

# The Concept of Resources in TRIZ: Past, Present and Future

Boris Zlotin and Alla Zusman  
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## Abstract

The term “resources” is widely used within many contexts to refer to natural resources, financial resources, human resources, etc. In TRIZ, the creative utilization of the resources available in a system to increase the system’s ideality is a cornerstone of inventive problem solving.

The concept was introduced in 1985 by Genrich Altshuller in the form of “substance-field resources,” a component in the Algorithm for Inventive Problem Solving (ARIZ). Later, this concept was expanded to include other types of resources such as functions, information, space, time, change, etc. A significant step in the formalization of the concept was the creation of checklists of typical resources (both readily-available and derived) embedded in various TRIZ software products.

Recently, the term *evolutionary resources*<sup>™</sup> has been introduced and constitutes a key concept in the Directed Evolution<sup>™</sup> process, where a comprehensive set of possible evolutionary scenarios are created for a given system.

This paper consists of two parts:

1. Theoretical findings related to the concept of resources
2. Practical instruments

# I. Theoretical Findings

## Historical review

The first utilization of the term “resources” was associated with *natural resources* – water, land, timber, minerals, etc. For centuries, an abundance of natural resources was the primary factor determining the strength of a country or region. Later, capitalism and the industrial revolution brought about the concept of *financial resources*. In the second part of the twentieth century, the concept of *human resources* was introduced by way of the management revolution. Just as natural resources play a critical role for nations in winning wars or gaining economic superiority, financial and human resources were seen as vitally important factors in winning in the marketplace. Various social theories have been based on and operate within the context of natural, financial and human resources.

Human evolution has always been accompanied by the consumption of available resources, often prompting fears that these resources will gradually disappear and produce a worldwide catastrophe.<sup>1</sup> At the same time, people have continually discovered and created new resources, such as inventing methods for mining and utilizing various metals, finding ways to produce and utilize steam and electricity, increasing agricultural efficiency with fertilizers, pesticides, the biological selection of plants and livestock, etc. Much innovative effort has focused on the improved utilization of natural resources: how to produce more metal from the same ore, how to yield a larger harvest from the same field, and so on. For a long time, however, there were no effective, reliable methods for achieving these results.

The first (and rather limited) methods targeting the cost-effect analysis of available resources were created by Lawrence Miles within the framework of Value Engineering Analysis (VEA)<sup>2</sup>. In 1977, Boris Zlotin, then a TRIZ specialist with three years’ experience, became the VEA leader at Electrosila, one of the largest electro-technical companies in the USSR. His goal was to bring VEA and TRIZ together for mutual benefit. In the process of his practical work and his teaching of a *TRIZ and VEA* course he constructed the first resource-related tool – a comprehensive table that helped reveal hidden resources for product development.<sup>3</sup> At this point, however, the table was not TRIZ-related.

We believe that the history of TRIZ resources began at the Petrozavodsk TRIZ conference in 1982, when Vladimir Petrov<sup>4</sup> presented a paper introducing the concept of *excessiveness in technological systems*. According to this concept, every technological system possesses more capabilities than are necessary for normal functioning; these

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<sup>1</sup> Malthusian theory, for example.

<sup>2</sup> Lawrence D. Miles, “The Fundamentals of Value Engineering,” Proceedings of the SAVE Convention, 1966.

<sup>3</sup> See Appendix 1, a table translated from Altshuller, Zlotin, and Philatov, *The Profession of Searching for New Ideas* (Kishinev: Kartya Moldovenyaska Publishing House, 1985), 156-161. In Russian. Also in [16].

<sup>4</sup> Certified TRIZ Master and President of the TRIZ Association of Israel.

excessive capabilities can be revealed and utilized to increase the system's ideality. In addition, it is possible to identify new applications for unutilized (or underutilized) substances, fields, information, etc. At the time, Mr. Petrov's work generated criticism from the TRIZ community, and this important new provision went unrecognized.

In 1985, Genrich Altshuller introduced a well-developed concept of the utilization of substance-field (SF) resources in the *Algorithm for Inventive Problem Solving* (ARIZ). Resources were grouped in the following categories:

A. Based on accessibility:

- Internal (limited to the main elements of the system).
- External, including resources from the general environment and those which are specific for the given system.
- Resources from the super-system or other accessible, inexpensive resources (including waste).

B. Based on readiness for utilization:

- Readily-available resources
- Derived (modified readily-available resources)<sup>5</sup>

At the 1985 Petrozavodsk TRIZ Conference, Svetlana Visnepolschi<sup>6</sup> presented the results of her work with Boris Zlotin and Alla Zusman related to the systematization and further development of the concept of resources. In particular, the definition of a resource was expanded to include, in addition to the substance and field resources introduced by Altshuller, additional categories such as space, time, information, and functionality. The paper also offered a graphical algorithm for revealing and utilizing resources (see Appendix 2).

At the same conference, Zlotin and Zusman presented a paper emphasizing the role of resources in root cause analysis and revealing the mechanisms of various effects (undesirable or neutral); the process of revealing and utilizing available resources was included as part of the analysis.<sup>7</sup>

The concept of resources and its close connection with the TRIZ concept of *ideality* attracted attention from other TRIZ specialists. Igor Vikentiev<sup>8</sup> introduced a definition of *differential resources* (resources produced by differing attributes or parameters, such as the voltage created by a difference in electrical potential); Zinovy Royzen<sup>9</sup> suggested another type of resources – *change resources* (resources produced by a change to the

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<sup>5</sup> For more information see *Tools of Classical TRIZ* (Southfield, Mich.: Ideation International, 1999), 44-5.

<sup>6</sup> Certified TRIZ Specialist, Ideation International, USA.

<sup>7</sup> This approach was later implemented in the Ideation TRIZ application Anticipatory Failure Determination<sup>®</sup> (AFD) and in solving scientific (research) problems.

<sup>8</sup> Certified TRIZ Master, Russia.

<sup>9</sup> Certified TRIZ Master, USA.

system). Vladimir Gerasimov<sup>10</sup> and Dr. Simon Litvin<sup>11</sup> introduced the concept of a *super-effect* – an additional benefit (resource) resulting from innovation that often goes unrecognized. It became clear that we were dealing with resources of a new type, which might be called *inventive resources* (in addition to natural, financial and human resources).

Until recently, the utilization of physical, chemical, geometric, and other effects has been regarded in TRIZ as another way to increase a system's ideality, as these effects often permit the substitution of a relatively complex system with a much simpler one.<sup>12</sup> In TRIZ, however, an effect can be defined as a predictable (i.e., pre-determined or statistical) response to a specific action or influence based on certain properties of participating elements. Because these properties (substance properties, for example) can themselves be considered resources, we suggest that the utilization of effects is yet another type of resource (see below).

Genrich Altshuller was the first to recognize the special role of effects in solving inventive problems; he encouraged the development of practical guides that listed specific effects and described how they could be used to obtain inventive solutions. Guides were created for the following types of effects:

- Physical effects – Yuriy Gorin, 1980s; the first guide was later expanded by other TRIZ practitioners.
- Chemical effects – Valery Michailov, Yuriy Salamatov, 1980s.
- Geometric effects – Igor Vikentiev, 1980s.
- Biological effects – Arcadiy Lihachev, 1980s.
- Psychological and social effects – Boris Zlotin and Alla Zusman, early 1990s.
- Evolutionary effects – recently (see below).

The next step in understanding the role of resources, particularly within the context of evolution, was made in the late 1990s with the introduction of the concept of *evolutionary resources* by Dr. Gafur Zainiev.<sup>13</sup> While inventive resources are limited to the existing system and its environment, evolutionary resources include ideas, concepts and other possibilities (technological and non-technological) created as a given system – and other, related systems – evolves. The concept of evolutionary resources lies at the core of Ideation's Directed Evolution™ (DE)<sup>14</sup> application.

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<sup>10</sup> Certified TRIZ Master, Ideation International, USA.

<sup>11</sup> Certified TRIZ Master, USA.

<sup>12</sup> For example, in the manufacturing of pre-stressed concrete slabs, thermal expansion can help stretch reinforcing rods instead of using a complex hydraulic device (when the rods are heated they expand by themselves).

<sup>13</sup> Certified TRIZ Specialist, Ideation International, USA.

<sup>14</sup> Boris Zlotin and Alla Zusman, *Directed Evolution: Philosophy, Theory and Practice*. (Southfield, Mich.: Ideation International, 2001).

## **Inventive resources**

In TRIZ, an inventive resource can be defined as:

- Any substance or anything made of a substance (including waste) that is available in the system or its environment.
- An energy reserve, free time, unoccupied space, information, etc.
- The functional and technological ability to perform additional functions, including properties of substances as well as physical, chemical, geometric and other effects.

### ***Inventive resources and ideality***

The concept of inventive resources is closely linked to ideality, which can be defined as follows:

$$\text{Ideality} = \frac{\text{All Useful Features and Benefits}}{\text{All Costs, Harmful Effects and Undesired Results}}$$

The utilization of the resources available in a system or its surroundings can increase ideality in several ways:

- Engaging unutilized resources to provide additional useful features (increasing the numerator)
- Reducing cost-related factors (denominator), in particular:
  - Eliminating unutilized resources
  - Utilizing internal instead of external resources
  - Utilizing less expensive or more accessible resources

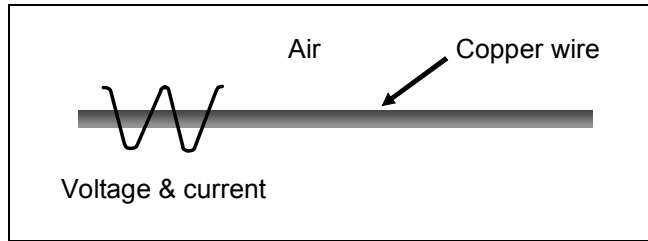
### **Revealing hidden resources**

The most important issue associated with inventive resources is that they are usually unobvious or hidden (the easily apparent resources having already been utilized).

EXAMPLE:

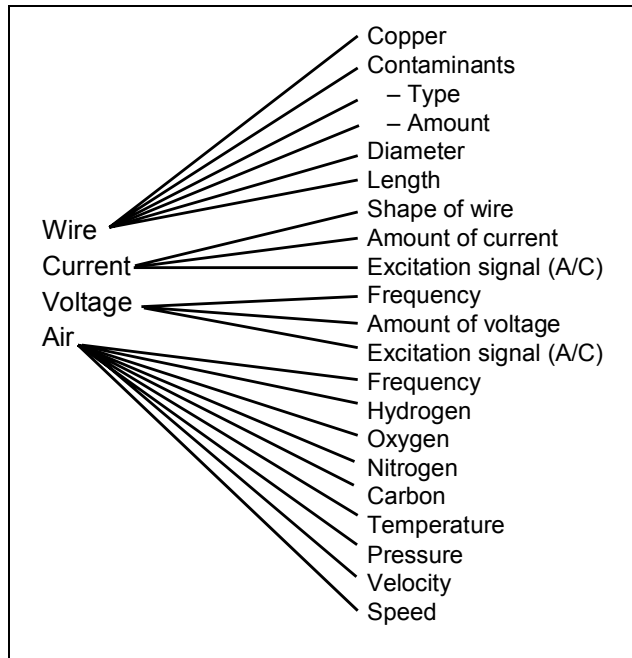
Most people would identify the following resources associated with a current-carrying copper wire: wire, air, voltage, and current (see Figure 1).

