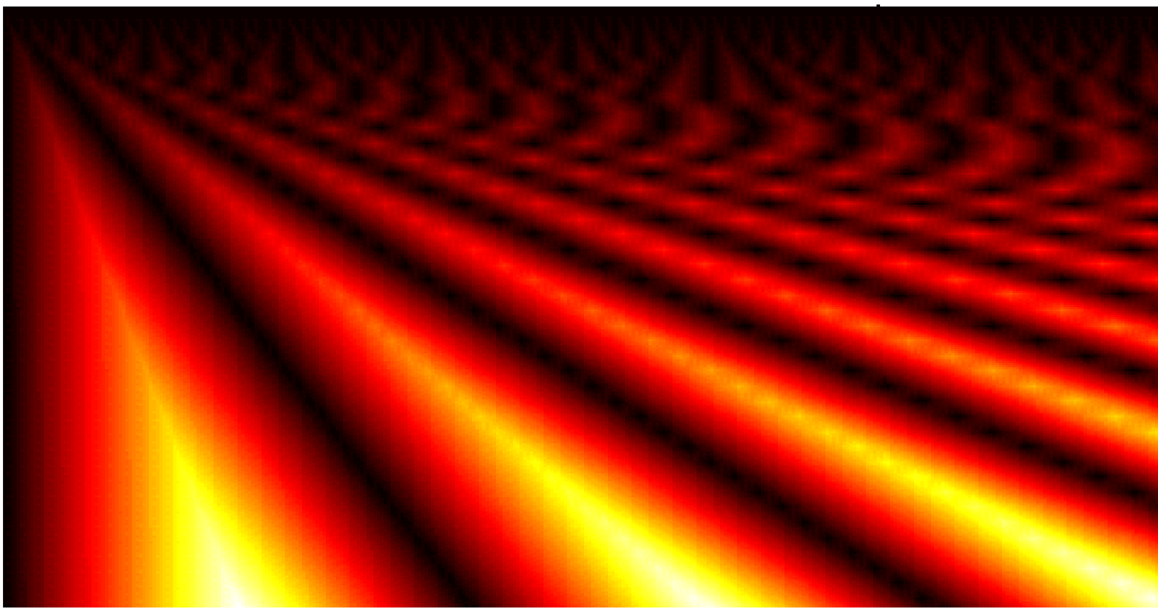

Heikki Hyötyniemi

Complex Systems – Searching for Gold

Inaugural lecture, March 12, 2002

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Complex Systems – Searching for Gold

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Abstract

In June 12, 2000, Helsinki University of Technology established a new professorship on *Complex Systems – Modeling, Simulation, and Control*. Heikki Hyötyniemi, Dr.Tech., was appointed, starting from Nov. 1, 2001. This text is a transcription of the manuscript for the inaugural lecture that will be given in March 12, 2002, at 14.15 in Auditorium B at HUT in Otaniemi (in Finnish). As it is formally stated: "All friends and supporters of research are welcome!"

1. Towards Golden Lands

In the old times, there were heroic men and women going west, conquering the frontier areas and finding gold. Today, nobody goes to Klondyke any more. The boundaries of the world have been discovered, there are no new gold rushes ahead. Are the times of big adventures gone forever? Can one still strike paydirt?

Yes, there still exists a mystery land. The device that can take you there is the *computer*. Within a computer, new worlds can be defined, where new strange creatures obey "laws of nature" as dictated by you. These creatures are processes defined through formal algorithms.

You can find deserted and dull worlds but you can also find worlds full of beauty. When extracting gold nuggets from the dirt, the computer is your gold washing pan – and everything has to be presented in a numeric form. The procedure goes like this: First take some dirt (numbers) and shuffle it (run them trough a function); this shuffling is continued until something interesting (hopefully) emerges. In mathematical terms, this iteration can be expressed in the form

$$x(k+1) = g(x(k)) , \qquad (1)$$

where g is some function, and $x(0)$ is some initial value. Indeed, if one selects the function to be iterated, for example, as

