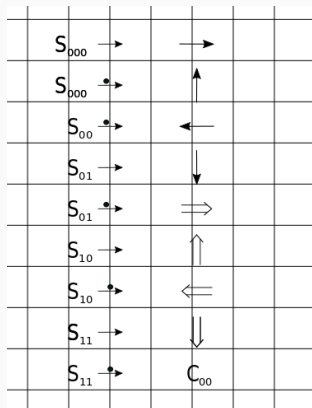
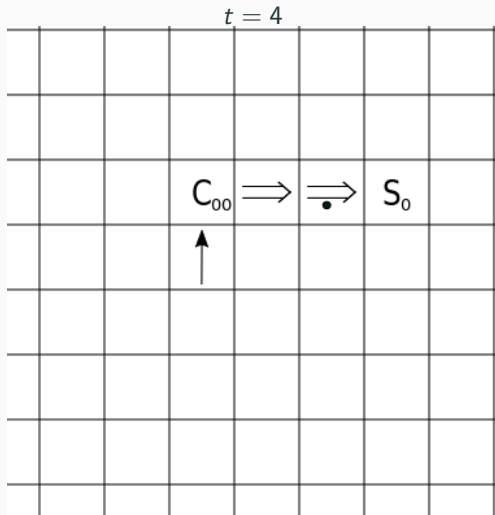
Construction



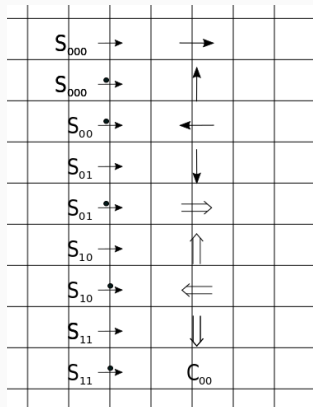
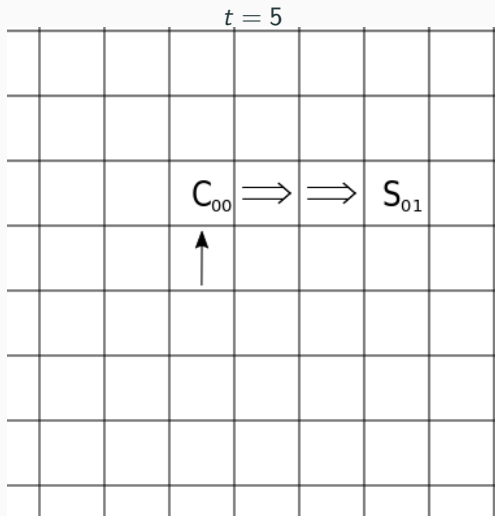
Construction



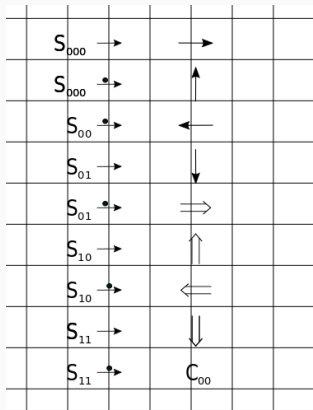
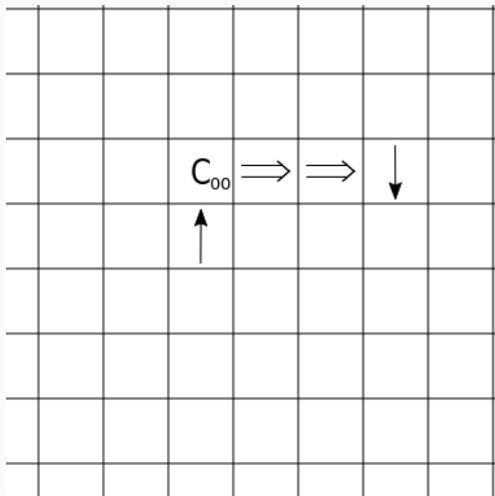
Construction