**Figure 1. Copper wire example**



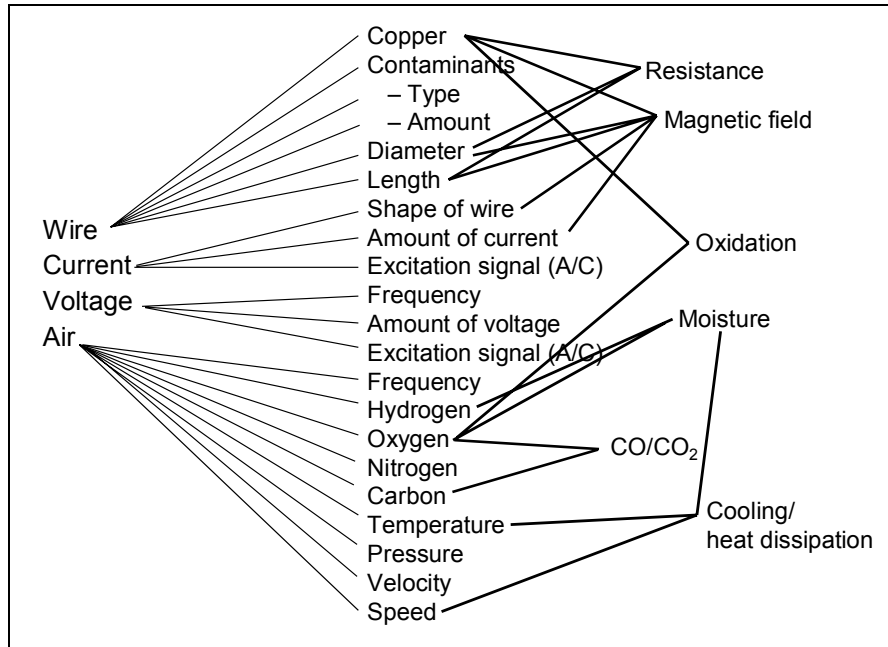
A thorough consideration, however, yields a different picture (see Figure 2):

**Figure 2. Readily-available resources (example)**



The resources listed in Figure 2 are those that are readily available. But things become more interesting still if we consider that the available resources can be modified to obtain even more resources (see Figure 3).

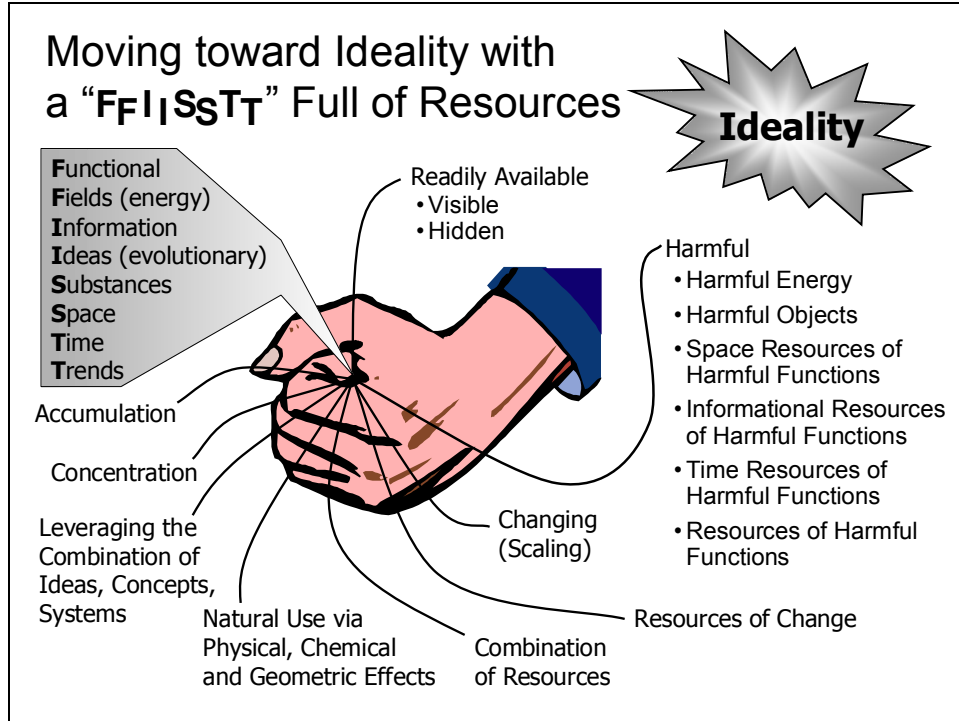
**Figure 3. Derived resources (example)**



Of course, in many situations some creativity is required to discover a usable resource that can help solve a problem. In such cases a systematic approach is very helpful to be sure that a resource isn't overlooked. (For example, to conduct a thorough search of a crime scene, the area is divided into small sections which are then carefully searched, one at a time.)

In addition to modification, other operations can be performed on resources, including accumulation, concentration, combination, etc.

Figure 4. Ideality and resources



A general view of inventive resources is shown in Figure 4, in which *ideas* and *concepts* are included as resources. These categories will be considered in more detail in the section entitled **Evolutionary resources**.

Following a systematic approach, we developed the following *resource checklists*:

***Readily-available resources***

- Substance resources
  - Waste
  - Raw materials, unfinished products
  - System elements
  - Inexpensive substances
  - Substance flows
  - Substance properties
- Field (energy) resources
  - Fields (energy) in a system
  - Fields (energy) from the environment
- Functional resources
- Space resources
  - Empty space
  - Another dimension
  - Reverse side

- Nesting (*matreshka*)
- Travel through
- Time resources
  - Preliminary action
  - Preliminary placement of an object
  - Create pauses
  - Eliminate idling
  - Concurrent operations
  - Group processing
  - Staggered processing
  - Post-process time
- Informational resources

### **Resources – inventive effects**

As mentioned earlier, the utilization of effects in TRIZ is seen as another way to increase a system's ideality, as effects are based on specific properties (physical, chemical or other) of the participating elements. Yet these effects – and their utilization – have their own histories. In the beginning, people were dealing with natural (often global) effects that could not be controlled; instead, people tried to seek protection from them. Technological civilization stimulated, and was affected by, the utilization of various mechanisms, based first on physical (mostly mechanical) operating principles (lever, wheel, etc.), then thermal, chemical and biological effects (producing metals from ore, treating leather, cooking food, distilling alcohol, etc.).

In the past, most effects were not recognized as effects but rather as a verbalized (or intuitive) understanding that certain actions produce certain results. Prior to the industrial revolution in the eighteenth century, the number of well-documented and widely utilized effects was rather limited. Their number started to grow with the industrial evolution, and in the nineteenth century many effects associated with electricity and magnetism were added. The twentieth century offered thousand of effects associated with hydro- and aerodynamics, solid materials physics, nuclear science, biological sciences (medicine, vitamins, genetic engineering, etc.) and other fields. During the past decade were added effects in the areas of nano-technology, high frequency waves, etc. The enormous number of discovered effects and combinations of effects offers unlimited possibilities. At the same time, the number of utilized effects grows much slower. The main challenge is to find a suitable effect for a specific function, along with a cost-effective way to implement it.<sup>15</sup>

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<sup>15</sup> An individual who has discovered the astonishing world of scientific and other effects often has the mistaken impression that extensive lists of effects, Internet search engines that allow information about effects to be found, and various knowledge bases are all that are required to produce inventions. Unfortunately, this is not the case, but rather is an illusion similar to believing that a new automobile can be built from Lego pieces. In fact, subject matter experts are usually well aware of effects utilized in their area, and only a relatively small number of effects from other areas (usually those that are easily transferred and implemented) can potentially be useful. More important is knowing how to apply and combine selected effects to achieve one's objectives.

## Inventive resources and software

The best way to utilize multiple checklists is to incorporate them into software. All Ideation software contains checklists organized around a specific purpose (see Figures 5, 6 and 7).

Figure 5. Innovation WorkBench® software

**Resources**  
Resources are substances, fields (energy), the properties of a substance/field, functional characteristics, and other attributes existing in a system and its surroundings, which can be utilized for system improvement.

**Readily-available resources** are resources that can be used as they are. Consider the following types of readily-available resources:

- [Substance resources](#)
- [Field resources](#)
- [Space resources](#)
- [Time resources](#)
- [Informational resources](#)
- [Functional resources](#)

**Derived resources** are resources that can be used after undergoing some kind of transformation. To utilize an available resource after transformation, consider the appropriate recommendation for that type of resource:

- [Derived substance resources](#)
- [Derived field resources](#)
- [Derived time resources](#)
- [Derived functional resources](#)
- [Derived resource accumulation](#)
- [Derived resource concentration](#)

**Readily-available substance resources**  
**Substance resources include any kind of material from which the system and its surroundings are composed.**

To utilize available substance resources, consider the following recommendations (Operators):

- [Waste](#)
- [Raw materials or unfinished products](#)
- [System elements](#)
- [Inexpensive substances](#)
- [Substance flows](#)
- [Substance properties](#)

**Resources - substance properties**  
Consider using additional properties of substances already available in the system or in the environment. For example, the ability of a substance to sense or transform fields (forces, effects or actions) can be used to provide information.

Illustrations:

- ★ [Cleaning filters automatically](#)
- ★ [Controlling spring stiffness](#)
- ★ [Controlling welding of thin pieces](#)
- ★ [Determining steel grade](#)
- ★ [Measuring charge temperature in cement kilns](#)
- ★ [Fish-luring trawl](#)
- ★ [Grinding piezoelectric plates](#)
- ★ [Milk sterilization](#)
- ★ [Rolling rails to repair railway lines](#)
- ★ [Spoons made of fusible metal](#)
- ★ [Storing hydrogen in hydrides](#)
- ★ [Un soldering with liquid nitrogen](#)
- ★ [Using lemons as batteries](#)

**Un soldering with Liquid Nitrogen**  
Components on prototype circuit boards may have to be repeatedly soldered and unsoldered, but microcircuits and other components can be spoiled by the heat used in unsoldering.

An alternative method for removing components is to touch each soldered joint with a probe cooled by liquid nitrogen. When cooled by this probe, the tin in the joint changes state, from white to gray tin, and increases in volume by 27 percent. The solder becomes a fine gray powder that can be shaken off.

Figure 6. Ideation Failure Analysis software

**Resources utilization**

Every object or process includes elements that can be utilized more effectively toward achieving some purpose – we refer to these as available resources. Inventing “new” resources is a more complicated approach, but still less expensive than introducing elements from outside the system.