$$g(x) = x^2 + C , \qquad (2)$$

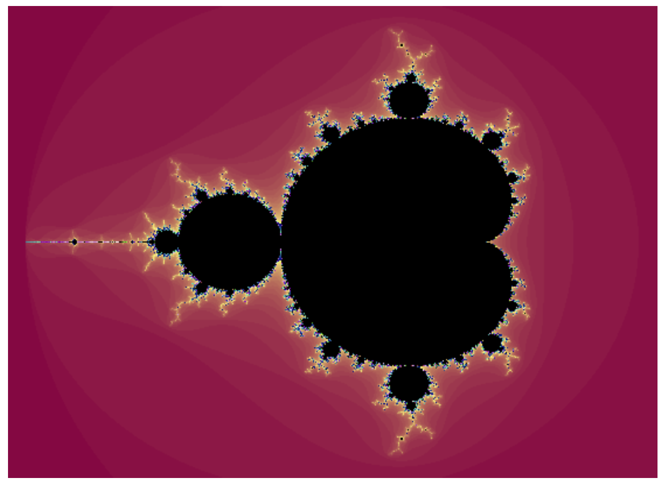

Figure 1. A Gold Nugget

where C is a complex-valued scalar constant, very complicated patterns of behavior emerge (for example, see Hyötyniemi, 2001). If one plots those values of C in the complex plane where the iteration remains bounded in black colour, the boundary between the black and the non-black areas is extremely complicated; this pattern is known as the *Mandelbrot set* (see Fig. 1). The celebrated ideas of *chaos, fractality*, *self-similarity*, etc., all are demonstrated in this little grain of intellectual gold.

This new Eldorado has been exploited by gold diggers for some time now, and all kinds of structures resembling natural forms have been found. We have heard of fantastic promises of how the new excavations in the wonderland will solve all mysteries concerning complex systems, including diseases, economics, and life itself. However, the gold diggers' moral is what is has always been – do not take everything too seriously! After all, even in the Golden Land you have to work hard.

The computer is no philosopher's stone that could change worthless materials into gold; it can only reveal the hidden treasures. And the key question in this field is that there is no way to tell beforehand whether something will be found after all. The analogues between

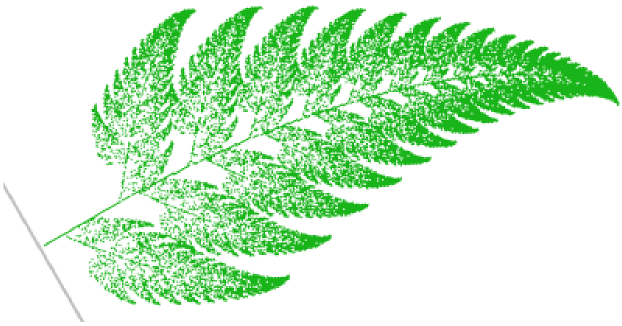

Figure 2. The Fern

natural systems and computer simulations are extremely vague – for example, study the celebrated self-similar "fern" structure in Fig. 2, being produced by a massive computer iteration. It looks like a natural thing, yes, but the underlying processes in the computer and in nature are totally different – this leaf gives no clue of the complex real processes taking place in a growing tree.

It is no doubt difficult to see the forest for the trees, when one cannot see the tree for the leaves! Is there any way of mastering the emergent phenomena?

2. First You Do Manual Excavations ...

Look the structure in Fig. 3. Rather than a gold washing pan, it is now a *sieve*: Each mark on it denotes a "hole", and grains are screened through it. In fact, now the grains are again numbers; when a set of numbers is screened through the sieve, some of them go trough and some (negative) do not – the numbers may also change in this process (see Fig. 4). A more technical explanation about the operation of the sieve is given later.

What happens when this screening process is continued long enough? The following sequence emerges:

Shuffle	Value
1	2
40	3
285	5
796	7
2418	11
4261	13
7961	17
11932	19
18504	23

It turns out that all values that are produced are successive *primes*, indivisible numbers. The primes have interested number theorists for thousands of years, but lately, the new ciphering schemes have increased also their practical value. There is no simple way to detect primes, and it can be claimed that the emergent structures produced by the presented sieve do now have some real relevance!

