

# Dynamical Systems that Heal

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“The Purpose of Computing is Insight, not Numbers.”<sup>1</sup>

Another Purpose of Computing is to Robustly Perform Tasks.

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<sup>1</sup>Richard Hamming. Numerical Methods for Scientists and Engineers. 1962.



# Healing and Hijacking in Biological Systems

## Healing:

- DNA Self-Repairs.<sup>2</sup>
- Vertebrate blood clotting is about 50-100 million years old.<sup>3</sup>
- Vertebrates cannot stop severe bleeding without outside help.

## Hijacking:

- Fungus hijacks ant muscle fibers.<sup>4</sup> (No brain infection.)

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<sup>2</sup>E.C. Friedberg, et. al. DNA Repair and Mutagenesis. ASM Press, 2nd Edition, 2006.

<sup>3</sup>R.F. Doolittle. Step-by-Step Evolution of Vertebrate Blood Coagulation. Symposia on Quantitative Biology. 74, Cold Spring Harbor Lab, 2009, 35–40.

<sup>4</sup>M.A. Fredericksen, et. al. Three-dimensional visualization and a deep-learning model reveal complex fungal parasite networks in behaviorally manipulated ants. 114(47), November 7, 2017, 12590–12595

# Self-Modifiability is Necessary for a Self-Healing System

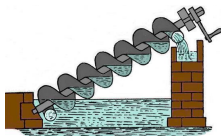
Our abstract system is analogous to a nervous system in biology.

Our research introduces the following two questions:

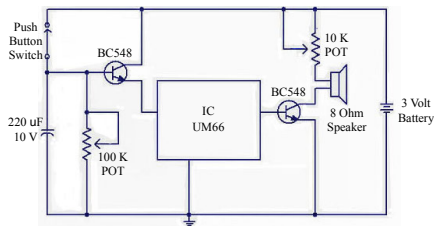
- What is self-modifiability?
- How can self-modifiability be mathematically or computationally modelled as a means for healing a system?

# Our Abstraction is Broader than Computer Programs

Register machine programs do not adequately model some systems.



A set of differential equations is sometimes a better model.



# The Principle of Self-Modifiability

A computer program is a dynamical system on a discrete space.<sup>5</sup>

Differential equations specify a dynamical system on a continuum.<sup>6</sup>

A finite set of rules governs both types of dynamical systems:

- Each instruction is a rule in a computer program.
- Each equation is a rule in a set of differential equations.

A dynamical system is *self-modifiable* if it can change its own rules:

It adds rules to itself; replaces rules with new rules; or deletes rules.

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<sup>5</sup>The Hamming metric on  $\{0, 1\}^n$  (bit strings of length  $n$ ) is a discrete space.

<sup>6</sup>The complex plane is a 2-D continuum. A unit circle is a 1-D continuum.

A sphere  $\{(x, y, z) \in \mathbb{R}^3 : x^2 + y^2 + z^2 = 1\}$  is a continuum.

## Related Work

Related research is split between biology and computer science.

- DNA repair <sup>7</sup> is over 50 years old. Models are biomolecular.
- Self-modifying systems<sup>8</sup> try to explain biological complexity. “In a formal system complexity can never increase at all.”<sup>8</sup>
- Benchmarked bugs repaired in programs (19% success).<sup>9</sup>
- Self-modifiable algorithms perform AI.<sup>10</sup> No explicit time.

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<sup>7</sup>D.E. Rasmussen, R.B. Painter. “Evidence for repair of ultra-violet damaged DNA in cultured mammalian cells.” *Nature*. 203, 1360–1362, 1964

<sup>8</sup>George Kampis. *Self-Modifying Systems in Biology and Cognitive Science*. Pergamon Press, 1991.

<sup>9</sup>Y. Ke, et. al. “Repairing Programs with Semantic Code Search.” 30th IEEE / ACM Intl. Conf. on Automated Software Engineering. 295–305, 2015.

<sup>10</sup>Eugene Eberbach. *Selected Aspects of the Calculus of Self-Modifiable Algorithms Theory*.” ICCI 1990. LNCS 468, Springer, 1991.

# Active Element Machine (AEM) Model

- Dendritic integration<sup>11</sup> inspires the Active Element Machine<sup>12</sup>
- Active elements compute simultaneously.
- AEM commands explicitly specify time.
- Standard compilers<sup>13</sup> & language theory<sup>14</sup> do not specify time.
- Built a software tool, coded in C, that simulates the AEM.

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<sup>11</sup>W. Rall. The Theoretical Foundation of Dendritic Function. MIT, 1995.