For these reasons, the first step is to consider the components of your object or process as available resources:

- Available materials or substances
- Produced or supplied energy
- Free moments or periods of time
- Vacant space within an object
- Object structure
- System functioning
- Information about the system

If no single, available resource can help to improve your system, consider [inventive ways to obtain new resources](#)

**Produced or supplied energy (energy resources)**

Consider as a resource any kind of energy available in the object or process. It might help to provide existing functions or operations, or to perform new ones.

Consider, in particular:

- Mechanical impacts of solid objects
- Mechanical impacts of liquids/gases
- Thermal impacts
- Chemical impacts
- Electrical fields
- Magnetic fields
- Radiation impacts

If you cannot find energy resources within your object or process, consider the resources within the nearby environment. In particular, consider the energy of the super-system of which your object or process forms a part.

**Radiation impacts**

Radiation impacts can be used for:

- destroying
- heating
- generating an electrical field
- comparing and distinguishing objects
- making objects visible
- developing a non-visible image
- marking parts
- image transformation
- documenting information

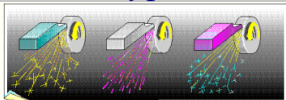
☆ [Hydrodynamic testing of ship models](#)

obtaining information concerning:

- presence and location of an object
- shape and dimension
- quantity
- movement
- state
- structure
- composition

☆ [Using sparks to determine steel type](#)

**Using sparks to determine steel type**



There are many methods for determining steel type. These include chemical analysis, spectral analysis, and taking complicated measurements of other parameters.

Use variations in energy as an informational resource. The sparks generated when a steel workpiece is treated at a grinding wheel can be observed. The color, form, density, and spatial distribution of the sparks indicate both the presence of large amounts of carbon in the steel and the presence of tungsten or other alloying elements.

**The result:** steel type can be easily determined.

Figure 7. Knowledge Wizard<sup>®</sup> software

The screenshot displays the Knowledge Wizard software interface, which is organized into four main panels:

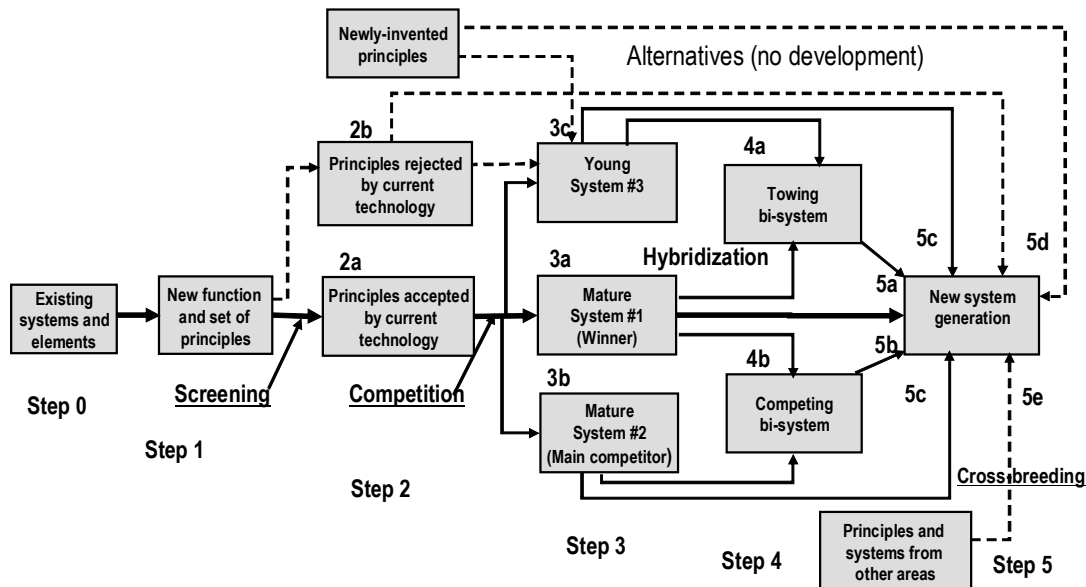
- Assessment of Resources:** This panel prompts the user to "Consider the following types of resources that might be available:" and lists four categories: Financial, Human, Technical, and Other business assets. A cartoon character of a man with a green bag and a tool is shown next to the text. Red arrows point from the Financial and Human links to their respective panels.
- Financial Resources:** This panel contains two main questions:
  1. Are you ready to carry the cost of implementing a solution, taking into consideration that it might constitute 10-15% of the expected gain?
  2. Are you able to use or acquire any of the following?
    - investment
    - cash reserve
    - loans
    - barter
    - other
- Human Resources:** This panel contains six main questions:
  1. Do you know people who view this situation as a high priority? Are they:
    - at the top level?
    - at your level?
    - at a lower level?
    - those on whom implementation will depend?
    - other individuals and/or groups inside the company?
    - people outside the company?
  2. Do you have allies who would support you if necessary?
  3. Should it be necessary, will you be able to contact all Subject Matter Experts (internal or external) that might be needed to work on the project?
  4. Do you currently have people capable of coming up with creative solutions?
  5. Are people available who can provide necessary testing and implement a solution?
  6. Are there ways to motivate people to improve the situation?
- Technical Resources:** This panel explains that "Because business situations are often linked to technology – i.e., improved through technology and vice versa – consider the following resources:" and provides detailed guidance for assessing various types of resources:
  - What substance resources are available? Look for:**
    - Elements of the system and/or its environment
    - Raw materials in the system and/or its environment
    - Products produced by the system and/or its environment
    - Waste materials produced by the system and/or its environment
    - Inexpensive substances such as water, air, sand, snow, etc.
  - What energy resources are available? Look for:**
    - Mechanical energy (actions, interactions, etc.)
    - Sound, oscillations, vibrations
    - Thermal actions and interactions
    - Chemical reactions
    - Electrical energy (actions, interactions, etc.)
    - Magnetic fields, actions and interactions
    - Electromagnetic fields, actions and interactions
    - Light and other types of radiation
  - What functional resources are available? Look for:**
    - Additional useful functions that the system and/or its environment can perform
    - Harmful actions, which can be used toward some benefit
  - What informational resources are available? Look for:**
    - Fields emitted from the system and/or its elements
    - Substances exiting the system
    - Properties of the system and/or its elements (such as temperature, transparency, natural frequency, etc.)
    - Variations in energy flows passing through the system and/or its elements
  - What time resources are available? Look for:**
    - Time before the process starts
    - Time during the process, such as:
      - Pauses
      - Idling motions
    - The possibility of performing several operations simultaneously
    - Post-process time
  - What spatial resources are available? Look for:**
    - Unoccupied space, including:
      - Space between elements
      - Space inside elements
      - Unoccupied surfaces of elements
    - Space occupied by unnecessary objects/elements
    - Space available in a dimension other than what is already being used

## Evolutionary resources

Evolutionary resources consist of the knowledge (including theories, facts, ideas, concepts, designs, processes, etc.), abilities, skills, etc. obtained as a result of prior evolution and capable of enabling a subsequent evolutionary step. From the evolutionary point of view, the most important components of these resources are general evolutionary knowledge and the creative capabilities and techniques that ensure continuous, progressive evolution – that is, an increase in the ideality of an existing system and invention of new systems. In fact, evolutionary resources help transform non-useful and even harmful elements into useful resources.<sup>16</sup>

The concept of evolutionary resources is closely connected with the typical general scenario of technological evolution shown in Figure 8.

**Figure 8. General scenario of system evolution**



According to this figure, as a technological system evolves it goes through five steps:

1. A system is built to perform a new function.
2. The overall technological level is screened, and the principles/ideas that cannot be effectively realized under current technological limitations are rejected.
3. Competition arises between alternative systems, based on principles that are supported by current technology.
4. Hybridization of existing systems.
5. Candidates for the next-generation system are considered.

<sup>16</sup> For many years, an African tribe made pottery from clay containing high levels of uranium; twentieth-century knowledge revealed powerful applications for uranium.

Typically, designers working on the next generation of a given system focus on recent designs; they pay little attention to old ideas, especially those that were once rejected for various (usually forgotten) reasons. These forgotten ideas and ideas from other areas of technology, together with knowledge from the given area, constitute the evolutionary resources existing in the given area.<sup>17</sup>

Based on Figure 8, we can identify the following categories of evolutionary resources:

- Resources developed in the given area starting at the moment the system was created (“big bang”).
- Resources from other areas of technology (including enabling technologies<sup>18</sup>) that can be utilized in the system.
- Resources from the areas of sociology, marketing, and psychology.
- Knowledge about evolution.

### **Evolutionary resources developed in the given area**

The evolutionary resources in this category are usually the easiest to reveal and utilize. As mentioned earlier, however, designers typically ignore previously-rejected ideas. Yet ideas are often rejected for the reason that, at the time, they are premature or impractical because the overall level of technology cannot support their being implemented. In other cases, psychological barriers or personal agendas can undermine their destiny.<sup>19</sup> In any event, even if the decision to abandon an idea was reasonable at the time, the reasons for the decision can change later and the rejected ideas employed.

Other important evolutionary resources include:

- Recent knowledge that has not yet been put to practical use.
- Knowledge about alternative (competing) systems.<sup>20</sup>

### **Evolutionary resources from other areas**

Knowledge (theories, facts, ideas, concepts, designs, processes, etc.) developed in other areas but, until recently, unused in the area in which the system resides can be a valuable resource for further evolving the system. This knowledge is unlimited, however, and thus is useless for practical purposes without effective tools and methods that allow for the identification of applicable information. The transfer of any technology – even a useful

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<sup>17</sup> See Boris Zlotin and Alla Zusman, “General Scenario of Technological Evolution,” *Izobreteniya*, 2004, 18-21.

<sup>18</sup> Newly-developed, general purpose technologies with numerous applications (e.g., voice recognition, wireless communications, LCD screens, microchips, etc.).

<sup>19</sup> Edison launched a “war” against alternating current.

<sup>20</sup> Ideas related to alternative (competing) systems can be utilized to develop a new generation of a system via hybridization. See more in Boris Zlotin and Alla Zusman, “General Scenario of Technological Evolution,” *Izobreteniya*, 2004, 18-21.

and valuable one – is no easy task, and is further complicated by the “Not Invented Here” syndrome as well as differences in corporate and national cultures and mentalities.<sup>21</sup>

In the process of transferring knowledge, one should look for knowledge related to:

- Systems that perform functions similar to the function of the given system.
- Systems that perform functions capable of replacing the functions of the given system or its subsystems.
- Systems that perform functions opposite to those of the given system.
- New ideas and technologies that could help carry out auxiliary functions or add new features to the given system (i.e., enabling technologies).
- Ideas and concepts for eliminating and/or preventing drawbacks or other undesired effects associated with the given system.