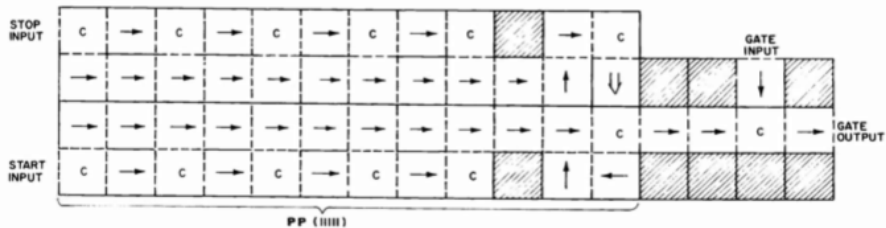
Construction



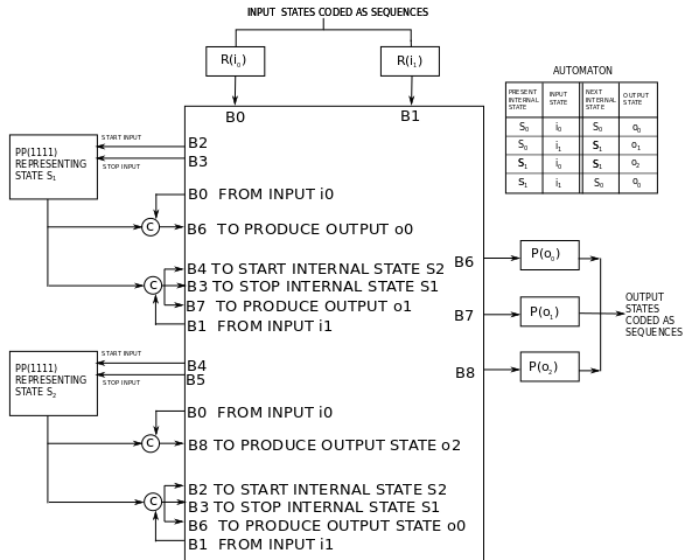
Construction



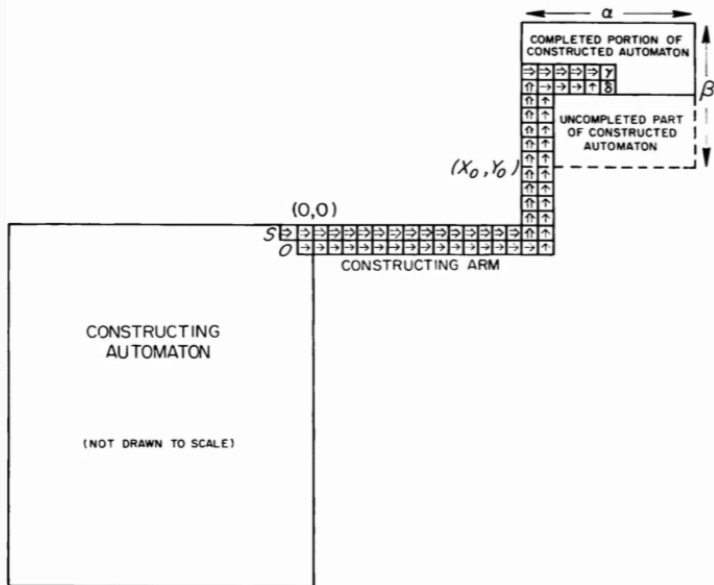
Periodic Pulser



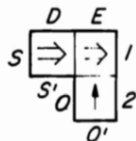
Finite Automaton



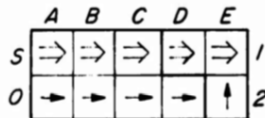
Construction arm



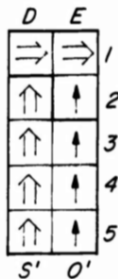
Construction arm



(a) Head of Constructing Arm



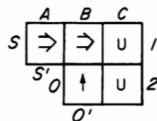
(b) Head Fed from Left



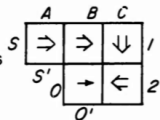
(c) Head Fed from Below

Horizontal Advance

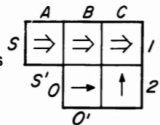
(a) Starting with



(b) $\Downarrow \Leftarrow \mathbf{U} \rightarrow$ into S or S' produces

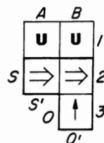


(c) $\mathbf{U} \uparrow \mathbf{U} \Rightarrow$ into O or O' produces

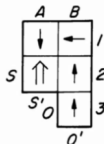


Vertical Advance

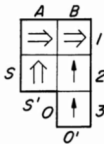
Starting with



$U \uparrow \leftarrow \downarrow \uparrow U$ into O or O' produces