<sup>12</sup>M.S. Fiske. The Active Element Machine. Proceedings of Computational Intelligence. Volume **391**. Springer, 2011, 69-96.

<sup>13</sup>A.V. Aho, R. Sethi, J.D. Ullman. Compilers: Principles, Techniques and Tools. Addison-Wesley, 1988.

<sup>14</sup>J. Hopcroft, J.D. Ullman. Intro. to Automata Theory, Languages, and Computation. Addison-Wesley, 1979.

# AEM Language: element, connection and fire commands

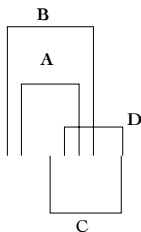
- Elements fire and send pulses along Connections.  
(element (time 0) (name E) (threshold 9) (refractory 4) (last 0)  
(element (time 0) (name A) )  
(fire (time 1) (name A))
- A connection specifies the pulse sent between two elements.  
(connection (time 0) (from A) (to E) (amp 5) (width 4) (delay 3) )
- An element  $E$  fires at time  $s$  if both conditions hold:
  - (1) Sum of  $E$ 's input pulses is greater than  $E$ 's threshold.
  - (2)  $E$ 's refractory period  $r$  has expired.

Refractory:  $s \geq r + l$  where  $l$  is  $E$ 's most recent firing time.



# A Simple AEM Program

```
(element (time 0) (name A))      (element (time 0) (name B))  
(element (time 0) (name C))      (element (time 0) (name D))  
(element (time 0) (name E) (threshold 9) (refractory 4) (last 0) )  
  
(connection (time 0) (from A) (to E) (amp 5) (width 4) (delay 3))  
(connection (time 0) (from B) (to E) (amp 9) (width 6) (delay 2))  
(connection (time 0) (from C) (to E) (amp -4) (width 5) (delay 5))  
(connection (time 0) (from D) (to E) (amp 2) (width 4) (delay 6))  
  
(fire (time 1) (name A))      (fire (time 1) (name B))  
(fire (time 1) (name C))      (fire (time 1) (name D))
```



## An AEM is Self-Modifiable with Meta Commands

A meta command can self-modify an AEM program.

(meta (name  $E$ ) (window  $b$   $e$ ) <cmds> )

<cmds> is one or more element, connection or fire commands.

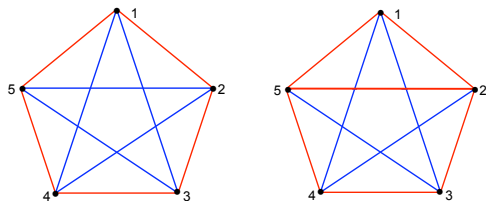
If  $E$  fires at time  $s$  within window of time  $[b, e]$ , (i.e.,  $b \leq s \leq e$ )

one or more <cmds> are adjoined to the AEM program at time  $s$ .

If no window exists and  $E$  fires, <cmds> are adjoined.

# Ramsey Numbers $r(j, l)$

Color each edge of  $K_n$  red or blue. Two distinct colorings of  $K_5$ :



$r(j, l)$  is the least integer  $n$  such that any coloring of  $K_n$  contains:

At least one complete subgraph  $K_j$  with only red edges OR

At least one complete subgraph  $K_l$  with only blue edges.

Determining  $r(m, m)$  is NP-hard.  $r(5, 5)$  is unknown.

## Summary of a Self-Healing AEM Program

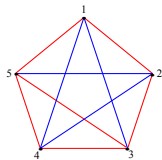
A Self-Healing AEM program that searches for red or blue triangles.

We sabotage one command in an AEM program.

Our sabotaged AEM program is healed with meta commands.

Example  $K_5$  AEM programs: <https://www.aemea.org/AEM>

We provide a general healing method for any AEM program.



# Self-Modifiable Differential Equations

Digital computers show Boolean functions can perform tasks.


Differential equations that compute Boolean AND, OR and NOT.

Meta variables and meta operators help heal differential equations.

Simulations in Julia.<sup>15</sup>

A damaged “OR” differential equation is healed.

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<sup>15</sup>J. Bezanson, A. Edelman, S. Karpinski, V. Shah. “Julia: A fresh approach to numerical computing.” SIAM review. 59(1), 65–98, 2017. 

# Research Summary

## SUMMARY:

Introduce the principle of self-modifiability to dynamical systems.

AEM uses meta commands to heal damaged AEM programs.

Differential equations use meta variables and meta operators.

## FUTURE RESEARCH:

Adversaries attacking the healing mechanisms.

Protecting the healing mechanisms.

Detecting a malfunctioning dynamical system.

## NEXT STEPS:

Implement the AEM (excluding meta command) in hardware.

Implement meta command in hardware.