There is another conceptual "device" quite related to the presented one: The *sieve of Eratosthenes* is an age-old, elementary method for screening out primes. However, this sieve has fixed, predetermined size, meaning that the upper bound for primes to be extracted has to be determined beforehand; what is interesting about the new sieve, on the other hand, is that *all* primes – and there are infinitely many of them – are produced if enough shuffling is done. Just as in the case of fractal images, one may ask oneself: How is it *possible* that a finite structure can produce a result having infinite complexity?

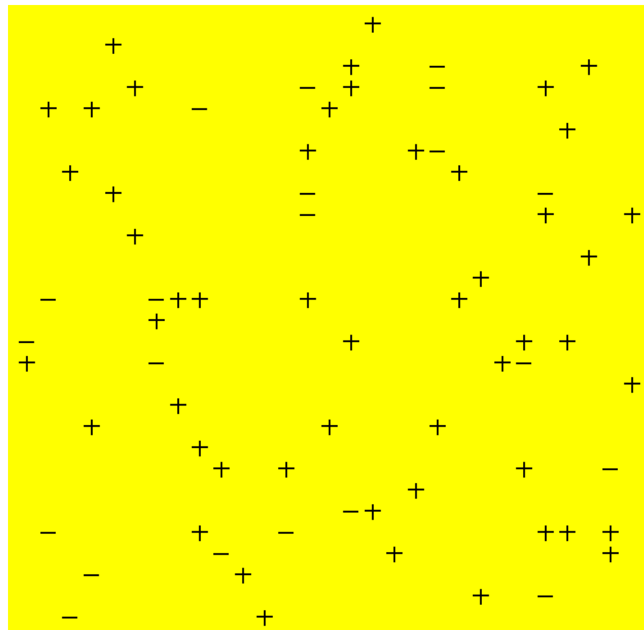

Figure 3. "Heikki's Sieve"

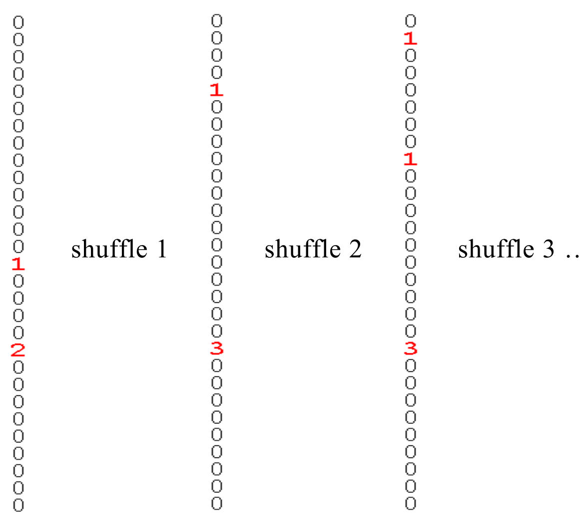

Figure 4. Sort the gold from the chaff

The key to understanding the presented sieve is given by computability theory. It can be shown that

> "All computable functions (this means that practically anything!) can be expressed in the form $x(k+1) = f\,(Ax(k))$, where A is some matrix, and the *cut function* is defined elementwise as
>
> $$f_i(x) = \begin{cases} x_i, & \text{when } x_i > 0 \\ 0, & \text{when } x_i \le 0, \end{cases}$$
>
> that is, all negative values are simply ignored, whereas positive values go directly through".

This result is shown in (Hyötyniemi, 1997), and it means that, for example, the definition of primes can be realized in this framework. Indeed, when the program code presented in Fig. 5 is compiled (for closer look on the language, see Hyötyniemi, 1998), the resulting data structures are shown in Fig. 11. Starting from the initial value $x(0)$, as shown also in Fig. 11, the computation continues *ad infinitum*, every now and then giving out newly resolved primes. It is exactly this matrix A that is shown in Fig. 3; the "–" signs stand for "–1" and "+" for "+1".

Even though the data structures may now be high-dimensional, the outlook of the iteration $x(k+1) = g(x(k)) = f\,(Ax(k))$ is still extremely simple. The linear mapping defined by the matrix A does not essentially complicate things, and, intuitively, you could not find a nonlinearity simpler than f (of course, this simplicity is misleading!).