Knowledge/technology transfer can be made via:

- Direct utilization of elements from other systems.
- Transfer of useful ideas with substantial adaptation
- Hybridization

Direct transfer works the best in the early stages of system development. Once the system has been improved and is more complex, direct transfer is more difficult, often requiring substantial changes or even new inventions.

### ***Knowledge/technology transfer with adaptation***

The following types of adaptation can be considered:

- Minimal adaptation – for example, using readily-available functional modules from other systems.
- Adaptation of auxiliary or secondary functions while the main function remains the same.
- Transfer with the conversion of specific secondary functions into main functions.<sup>22</sup>
- Conversion of certain harmful functions into useful features or even main functions.<sup>23</sup>

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<sup>21</sup> Implementation of Japanese Quality Function Deployment or Russian TRIZ in the United States are good examples.

<sup>22</sup> A plastic material developed for military purposes possessed high elasticity. This material was utilized to produce new poles for pole vaulting.

<sup>23</sup> Exhaust gases produced by motorized plows are pumped into the soil to increase its productivity.

## ***Hybridization***

As with biological systems, the process of hybridization involves combining certain useful features of selected systems in the most effective way.<sup>24</sup> To date, a number of different types of combinations have been revealed;<sup>25</sup> from the evolutionary point of view, the most interesting are:

- Close hybridization – integration of systems from the same family of designs, functions, uses, or other features.
- Remote hybridization or cross-breeding – combining systems from different areas.
- Complementary hybridization – combining systems with complementary features.
- Towing hybridization – combining designs of different generations of the same system.
- Hybridization of competing systems – combining mature systems that compete in the same market.
- Alternative hybridization – combining systems that perform opposite functions.
- Hybridization of branches – combining specialized systems developed from the same base system.<sup>26</sup>

Knowledge/technology transfer and adaptation, while providing technical advantages, is a gradual process of change. At the same time, however, it stimulates system development and steers innovation, creativity and acceptance of change.

## **Knowledge about evolution**

General evolutionary knowledge includes:

- Trends, patterns and lines of evolution (universal, general and specialized).
- Evolutionary effects

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<sup>24</sup> Combining competing systems in technological evolution was first described by Boris Zlotin in a paper published in the *Russian Journal of Inventors and Innovators* in 1983. In the late 1980s, Vladimir Gerasimov and Simon Litvin developed the first step-by-step procedure for this integration (“Why Does Technology Favor Plurality?,” *Journal of TRIZ* vol. 1, no 1, 1990). Later, Gerasimov teamed with Valery Prushinskiy and Gafur Zainiev (who suggested the name “hybridization” to emphasize the parallel with biological evolution) to advance the procedure. See *TRIZ in Progress* (Southfield, Mich: Ideation International, 1999).

<sup>25</sup> The most comprehensive list of possibilities is presented in Ideation’s Innovation WorkBench<sup>®</sup> software.

<sup>26</sup> In the process of evolution, a system might continue to develop in different directions (e.g., a “general” airplane becomes a fighter, bomber, cargo plane, etc.). Once separate development starts, different branches follow their own paths, yielding different features that could be complementary and interchangeable between branches. For example, hydraulic control of a bomber’s steering system was adopted by fighter planes. A combination fighter-bomber was also developed.

We have addressed trends, patterns and lines of evolution in both technical and non-technical areas in earlier publications.<sup>27</sup> In this paper we will focus on the patterns and lines related to evolution toward the increased involvement of resources (see Part II).

### **Evolutionary effects and non-linear systems**

The evolution of real systems is associated with a mix of regular, deterministic, and highly predictable events along with events that are random, stochastic, haphazard, difficult-to-predict, etc. A small influence often produces enormous (and unexpected) results, while in other situations extensive efforts produce an inadequate outcome. Typical examples are: skidding on a slippery road, stock exchange operations, economical booms or crises, tropical hurricanes, an ever-changing fireplace flame, snowflake structure, locust invasion, etc. – results of non-linear system behavior. A main characteristic of non-linear systems is the possibility that their properties will change under the influence of processes taking place within them, either accelerating (positive feedback) or stabilizing (negative feedback) these processes.

Non-linear system behavior is described by non-linear differential equations. Unfortunately, only a very limited number of differential equations can be solved analytically, and a large number cannot be solved even with numerical (digital) modeling. The biggest challenge in working with non-linear systems is that, in addition to exhibiting logical and clearly understood behavior, they often perform in ways that contradict logic, intuition and common sense.

As a non-linear system evolves, the following events typically occur:

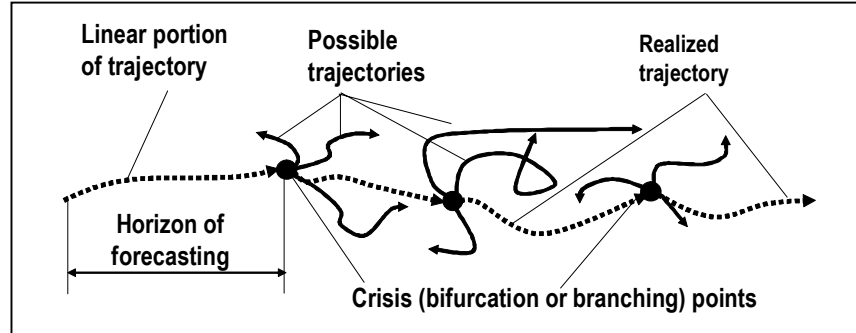
- Evolution along a highly predictable, logical and stable trajectory (trend), ending when the system has evolved to the point of being unstable and therefore unpredictable (see Figure 9). These “crises” are called **bifurcation** (branching) points.<sup>28</sup> The following types of crises have been identified:
  - Events that are planned, expected and well prepared for (starting college after graduating from high school, marriage, retirement, etc.).
  - Induced by a super-system (economic crisis, war, etc.).
  - Catastrophic (earthquake, tsunami, terrorist attack).
  - Haphazard (accident, winning the lottery).
  - Self-induced in the process of system evolution caused by loss of stability.

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<sup>27</sup> Boris Zlotin et al., “TRIZ Beyond Technology. The theory and practice of applying TRIZ to non-technical areas,” *Proceedings of TRIZCON 2000*, 135-176. Also available on [www.ideationtriz.com](http://www.ideationtriz.com).

<sup>28</sup> Ilya Prigogine and Isabelle Stengers, *Order Out of Chaos* (Random House, 1984).

**Figure 9. Evolution of non-linear systems**



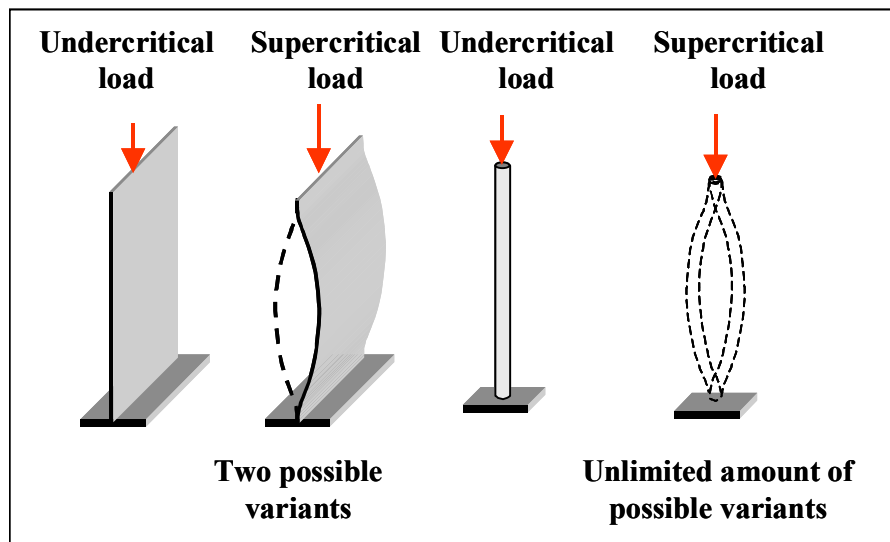
- At a bifurcation point, system evolution can continue in different (alternative) directions. The actual trajectory will depend on haphazard and often weak (infinitely weak, theoretically) influences. In other words, at a bifurcation point the system becomes vulnerable to weak impacts.
- Once the next stable trajectory is selected, stable evolution continues until the next bifurcation point.

Bifurcations points in non-linear system evolution impose a fundamental limitation on the accuracy of predicting system evolution; that is, accurate forecasting is possible only within linear zones between bifurcation points.

EXAMPLE:

A simple analogy helpful in understanding the nature of instability at a bifurcation point is a thin elastic rod or membrane compressed as shown in Figure 10.

**Figure 10. Bifurcation point (example)**



Under a certain critical load the membrane will bend in one of two possible directions, however it is impossible to predict which one. The rod with a round cross-section has an unlimited number of possibilities.

Non-linear effects are most common in systems with delayed responses – i.e., when the results are not immediately effective (or visible). For example, one distant result of the baby boom in the late 1940s will soon impact the social security system, when most baby boomers reach retirement age. In such systems, cyclical, self-supporting, auto-oscillating processes are inevitable. In population dynamics these processes can render a particular population small and vulnerable to weak impacts, leading to extinction or dramatic growth. In the delayed-response system composed of predator and prey, remarkable effects are observed when the prey population is larger when the predator is present than when it is absent.<sup>29</sup> A comprehensive list of evolutionary effects is given in Part II.

## **Evolutionary resources and the control of evolution**

Many of the evolutionary effects described in Part II work together to create a very diverse complexity of life; understanding this complexity usually changes our perception of the world.

### **Deviation from deterministic cause-effect relationships**

Our usual perception is that there should be a clear and definite connection between a particular cause and a particular effect. However, the non-linear behavior of a complex system offers different relationships, such as:

- An event may have more than one root cause, some of which may be unclear or unknown.
- The same or seemingly same events may have different root causes.
- The same influences on a system may produce different – and sometimes unpredicted – results.
- Different influences can produce the same results.
- A combination of several influences can produce unexpected super-effects.
- Reactions to influences may be delayed; distant (long-term) results may be opposite to short-term results.
- A system can resist the influences impacting the influencing agents.
- A system can “provoke” a desired influence.<sup>30</sup>

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<sup>29</sup> The extinction of a species is often blamed on human civilization, while in many cases involving delayed-response systems it is a normal event (similar to forest fires that are vital to the forest’s existence).

<sup>30</sup> The behavior of a complex, evolving system (natural or man-made) can be similar to that of a living organism, as if it had a mind of its own.

In systems like those described above, the question of which came first – the chicken or the egg – makes no sense; in this world demand creates supply and supply creates demand. What does make sense in such a world are Dante’s maxim “the road to hell is paved with good intentions,” which troubles those who believe in logic and being able to differentiate good and evil. This doesn’t mean that it’s hopeless to try, however, as most of these deviations from conventional logic occur close to bifurcation points – and even then, probabilistic methods might allow for the identification of possible system reactions.