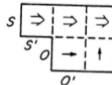


$U \Rightarrow U \Rightarrow$ into S or S' produces

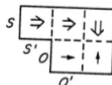


Horizontal Building and Retracting

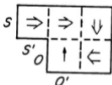
Starting with



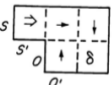
$u \downarrow$ Into O or O' Produces



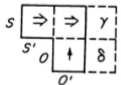
$u \leftarrow u \uparrow$ Into S or S' Produces



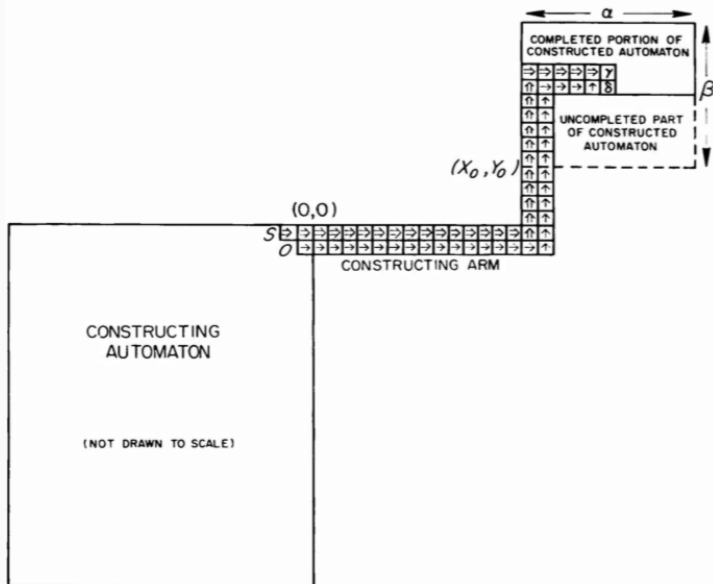
$u \rightarrow u \downarrow u \delta$ Into O or O' Produces



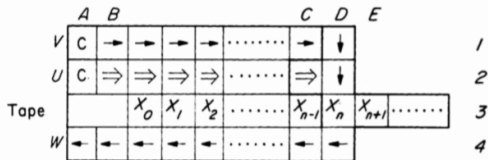
$u \Rightarrow u \gamma$ Into S or S' Produces



Construction arm



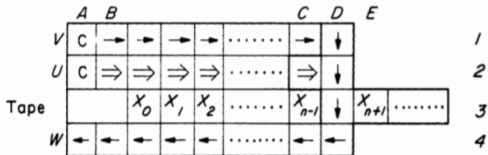
Tape Reading



(a) Before Reading

X_n is in **U** for "zero"

X_n is in **↓** for "one"



(b) After Reading

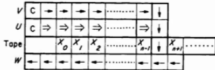
Tape Writing and Advancing



$U \downarrow U \downarrow U \Rightarrow \leftarrow$ into U produces



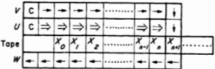
Then $U \downarrow U \downarrow U \leftarrow$ into V produces