As a conclusion, it can be noted that this "Midas" compiler transforms all algorithms into gold nuggets – writing the program code ourselves we already know that something interesting to us will emerge!

3. ... But Have Someone Dig the Dirt!

The assumed system structure $x(k+1) = f\,(Ax(k))$ is very general (indeed, as shown it is *universal*). Could one apply it to some really relevant task – such that perhaps has not yet been solved by any other means? In this context, experiments with modeling of *mental functions* are reviewed. It seems that in this application it is not only the surface form but also something intuitively deeper that can be captured by the sieve paradigm.

Donald O. Hebb recognized in 1940's that the operation of neural cells can be explained in terms of *correlations* – that is, synapses adapt according to observed interdependencies between signals. And, indeed, what the matrix operation Ax does in our sieve formula, is essentially to calculate correlations between the vector x and the rows of A. In a sense, we can interpret the sieve as a *recurrent neural network* structure (see Fig. 6).

And it is not only the physiological level of neurons that can be simulated in the proposed framework: It has been claimed that the mystery of *intelligence* itself is an emergent phenomenon, being a result of a huge number of elementary data processing tasks cumulating. Assuming that this view of the nature of intelligence holds, we now have a framework to attack the eternal challenge of "deep AI" – it is large numbers of elementary-level correlations that are now repeated (this long line of studies starting in Hyötyniemi, 1995). As shown for example in (Hyötyniemi, 1998), different kinds of conceptual tools can be constructed in this framework for better managing the complexity: In addition to

```
1    VAR A=2
2    VAR B=0
3    VAR C=0
4    VAR D=0

5    A=A+1 GOTO 6
6    IF B=0 AND D=0
     THEN GOTO 9
     ELSE B=B-1 D=D-1 GOTO 6
9    B=B+1 GOTO 10
10   B=B+1 GOTO 11
11   IF A-B=0
     THEN prime! B=B-1 GOTO 5
     ELSE GOTO 14
14   IF C=0
     THEN GOTO 17
     ELSE C=C-1 GOTO 14
17   IF D=0
     THEN GOTO 20
     ELSE D=D-1 GOTO 17
20   C=C+1 D=D+1 GOTO 21
21   IF (B-D)+(A-C)=0
     THEN A=A+1 GOTO 6
     ELSE GOTO 24
24   IF A-C=0
     THEN GOTO 10
     ELSE GOTO 27
27   IF B-D=0
     THEN GOTO 17
     ELSE GOTO 20
```

Figure 5. The "Prime Sieve" source code written in the "Midas" language

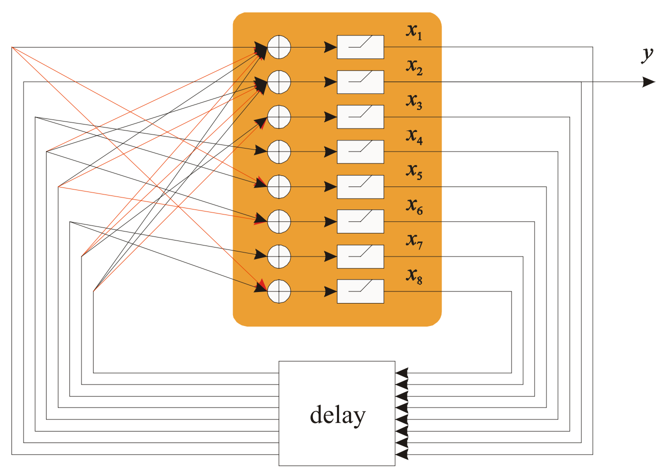

Figure 6. "Neural network" implementing the parity function (see Hyötyniemi, 2001)

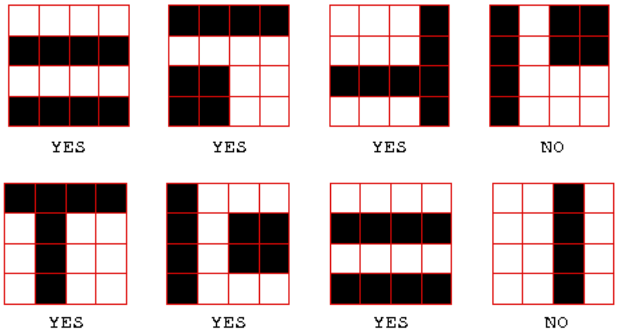

Figure 7. 'Intelligence tests' solved by the computer: What is the simplest underlying principle that makes the three first figures differ from the rightmost one? (Answers: "Horizontal line" / "Two objects")

arbitrary algorithms, also reasoning and associative matching of patterns can be implemented.