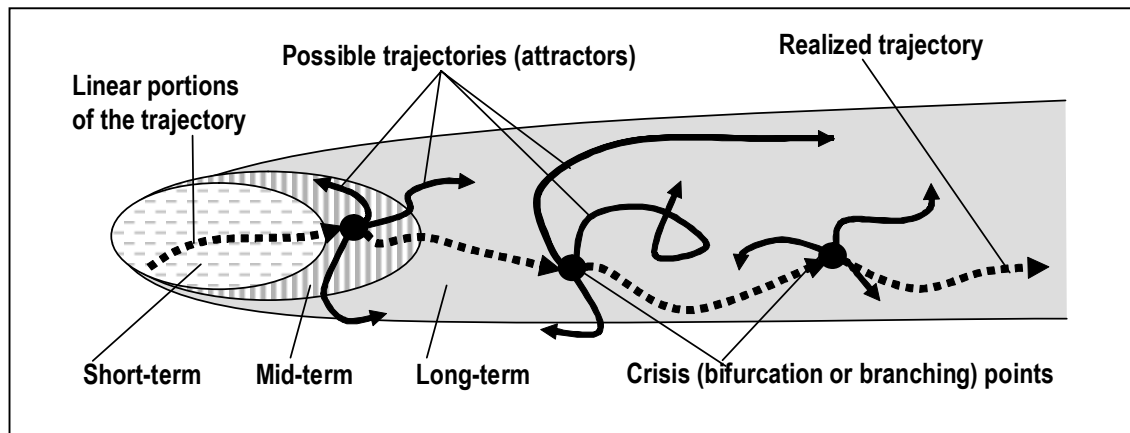
### **Forecasting – possibilities and limitations**

Forecasting is a very important aspect of controlling a system’s evolution. Based on the general picture of non-linear system evolution, it is possible to explain and utilize the specifics of short-, mid- and long-term forecasting.

#### ***Short-term forecasting zone***

We can consider the short-term forecasting zone as a linear zone between past and future bifurcation points (see Figure 11).

**Figure 11. Forecasting zones**



The short-term zone is characterized by smooth evolution, gradually engaging available internal resources without sharp and/or unexpected changes in course. Because of the zone’s linear nature, short-term forecasting can be fairly reliable, enabling detailed planning based on the knowledge of experts in the given area, traditional marketing analysis, etc.

#### ***Mid-term forecasting zone***

The mid-term zone (Figure 11) is close to the nearest bifurcation point – a crisis point capable of substantially changing the course of further evolution. Here the probability of accurate forecasting is lower, as the selection of the evolutionary trajectory depends on many, often unknown, factors. Given this, it is more important at this point to evaluate

possible directions, select the most desirable variants, and develop the necessary skills and techniques that will help effectively manage the crisis to achieve desirable results.

### ***Long-term forecasting zone***

The long-term zone is located beyond the nearest bifurcation point, making subsequent bifurcations unpredictable by definition. At this point, new generations of the system can emerge which have little to do with the existing system and employ a different operating principle (e.g., a laser pointer instead of a wooden stick), beget new and unexpected applications (lasers used in cosmetic procedures), and so on. Resources available in the existing system play a rather insignificant part compared to the outside resources supplied by new technological possibilities in different areas. Long-term forecasting in this case should be based on general evolutionary knowledge, including the evolution of human needs, markets, new technologies, etc. and will require different techniques and tools than those used for short- and mid-term forecasting. This can explain why the opinions of recognized experts in a given area (especially when collected, averaged and verified using probabilistic models like the Delphi method) can be more harmful than useful.<sup>31</sup>

Given the above, long-term forecasting should be focused on identifying strategic goals, considering large-scale changes, revealing potential dangers, and identifying resources that could become necessary in the future, along with the methods for creating and accumulating them.

### ***Suggested sequence of forecasting work***

The following sequence of work can be suggested to maximize the results of forecasting:

1. Study the given system to identify possible bifurcation points. Determine which is the nearest bifurcation point and identify what can change at this point and in what direction. Identify the important influencing factors, symptoms and signs.
2. Define the short-term zone – i.e., the time before a potential crisis arrives – and conduct a short-term forecasting for this zone (using, for example, traditional forecasting methods such as extrapolation of smooth trends).
3. Work on a mid-term forecast – identify the main factors associated with the next bifurcation point:
  - What will change, and what won't change?
  - What do we want?
  - What are the control factors?
  - How can the results be controlled?
4. Work on a long-term forecast: identify goals, possible dangers, the potential evolutionary direction based on available and new, evolutionary resources.

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<sup>31</sup> The Delphi method is one of the techniques utilized within the framework of traditional technological forecasting. See Joseph P. Martino, *Technological Forecasting for Decision Making* (New York, 1972).

## **Technology as the main evolutionary resource**

### **Technology and ecology: the Malthusian scare**

In the beginning of the nineteenth century, in response to an optimistic view of societal evolution, Thomas Malthus put forth his principle that population growth can and will outstrip the food supply, because population grows in a geometric progression while food production grows in an arithmetic progression.<sup>32</sup> The Malthusian principle became an extremely strong argument that was used in numerous economical and social theories. Karl Marx, the founder of communism, used the Malthusian approach as a foundation for his theory of reducing the profit margin and to prove the inevitability of communist revolutions. Most of the catastrophic predictions made by the Club of Rome (a German-based global think tank) in the 1960s and 1970s were based on the same ideas.

The main point made by Malthusians was that all natural resources are limited and were near exhaustion. According to them, the situation became much worse in the twentieth century because of the enormous growth of waste – in fact, some predicted that humanity would “suffocate in waste.” These theories had a specific basis: in the 1960s the Rhine River was effectively a sewer; the water was so contaminated with chemicals that it could be used to develop photographic film. A similar situation existed in the Great Lakes on the North American continent. Today, however, sturgeons grow in the Rhine and water from the Great Lakes is drinkable. This hasn’t discouraged recent Malthusians, however – they have simply incited new scares such as holes in the ozone layer, the Greenhouse Effect, the risks of genetically modified plants, and so on.

For centuries the Malthusian principle has been used to justify wars and revolutions as methods of reallocating unfairly distributed resources (rich people or rich countries have everything) and became the strongest argument used by every totalitarian regime (it is easy to convince poor people that they are poor because of limited resources). At the same time, recent agricultural and other technologies provide food, clothing and shelter for every individual on Earth – anything short of this is the result of incompetence or politicians who rule by using hunger or deficits as a main control factor.

In developed countries, the Malthusian approach forms the foundation of ecological extremism. In general, ecological concerns play a positive role in society, emphasizing the need to keep our lands clean and free of harm. Some ecological movements exist in extreme form, however, and are waging a war against technology, trying to curb its development in order to conserve natural resources.

### **Technological solution to problems originated by technology**

For centuries it seemed obvious that prosperous countries thrived due to an abundance of natural resources, including land, minerals, water, woods, and people. For example, one of the reasons Germany and Japan lost WWII was a lack of natural resources. However,

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<sup>32</sup> T. R. Malthus, *An Essay on the Principle of Population*, 2<sup>nd</sup> ed. (extended), 1978.

history has always had exceptions that undermine this conclusion such as the rich, ancient cities of Carthage or Jerusalem (located in the near desert), ancient Greek cities scattered along small and predominantly rocky islands (powerful but poor in natural resources) Holland in the sixteenth and seventeenth centuries, England in the nineteenth century, modern Taiwan, Singapore, Japan, etc. In contrast is Russia – a poor country vast in both size and natural resources. The explanation for this paradox might lie in a new approach to resource theory, which introduces two types of resources:

- Basic or natural resources, including productive land, oil, gas, metals and minerals, woods, etc. Each of these resources, considered separately, might be limited.
- Superior or man-made resources, including knowledge, skills, abilities (creativity), motivation, dedication, etc., enabling people to produce and invent. These resources are practically unlimited.

Superior resources ensure that people use limited basic resources in the most effective way, while continuously discovering new basic resources. In the absence of superior resources a country cannot truly be rich.

Given the above, we can see that in many cases resources grow rather than diminish, due in particular to:

- The continuous discovery of new types of resources. Oil, aluminum, plastics, silica, nuclear power, etc. were discovered in the twentieth century.
- New technology that allows for a reduction in the cost of exploring and producing traditional resources (for example, pumping oil that is kilometers deep today is often less expensive than from dozens of meters 100 years ago). This makes it possible to explore and produce resources located in places that had previously been inaccessible (the sea bottom, for instance).
- A dramatic reduction in resource consumption with the same or better results (lighter construction materials, increasing miles per gallon, etc.).
- The invention and development of low or no-waste production; new waste treatment technologies.
- The invention of new methods of replenishing resources (reconstruction and enrichment of agricultural fields, closed-cycle technologies, etc.).

There is no reason to expect that these positive factors will suddenly stop. In fact, *technology itself is becoming an effective cure for the social ailments that are caused by technologies*. At the same time, the fear that a resource *might* become depleted is in and of itself a serious evolutionary problem. The origins of this fear are a lack of trust in the capabilities of the human mind and good moral intentions, which turn people against change and new developments.

The transition from the utilization of basic resources to high-level, man-made resources has never been easy, and is typically initiated by a serious crisis that leaves people with

no choice – they must move forward or die. The most important factor in this transition is a free market economy, which encourages entrepreneurship and therefore allows everyone to apply his/her intellectual capabilities. Although the lack of natural resources contributed to Germany and Japan’s defeat in WWII, the democracy, free economy and liberated minds that resulted from this defeat brought about the wonderful “reincarnation” of these nations. In the absence or limited economical and political freedom we can see the countries like Russia, Iraq, etc. staying poor in spite of rich natural resources.

### **Win-win strategies and resource utilization**

In mathematical game theory two types of game exist:

- Games with a fixed overall outcome wherein if one wins, the other loses (win-lose situations like card games, sports, etc.).
- Games with a non-fixed overall outcome, wherein both sides can lose (Pyrrhic victory) or win (win-win situations).

Win-win situations have been rare in history due to the inherent vulnerability of human flaws such as greed, short-sightedness, untrustworthy relationships, etc. No matter how good the expected outcome, players who expect deception are more likely to violate the rules first, ruining an otherwise (possibly) lucrative outcome. Fortunately, the situation is changing with better business practices and an improved environment, in particular:

- The growth of potential resources and their creative utilization increases the probability that win-win strategies will succeed.
- The introduction and enforcement of laws that protect people from fraud and deception; an increase in the “transparency” of society, with a decreasing tolerance of unethical business practices.
- An increase in overall moral values and trust, along with a decreased tolerance of dishonesty.
- The establishment of measures to protect businesses, including government insurance of bank deposits, hedge funds, etc.<sup>33</sup>

The effective realization of win-win strategies requires creative approaches and depends on effective tools for utilizing, recognizing and creating resources; these tools already exist and have recently become available in TRIZ.

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<sup>33</sup> Compare the 1929 stock market crash with the recent “dot com” crash.