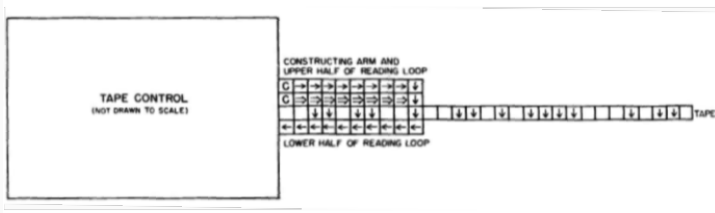
And $U \Rightarrow \uparrow \leftarrow U \rightarrow$ into U produces



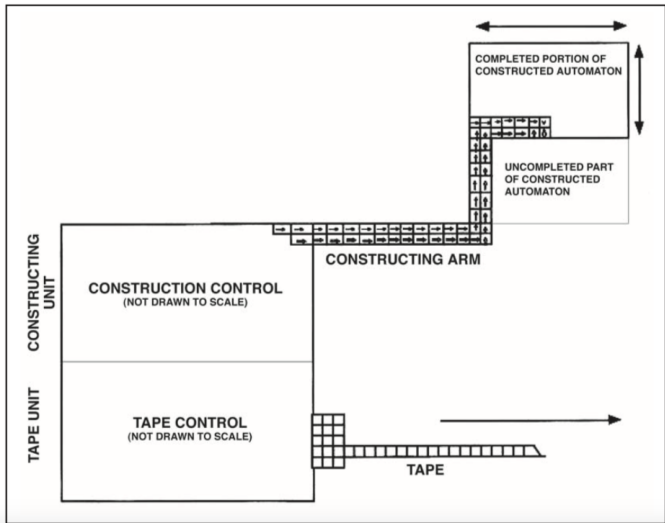
Finally $U \downarrow U \downarrow$ into V produces



Tape Control



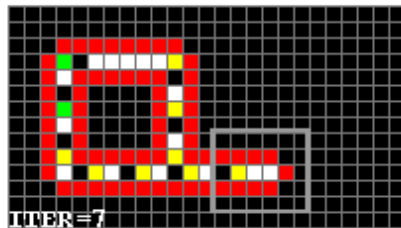
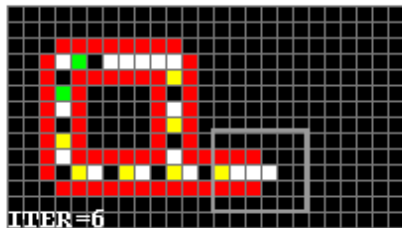
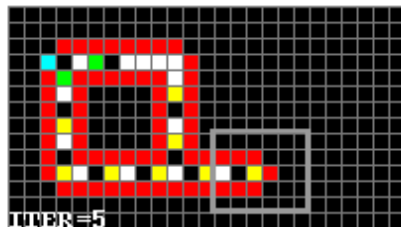
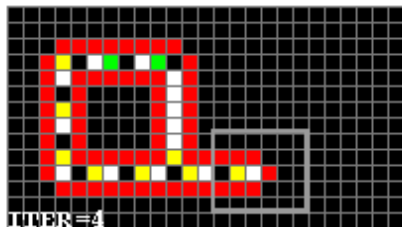
Universal Constructor



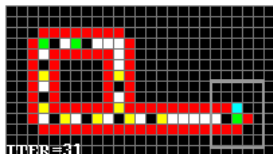
- difficult to simulate (millions of simultaneously active cells)
- simulation is not efficient for computational purposes

Other Self-Replicating Automata

Langton's Loops



Langton Loops



Future Plans

Von Neumann Probes

- machines capable of self-replication
- goal: colonize other solar systems

- "nano robots" able to operate with structures on molecular level
- goal: repair the human body

Thank you for your attention.