It is perhaps difficult to see how something essentially new could emerge from repeated calculation of correlations. The theoretical justification for this, of course, is that the calculations are not strictly linear – remember the function f in the formulas. Intuitively, perhaps the best illustration of the emerging "intelligence" is given in Fig. 7: The computer can pass the IQ test!

Just as in all AI applications, knowing how it is done, destroys all magic. For example, lines consist of a combination of dots, where successive locations correlate positively, etc. Defining higher and higher levels of concepts, little by little making them more abstract, it turns out that between successive levels the definitions are always based on some kind of correlations. Indeed, on the "highest level" – you either become a member of Mensa or not! – when taking a formal intelligence test, it is again the question of finding the underlying rule – or correlation – between the sample patterns.

Of course, the above example is more like a joke, perhaps best illustrating the deficiency of the formal IQ tests, not really measuring the real essence of human intelligence but some very constrained aspect of it. There exist much more relevant tests for AI models, where the plausibility of the approach can really be evaluated. One of such tests can be formulated using the *game of chess* as a test bench.

The chess game is the "banana fly" of cognitive science: It offers an extremely constrained environment, while still reflecting many of the fundamental phenomena concerning mental processes. For example, it has been recognized that chess experts, after looking at a configuration on the board for a few seconds (see Fig. 8), are capable of recalling almost all pieces; novice players can recall just a few pieces. Nothing strange here really – but the problem setting becomes interesting when one notices that this holds only if the configuration on the board is meaningful: If the pieces are located randomly,