## Conclusion

1. TRIZ-based inventive resources as well as evolutionary resources have become an important factor in every aspect of our lives, joining the suite of natural, financial and human resources.
2. Typical inventive and evolutionary resources and many related lines of evolution have been revealed from various sources of knowledge (technical, social, economic, business, etc.); once documented and organized, this information becomes an indispensable tool for developing practically exhaustive sets of innovative solutions and scenarios for further evolving a system.
3. Knowledge about resources and the lines of evolution of resource involvement represent an essential portion of the innovation knowledge base embedded in various Ideation software products, enabling effective innovation processes and the Directed Evolution™ application.

## II. Practical Instruments

### **Pattern: Evolution toward the increased involvement of resources**

In addition to other factors, the evolution of man-made systems is a result of the accumulation of knowledge, contributing to the increasingly efficient utilization of resources, both internal and external.

Every step in a system's evolution:

- Is made possible by the utilization of particular resources.
- Consumes certain resources, depleting these resources and/or increasing the cost of obtaining them.
- Creates new resources that can be utilized for further evolving the given system or other systems.
- Creates harmful resources capable of producing undesirable effects (in the immediate and/or distant future).

The evolution of resource utilization proceeds in a direction that involves increasingly diverse and complex resources, in particular:

- From basic resources (land, metals, minerals, fossil fuel, the physical energy of people and animals, etc.) to high-level, man-made resources (ideas, knowledge, skills, etc.).
- From readily-available resources to resources produced through the use of increasingly sophisticated technologies.
- From plain resources to “smart” resources produced by human intelligence and creativity.
- From the utilization of selected resources to the systemic combination of resources.

A system's evolution slows down and can eventually stop (i.e., reach the maturity stage on its S-curve) due to the exhaustion of the available resources as well as those originating from the realization of the system's main concept.

Seen below are the lines of evolution related to the pattern described above. These lines are divided into the following groups:

- Evolutionary resources
- Resource diversity
- Intensification of resource utilization
- Utilization of effects as a resource

## **Evolutionary resources**

This group includes the following lines of evolution:

- Opportunities for evolution
- Collection and utilization of knowledge
- Technology transfer
- Technology adaptation

### ***Line: Opportunities for evolution***

1. Development of new knowledge and skills.
2. Utilization of existing knowledge and skills in new areas.
3. Accumulation of various resources, especially highly-effective tools, necessary materials, etc.
4. The emergence of highly educated and motivated people.
5. The possibility of accumulating capital and investing in evolution, from R&D efforts to building production facilities, creating distribution outlets, etc.
6. The gradual lifting of limitations for evolution, including technological, social, psychological limitations, etc.

### ***Line: Collection and utilization of knowledge***

1. Knowledge developed in the given area, including:
  - Knowledge created as the system emerges (“big bang”)
  - Prematurely-developed ideas
  - Rejected ideas or ideas not given serious consideration for some reason
2. Knowledge, inventions and ideas developed in other areas of science and technology, including that related to:
  - Systems that perform functions similar to the function of the given system
  - Systems that perform functions capable of replacing the functions of the given system or its sub-systems.
  - Systems that perform functions opposite to those of the given system
  - New ideas and technologies that can help with the performance of auxiliary functions or add new features to the given system.
  - Ideas and concepts for eliminating and/or preventing drawbacks or other undesired effects associated with the given system.

3. Knowledge of culture, marketing, psychology, sociology, etc. helpful in finding new applications and new market sectors.
4. Knowledge about evolution, including:
  - Trends, patterns and lines of evolution (universal, general and specialized)
  - Evolutionary effects

***Line: Knowledge transfer***

1. Direct utilization of elements from other systems.
2. Transfer of useful ideas with substantial adaptation.
3. Hybridization, including:
  - Close hybridization – integration of systems from the same family of designs, functions, utilizations or other features.
  - Remote hybridization or cross-breeding – combining systems from different areas.
  - Complementary hybridization – combining systems with complementary features.
  - Towing hybridization – combining designs of different generations of the same system.
  - Hybridization of competing systems – combining mature systems that compete in the same market.
  - Alternative hybridization – combining systems that perform opposite functions.
  - Hybridization of branches – combining specialized systems developed from the same base system.

***Line: Adaptation of technology in the process of knowledge transfer***

1. Minimal adaptation, for example using readily-available functional modules from other systems.
2. Adaptation of auxiliary or secondary functions while the main function remains the same.
3. Transfer with the conversion of specific secondary functions into main functions.<sup>34</sup>
4. Conversion of certain harmful functions into useful features or even main functions.

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<sup>34</sup> A plastic material developed for military purposes possessed high elasticity. This material was utilized to produce new poles for pole vaulting.

## **Resource diversity**

The normal way to mobilize the resources associated with using trial-and-error to solve problems and develop products is the following: First use the resources that are easier to find. This is often satisfactory, especially when the most visible resources are also the most effective ones. However, any real system of medium complexity could have many resources – the more complex the system, the more resources (including unexpected ones) it might have. In fact, the richest resources of a complex system are diversity and the possibility to make changes that will yield additional resources.

The following lines help in the systematic exploration of a complex system to reveal its resources in the most effective way.

- Basic involvement of resources
- Resource diversity
- Resource consumption
- Expanding the sources of resources
- Interchangeability of resources
- Resources from the environment

### ***Line: Basic involvement of resources***

1. Increased utilization of readily-available resources (as they exist in the system or its environment).
2. Reduced cost of resource utilization, including searching for cheaper resources and technologies to explore and produce them.
3. Increased efficiency of resource utilization; introduction of resource-saving technologies, including recycling.
4. Transition to the utilization of derived (prepared, accumulated, physically- or chemically-treated) resources.
5. Transition from simple to “smart” resources, including various effects (physical, chemical, social, psychological, etc.) capable of providing the adjustment, adaptation, selectivity, creative utilization, etc. of resources.

***Line: Resource diversity***

<b>Type of Resource</b>	<b>Description</b>
Substance resources	Any substances and/or material available in the system or its surroundings, including environmental resources, finished or semi-finished products, waste, etc.
Field (energy) resources	Any energy available in the system and its environment – mechanical, thermal, chemical, electrical, magnetic, electromagnetic, etc.
Space resources	Any vacant space in the system or its environment. The most effective way to utilize a space resource is use a void instead of a substance.
Time resources	Any time before, after and between the cycles of a technological process; idle time and pauses that are unutilized or only partially utilized.
Functional resources	The potential of a system or its environment to perform additional functions; standard elements for multipurpose use, such as batteries, cartridges, bearings, fixtures, etc.
Informational resources	Any information about the system and its environment be obtainable from substances and/or fields leaving the system, including dissipation fields.
Systemic resources (super-effects)	New, useful properties or potential that the system can possess as a result of combining systems or parts of systems or forming new links and connections.
Specific resources	Unutilized properties (physical, chemical, geometric, etc.) inherent to the given system (e.g., resonance frequency, frequency transparency, magnetism, radiation, etc.).
Structural resources	Existing but unutilized structures, or structures easily created in the system (positioning or organization of system elements, etc.).
Differential parameters	Differences in parameters that can potentially be utilized for a useful purpose (temperature or pressure gradients; electrical potential; differences in the speed, center or periphery of flows; difference in altitude, etc.).
Resources of change	New properties or characteristics (often unexpected) that emerge as a result of changes in the system or its elements.
Evolutionary resources	Knowledge, theories, experience, know-how, patents, etc. that enable further evolution of the system.
Marketing resources	Existing or potential need/demand for a product or service; existence of targeted clients, brand names, etc.
“Pennyworth” resources	Having sufficient resources in the system, or inexpensive resources from outside the system such as water, wind, solar heat and light, sand, waste, dissipated energy, etc.
Harmful resources	Waste or other harmful substances or energy that are rendered harmless in the process of utilization.

***Line: Resource consumption***

1. Utilization of limited useful resources consumed in the process of utilization.
2. Utilization of unlimited useful resources consumed in the process of utilization (air, sea water, etc.).
3. Utilization of resources without their being consumed (catalysts, water as ballast, etc.).
4. Utilization of harmful resources consumed and transformed (rendered harmless) in the process of utilization.

***Line: Expanding the sources of resources***

Typically, the closer the source of a resource, the easier it is to utilize it. The typical places to look for resources are (in the order of preference):

1. The system itself.
2. The system's elements and sub-systems.
3. One or more super-systems of which the given system is a part.
4. The system's surroundings – the environment or adjacent systems.
5. Easily-accessible and inexpensive resources from other systems, including remote systems.

***Line: Interchangeability of resources***

1. Substituting one resource for another of the same nature (for example, one substance resource for another).
2. Substituting one type of resource for another (for example, replacing space resources with time resources, a substance with energy, etc.).
3. Substituting one type of resource for a combination of resources.

***Line: Resources from the environment***

1. Protection from the environment.
2. Passive utilization of the environment (as a foundation for shelter, land fill, etc.).
3. Active utilization of the environment, including:
  - Using an element of the environmental “as is” (as ballast, air for inflated constructions, etc.)
  - Using a modified element of the environment (using oxygen for burning, cooled water for cooling, etc.).

## **Intensification of resource utilization**

Although as most systems evolve their resources are used more effectively, a systematic approach to finding more effective ways to utilize resources can be helpful. This group includes the following lines:

- Resources and functions
- Increased effectiveness of resource utilization
- Combining resources
- Handling and transformation of resources

### ***Line: Resources and functions***

1. Utilization of resources to increase the effectiveness of the main function.
2. Utilization of resources to perform and/or increase the effectiveness of an auxiliary function.
3. Utilization of resources to reduce the cost of system functioning and of producing the system.
4. Utilization of resources to prevent/eliminate harmful functions.

### ***Line: Increased effectiveness of resource utilization***

1. Division of labor and specialization.
2. Technological improvements that reduce resource consumption.
3. Elimination of wasteful activities and loss of resources.
4. Dynamic planning of the production and consumption of resources in accordance with customer requirements.
5. Effective distribution of resources.
6. Restoration of resources.

### ***Line: Combining resources***

1. Utilization of one type of resource
2. Joint utilization of two or more resources of the same nature
3. Joint utilization of two or more resources of the different nature (for example, a substance and a field).
4. Utilization of one type of resources to transform another type of resource (for example, use a field resource to transform a resources substance).