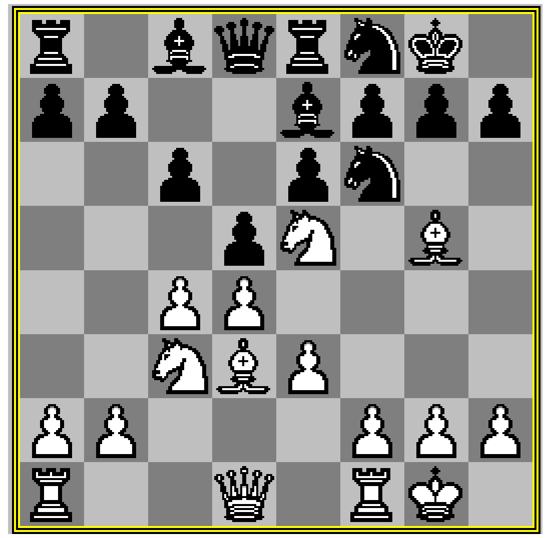

Figure 8. Typical configuration in chess

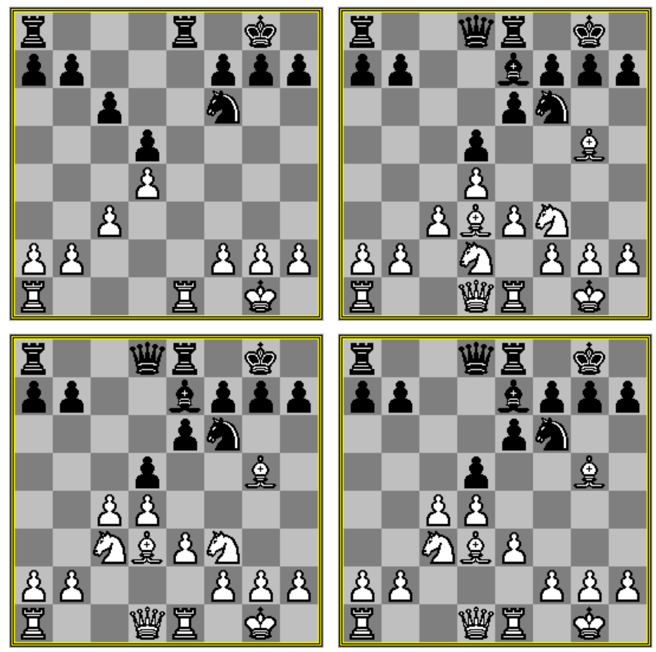

Figure 9. "Chunk representation" for the configuration in Fig. 8. When "expert chunks" are added together, the "mental image" starts resembling the original one (starting from upper left, ending in lower right)

there is no significant difference between the expert and the novice. What happens here? It turns out that there are some more or less "hard-wired" constraints what comes to the human brain: It is some seven separate things that can be kept in mind simultaneously. This explains why the novices can recall only a few pieces. The chess experts, on the other hand, do not think in terms of individual pieces: they have (subconsciously) constructed higher level representations for the chess configurations. These "atoms of perceiving" or "chunks" are again based on the underlying correlation structures: The expert's perception machinery has (somehow) recognized that there are some piece combinations that often pop up, and these combinations are then stored as a single perceptual unit.

When these phenomena were studied in the discussed framework (Hyötyniemi & Saariluoma, 1999), promising results were found (see Fig. 9). Using just one chunk, the most characteristic patterns (castlings and pawn chains) were already recovered. However, of course there are differences between games, and the successive chunks are needed to fix the discrepancies (the technical details of the implementation are skipped here). Note that in this experiment, the numeric chunks extended possibly over the whole board, whereas in standard chunk theory these (symbolic) constructs seem to be more localized.

There are dozens of different kinds of mental models proposed. Mostly they have been tailored to reflect some specific cognitive phenomenon, and they cannot predict behaviors in different situations. The plausibility of the model can also be tested by exceeding the capacity of the model, and checking whether the collapse in the behavior is graceful or catastrophic – and sudden collapses give a hint that there must be something unnatural about the model. Indeed, when the above model was evaluated in this way, it turned out that the errors it made were rather expert-like (see the last image in Fig. 9): The rook on the bottom row is in incorrect place, but – according to chess experts – this kind of mistake is something that could also be done by a human!

However, all of the experiments with the proposed model have been implemented in "toy worlds", studying just one level of processing at a time. And it is the extension, or scaling up of the models that has always turned out to be extremely difficult in AI research. In (Hyötyniemi, 2000), a more systemic approach to mental modeling is discussed based on the proposed framework – however, there is still an uneasy feeling, and, clearly, the uniting view is missing.

5. Conclusions

So we started our journey in the Golden Land by taking the gold washing pan and shuffling … later, we found a mine of endless resources of gold nuggets … but as an engineer, we cannot be satisfied until this hard labor also is automated.

When using the sieve system, it is still the human who has to define the gold nuggets him/herself. The problem here is that you can only find such nuggets you already know to exist – and there are many things that are precious even if they do not shine. So, our dream (or nightmare) is a clever "brain machine", cleverer than us (at least in sniffing out gold), capable of finding the gold veins all by itself.

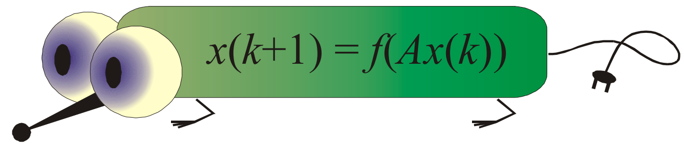

Figure 10. The "Aivokone" Piggie – always searching for gold truffles

With this kind of piggie (see Fig. 10), you could go to the forest of gold truffles, admire the trees, forgetting about the leaves, just enjoying the complexity – and let the piggie dig the dirt!

What is certain is that there are adventures ahead of us, perhaps even a golden era of increased understanding of complex processes. However, today we still cannot see the "golden ratio" between the piggies, chaos, and complexes – perhaps the best conclusion at this time is to trust intuition, and think of these mysteries and the approaches to explaining them more as an art than as a serious science – a wonderland for everybody looking for adventures (see Fig. 12).