***Line: Handling and transformation of resources***

1. Accumulation
2. Transporting resources to different locations (distribution in space)
3. Distributing resources according to a time schedule (distribution in time)
4. Concentration or de-concentration of resources
5. Small changes, including:
  - Separation, purification, concentration of materials
  - Transformation of energy without changing its nature
6. Substantial physical and chemical transformations, including:
  - Phase transformations
  - Chemical transformations (oxidation, decomposition, synthesis, polymerization, etc.).
  - Transformation of energy with a change in energy type

**Utilization of effects as a resource**

***Line: Basic groups of effects***

<b>Group</b>	<b>Examples</b>
Physical	A lever transforms force; a change in temperatures impacts the dimensions of an object; a change in turbulence changes the profile of liquid flow in a pipe, etc.
Chemical	Decomposition and synthesis of substances; oxidation; polymerization, etc.
Geometric	Möbius strip, parabolic shapes, etc.
Technical	Simple machines and devices such as gears, switches, etc.
Biological	Natural or artificial evolution of plants and animals, vaccination, co-evolution of predator and prey, etc.
Social	Emergence of certain organizational structures around flows of goods; supply-demand model; Pareto law; etc.
Psychological	Freud's superego; supplanting negative emotions; the effect of a smile; projecting one's emotions onto others, etc.
Evolutionary	Self-organization; the formation of fractal borders; feedback; etc.
Global	Coriolis force associated with the Earth's rotation; climate changes; hurricane formation; etc.

***Line: Effects associated with multi-step transition to the micro-level***

The utilization of effects is closely connected to the increased involvement of levels of matter, in particular:

1. Mega-systems – systems with dimensions (or coverage) substantially larger than a human (natural systems such as oceans and mountains; high-rise buildings; chemical plants; cruise ships; etc.).
2. Macro-systems – parts or objects with specific shapes that do not require special devices for handling or observation.
3. Macro-polysystems – combinations of elements with simple shapes (balls, boards, sheets, rods, thread, etc.).
4. Dispersed polysystems – powders, emulsions, aerosols, suspensions, etc.
5. Micro-systems – utilization of effects associated with micro-sized dimension.
6. Nano-systems – utilization of effects associated with nano-size dimension.
7. Systems using molecular phenomena and interactions (chemical transformations).
8. Systems using nuclear and quantum phenomena (ionization, isotopes, radiation, atomic orbits, etc.).
9. Systems using fields instead of substances.

***Line: Changing the aggregate state of a utilized substance***

1. Utilization of solid substances.
2. Utilization of liquid substances.
3. Utilization of gaseous substances.
4. Utilization of plasma.
5. Utilization of combinations and mixes of substances in different aggregate states (suspensions, colloidal solutions, emulsions, aerosols, foams, pastes, gas-saturated liquids, liquid-filled porous or capillary substances, etc.).
6. Utilization of substances in intermediate states (raisins, gels, overheated and overcooled liquids, super-critical liquids, etc.).
7. Utilization of transitions to a different state (melting-solidification, evaporation-condensation, etc.).

***Line: Utilization of more effective fields***

1. Mechanical fields, including:
  - Moving objects (displacement)
  - Gravity, inertia, centrifugal force, reactive force, coriolis forces, etc.
  - Shocks, vibration, pressure changes, acoustic fields (sound, infra- and ultra-sound), etc.
  - Aero- hydrodynamic forces – Archimedes force, stream pressure, hydrodynamic shock, vortexes, etc.
  - Resistance to deformation, mechanical tension and stress, elastic forces, etc.
  - Mechanical fields on molecular level: friction, surface tension, adhesion, osmosis, diffusion, etc.
2. Thermal fields, including:
  - Heating
  - Cooling
  - Thermal spatial gradients
  - Temperature changes in time (linear, cycling, or specific time schedule)
3. Chemical fields, including:
  - Synthesis and decomposition of substance
  - Catalysts and inhibitors
  - Especially active substances (ozone, fluorine, acids, etc.).
  - Inert mediums
  - Biological substances
  - Substances with strong scent or taste
4. Electrical fields, including:
  - Electrostatics: repulsion and attraction of electric charges, charging, discharge, etc.).
  - Electric current and effects associated with its passing through a substance – heating, creation of mechanical forces, magnetic field, electro transportation of substance, electrochemical reactions, arc, substance ionization, etc.
5. Magnetic field, including:
  - Permanent magnets, electromagnets, paramagnetism and diamagnetism
  - Magnetizing ferromagnetic materials, magnetic saturation; effects associated with magnetic field on substances.
  - Interaction with electrical currents and moving charges (attraction, repulsion, eddy currents, etc.).
6. Electromagnetic fields, including:
  - Light, infrared and ultraviolet, X-rays, Gamma-rays, radio waves, eddy currents, etc.

***Line: Utilization of two-field combinations***

<b>Fields</b>	<b>Explanation and Examples</b>
<b>1. <i>Mechanical field</i> combinations</b>	
Mechanical/ Mechanical	Activation of processes by applying two different mechanical fields, e.g., permanent pressure and vibration, or a combination of stretching and compression forces.
Mechanical/ Thermal	Heating and cooling under mechanical impact, e.g., as a result of shock, compression and expansion of gases, friction, deformation, etc.
Mechanical/ Chemical	Chemical reactions in the presence of mechanical impacts (steering, mixing, friction, etc.).
Mechanical/ Electrical	Creating electrical fields and associated effects using mechanical fields (e.g., charging by friction, substance pulverization, piezoelectric effect, movement of electrical charges and conductors with current, etc.).
Mechanical/ Magnetic	Impact of mechanical fields on magnetic materials (demagnetization and magnetization under shock and friction).
Mechanical/ Electro- magnetic	Mechano-luminescence, generation of high-frequency electromagnetic fields upon crystal destruction.
<b>2. <i>Thermal field</i> combinations</b>	
Thermal/ thermal	Process intensification by applying two different thermal fields, e.g., general and local heating, or a combination of heating and cooling.
Thermal/ Mechanical	Thermo-mechanical effects (changing properties of substances by heating or cooling).
Thermal/ Chemical	Changing chemical properties of substances and controlling chemical processes with temperature change.
Thermal/ Electrical	Creating and controlling electrical fields using temperature change (thermocouples, changing electrical conductivity, etc.).
Thermal/ Magnetic	Controlling magnetic fields using temperature change, e.g., disappearance of a magnetic field when heated above the Curie point; intensifying the field by heating, (Hopkins effect), etc.
<b>3. <i>Chemistry field</i> combinations</b>	
Chemical/ Chemical	Combination of two chemical processes.
Chemical/ Mechanical	Creating mechanical fields using chemical processes (e.g., burning and explosion).
Chemical/ Thermal	Heating and cooling in exothermic and endothermic reactions.
Chemical/ Electrical	Creating electrical current using chemical reactions (batteries, electrochemical elements).

<b>4. <i>Electrical field</i> combinations</b>	
Electrical/ Electrical	Combinations of two electrical fields, e.g., direct and alternating currents flowing in opposite directions; high and low voltage; positive and negative charges; etc.
Electrical/ Mechanical	Mechanical actions of charges or currents (attraction, repulsion, rotation of charged particles in electrical field, etc.)
Electrical/ Thermal	Heating created by electrical current passing through; cooling thermocouples with electrical current (opposite to the Peltier effect).
Electrical/ Chemical	Chemical action of electrical current (galvanic dissolution and deposition of metals and other elements, electro-osmosis, electrophoresis, etc.).
Electrical/ Magnetic	Electromagnetic induction, creating mechanical forces, etc.
Electrical/ Electromag.	Kerr effect – controlling the transparency of a substance using an electric field.
<b>5. <i>Magnetic field</i> combinations</b>	
Magnetic/ Magnetic	Attraction and repulsion of magnets (electromagnets); magnetic saturation using superposition of several magnetic fields.
Magnetic/ Mechanical	Mechanical phenomena created by magnetic field influence; attraction and repulsion, interaction with electrical charges and current conductors, etc.
Magnetic/ Thermal	Heating a substance with a magnetic field; cooling a substance with demagnetization, etc.
Magnetic/ Chemical	Impact of a magnetic field on certain chemical reactions.
Magnetic/ Electrical	Various effects produced by the interaction of magnetic and electrical fields – electromagnetic induction, etc.
Magnetic/ Electromagn.	Faraday effect – changing the transparency of a substance to light using a magnetic field.
<b>6. <i>Electromagnetic field</i> combinations</b>	
Electromagn./ Electromagn.	Coherence, light interference, interaction of original and reflected electromagnetic waves, etc.
Electromagn./ Mechanical	Ponderomotive force, light pressure, etc.
Electromagn./ Thermal	Heating by eddy currents.
Electromagn./ Chemical	Activation of various chemical reactions by electromagnetic field, light, UV, X-rays, gamma rays, etc.
Electromagn./ Electrical	Generation of eddy currents.

***Line: Increasing effectiveness of field combinations***

1. Applying a second field of the same nature, including:
  - Randomly directed
  - Orthogonally
2. Matching the frequencies of utilized fields
3. Matching the spatial parameters of utilized fields
4. Applying a second field of a different nature, including:
  - Matching the frequencies of utilized fields
  - Matching the spatial parameters of utilized fields
5. Superposition of several fields, including:
  - Matching the frequencies of utilized fields
  - Matching the spatial parameters of utilized fields
6. Field transformation

***Line: Increasing effectiveness of a certain field***

1. Permanent unidirectional field
2. Combining permanent fields of opposite direction
3. Permanent fields of different directions
4. Alternating fields
5. Pulsed fields
6. Combining permanent and alternating (pulsed) fields

***Line: Increasing field structure***

1. Uniform (permanent) field
2. Field with spatial structure
3. Field that changes in time according to a particular schedule
4. Matching a field structure (schedule) with the natural frequencies of the system or substances, for example:
  - Using resonance frequencies
  - Using standing waves whose wavelength is a multiple of the system dimension.

***Line: Changing field energy***

	<b>Increasing energy</b>	<b>Decreasing energy</b>
1	Concentrating (focusing) a field using a suitable substance or device.	De-concentrating (dissipating) a field using a suitable substance or device.
2	Accumulating small amounts of energy using a suitable substance or device, then quickly releasing the energy later.	Slow release of energy accumulated earlier using a suitable substance or device.
3	Release of energy inherent to certain substances (e.g., gun powder, explosives, etc.).	Dissipating additional energy using specific substances (e.g., melting or evaporating substances, chemical compositions with endothermic reactions) or devices (dampers, radiators, etc.).

***Line: Evolution of methods for obtaining fields***

1. Utilizing fields available in nature.
2. Transforming natural fields without changing their type (e.g., changing direction or intensity; reflecting or focusing light).
3. Changing the nature of a field (transforming a thermal field into light, etc.).
4. Generating a field using methods similar to natural ones, e.g., using a torch as light.
5. Generating fields using technical means, such as produced light with a laser or a luminescent lamp.

## **Non-linear effects in evolution**

### **Cooperative effects**

#### *Cooperative effect*

Typically the result of combining two elements is very predictable. However, there is always the possibility of an unexpected result, either desirable or undesirable. For example:

- The properties of a water molecule are not the summation of the properties of hydrogen and oxygen.
- Group or mob behavior is difficult to predict, even if all the individuals in the group are well known.
- Connecting two boats with a rod creates a catamaran – a boat with far greater stability than a single-keeled boat.
- Two electric generators switched in parallel can generate oscillations, resonance, etc. capable of destroying them.