References

Below, some articles that are related to the above discussion are listed; they can also be accessed through Internet (if requested):

Hyötyniemi, H. (1995): Correlations – Building Blocks of Intelligence? In Haaparanta, L., Hyvönen, E., Seppänen, J., and Silvonen, J. (eds.): *History and Dimensions of Intelligence*. Finnish Artificial Intelligence Society, Helsinki, Finland, pp. 199-226.

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Hyötyniemi, H. (2001): Complex behavior from simple nonlinear feedback. In Hyötyniemi, H. (ed.): *Feedback to the Future*. Finnish Artificial Intelligence Society, Helsinki, Finland, pp. 123-136.

$$A = \begin{pmatrix}
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0 \\
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0&0&-1&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0
\end{pmatrix} \quad \text{and} \quad x(0) = \begin{pmatrix} 0\\0\\0\\0\\0\\0\\0\\0\\0\\0\\0\\0\\0\\0\\1\\0\\0\\0\\0\\2\\0\\0\\0\\0\\0\\0\\0\\0\\0 \end{pmatrix}$$

Figure 11. The description of the dynamic "Sieve System" (see text on page 31)

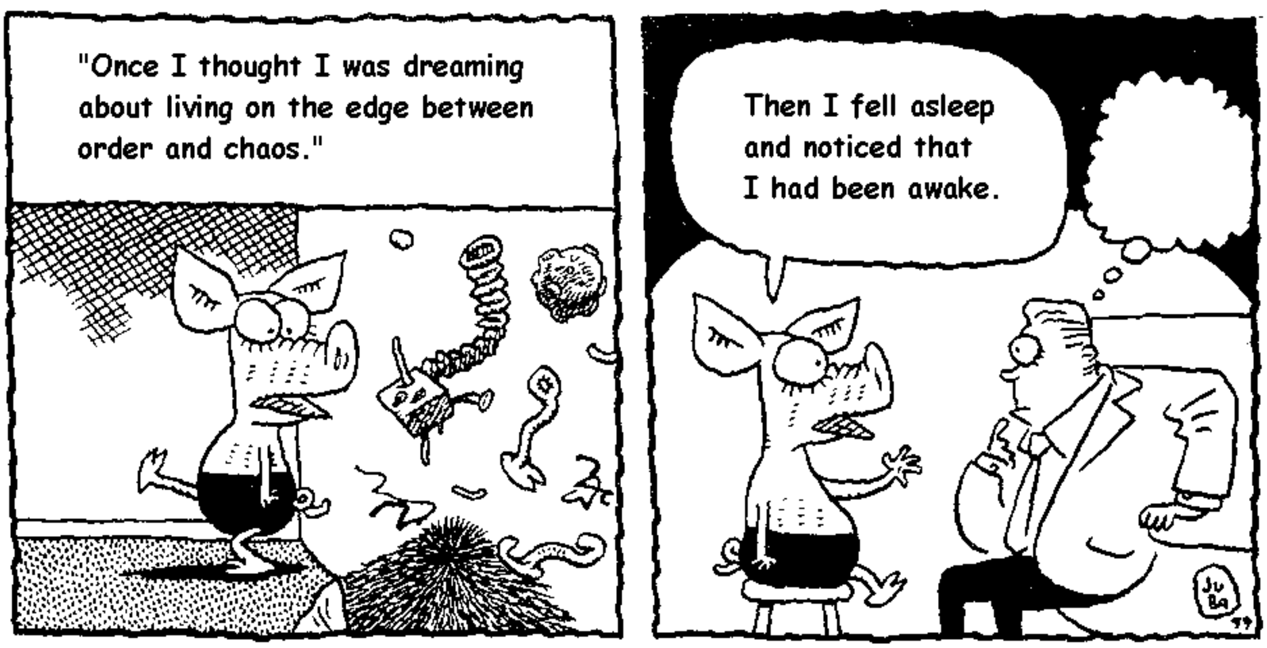

Figure 12. Wagner the Piggie, having a complex about chaos. Courtesy of Jussi ("Juba") Tuomola