From the above examples it is evident that some cases we obtain additional useful features (as with water molecules and the catamaran), and in other cases unexpected failures or accidents result (as with the generators). These new properties are typically referred to as *systemic*, *cooperative* or *super-additive*.

#### *Scale effect*

The scale effect, which is well-known in the chemical industry, occurs when the behavior of a chemical reaction changes (often in a disappointing way) when the reaction is moved from a small lab or intermediate plant to a high-scale production.

On a positive note, the new field of nanotechnology (the utilization of objects with dimensions less than  $10^{-3}$  mm) offers many exciting possibilities.

#### *Intermediate statistical effect*

A good pool player can foresee the result of the sequential collisions of several balls. With substantial effort, a mathematician can calculate the result of a dozen collisions. Statistical analysis can predict the result of hitting a large number (e.g., in the thousands) of balls – the more balls, the more accurate the result. At the same time, there is really no way to predict the behavior of a system on an intermediate level – there are too many systems for precise calculation and not enough for statistical analysis.

### ***Global connections***

The evolution of most man-made systems is closely connected to the evolution of other man-made or natural systems; these links grow closer as the systems evolve, with the following results:

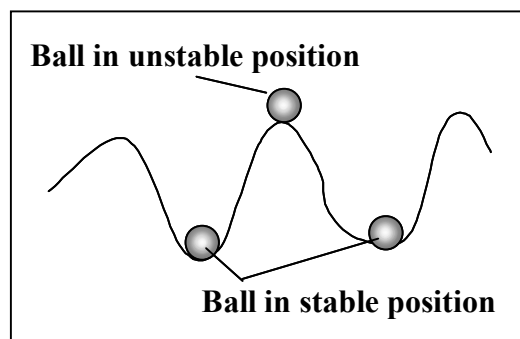
- Different technological systems create evolutionary resources for each other.
- Different technological systems impose limitations on each other's evolution.
- Changes in one technological system cause changes (both directly and indirectly) in other systems.
- As different systems evolve, feedback relationships can take place, including:
  - Positive (reinforcing loop) connections that accelerate the evolution of the systems involved (accelerated evolution of competing products).
  - Negative (stabilizing loop) connections, where the evolution of one system hinders the evolution of others.
- In many cases the predictions regarding the behavior of even thoroughly-studied systems fail, because feedback or other important connections have not been taken into consideration.

### **Regular-accidental (random, haphazard) effects**

#### ***Stability-instability***

A system is considered stable at a certain point if it tends to return to this point after sustaining a small deviating impact. If the system continues to deviate rather than trying to return to its initial position, the system is unstable (see Figure 12).

**Figure 12. Stable and unstable systems**



System instability can exhibit different natures, in particular:

- Equilibrium – when two (or more) forces are equal and none can prevail, an accidental event or a small third force can become the decisive element.<sup>35</sup>
- Strong fluctuations<sup>36</sup>
- Instability caused by a specific combination of parameters<sup>37</sup>
- Self-excited oscillations and resonance<sup>38</sup>
- Threshold effect<sup>39</sup>
- Trigger effect<sup>40</sup>

### ***Haphazard events***

Haphazard events in a complex, evolving system are capable of initiating a crisis or determining the direction of further evolution in a crisis situation. Often, certain actions of individuals seriously impact the course of history.<sup>41</sup> Things become even more unpredictable when several haphazard factors occur.<sup>42</sup> A haphazard impact can be amplified by uncertainty caused by the fact that, in a complex evolving system, it is often difficult to reveal actual cause-effect relationships when many factors of different nature and strength are at work.

### ***Attractors and trajectories***

In non-linear systems theory, attractors represent certain stable conditions or a working mode that is “attractive” to the system and which the system tries to reach on its own.

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<sup>35</sup> This is a common situation in certain parliaments when the “right” and “left” wings are equally strong; a small group or even independent members joining one or the other party can influence important decisions.

<sup>36</sup> From the Latin *fluctuatio*, meaning to move backwards and forwards – haphazard deviations of parameters from the average. In 1982 the American scientist Kenneth Wilson received the Nobel prize in physics for his research finding that a complex non-linear system at a critical point (e.g., a liquid or gas in a phase transition zone) is susceptible to principally unpredictable fluctuations of different scale – from atomic to macro-level, limited by the volume of the vessel containing the liquid or gas.

<sup>37</sup> In real systems, every parameter can vary within a certain range without creating serious problems. In non-linear systems, however, certain combinations of variations in several parameters can, in some cases, cause an abrupt loss of stability.

<sup>38</sup> Certain non-linear systems can produce oscillations of constant or growing magnitude that are capable of destroying the system.

<sup>39</sup> A system does not react to an external impact until the impact reaches a certain magnitude, after which the system reacts in an abruptly strong way.

<sup>40</sup> A threshold effect combined with energy accumulated in the system. The energy is released by a triggering action (as a gunpowder explosion is triggered by a spark or shock).

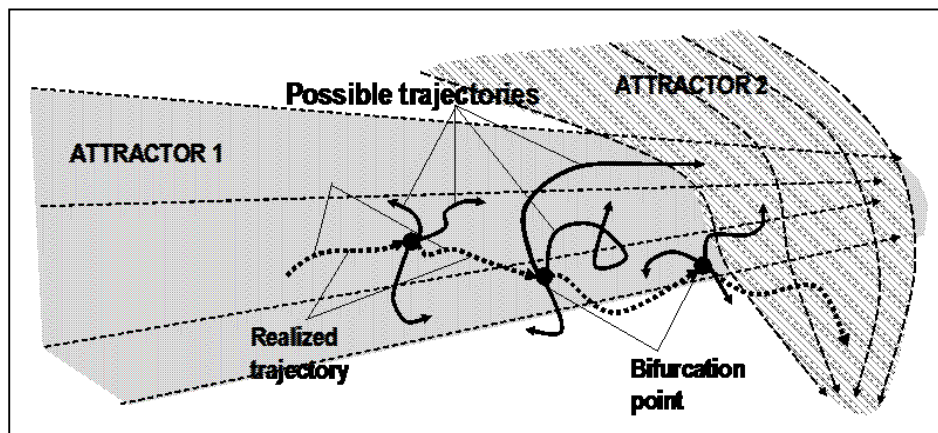
<sup>41</sup> During the rule of France’s King Charles V (called Charles the Wise for good reason), the English invaders were driven out, finances were in good order, and the country was stable. After his successor, Charles VI (Charles the Mad) came to power, the English returned and the Jacquerie revolt ensued ...

<sup>42</sup> In 1907-1908 devastating crop failure in Mexico together with recession in US caused huge loss of jobs for Mexican workers. It undermined the trust in the Mexican government trying (not very successfully) to make a transition to a free market economy and democratization. The result was a revolution and a civil war that pushed the country long back and cost enormous amount of lives.

The initial system position or situation notwithstanding, sooner or later the system will reach an attractor; if there are several it is difficult to predict which will be chosen (see Figure 13). In addition, the path by which the system approaches the attractor is not random but according to preference.

The attractors and trajectories that determine system behavior can be seen as certain trends and evolutionary patterns that a system follows. Although these trends and patterns do not eliminate the unpredictability of system evolution, they can substantially reduce uncertainty, explain what can and cannot be expected, and provide clues as to the most promising directions.

**Figure 13. Attractors and trajectories**



EXAMPLE:

For centuries people have studied history in the hope that it will shed light on evolution so that, ultimately, it can be controlled. Does history provide us with one lesson only – that there are no lessons to be learned from history? Early on in the evolution of science, Laplace stated that if he could get the spatial coordinates and velocities of every atom in the universe, he could predict the future. Today we know that bifurcation points make multiple futures possible – that is, the past impacts the future but not in an entirely deterministic way. At the same time, the study of history gives us a very important tool for prediction: the patterns of evolution of various systems.

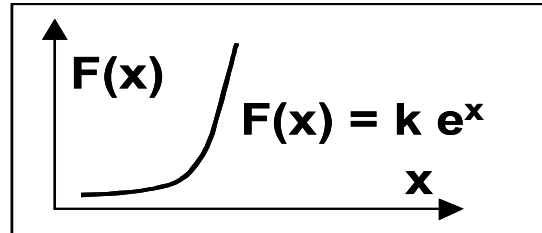
### **Feedback (loops)**

#### *Chain reactions*

Chain reactions occur in positive feedback situations (reinforcing loops), when the outcome is capable of amplifying the process itself, causing an increase in the outcome, and so on. For example, when a particular product becomes fashionable, the demand for it increases; as a result, more money is invested in production and development, which in turn makes the product more successful and thus more fashionable. This cycle repeats

itself to create a marketing “tornado.” Mathematically, the chain reaction (avalanche effect) is an exponential function that can be represented as shown in Figure 14.

**Figure 14. Chain reaction (avalanche effect)**



In addition to positive feedback, a condition necessary for a chain reaction is the accumulation in the system of a certain amount of energy (or something that can be transformed into energy). The ignition of a chain reaction forces the system into a process that cannot be stopped until all available energy is consumed.

The evolution of technology offers many examples of innovation tornados; these are typically activated by a specific invention that often appears insignificant at first. However, if this initial invention exposes and taps into a new source of rich evolutionary resources, it serves as a trigger igniting a powerful avalanche of new possibilities.

**EXAMPLE:**

In 1840, a lamp that burned whale oil in a specially-shaped glass was invented. This remained a “small” invention until 1855, when kerosene was invented. Kerosene had the following benefits: It produced a pleasant, bright white light; it was smokeless; and it was safe (other gas lamps had a tendency to explode).

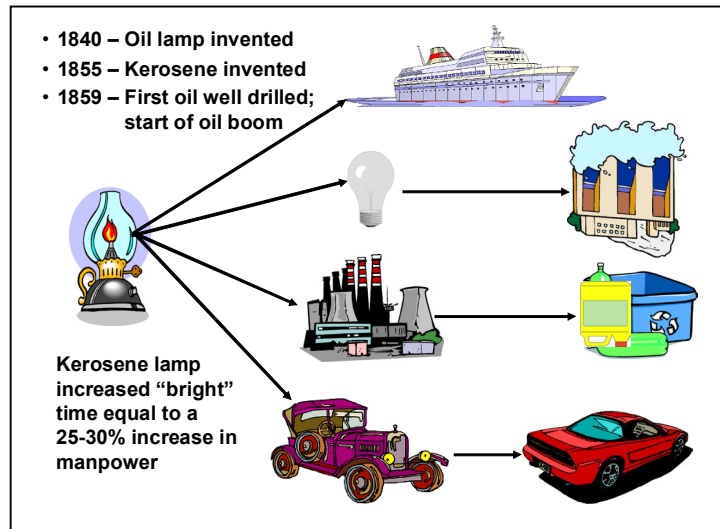
The invention of the kerosene lamp abruptly increased the demand for oil which, at the time, was available only from oil pits. To satisfy the growing demand, exploration and new oil production methods were necessary; in 1859 the first successful oil drill launched the oil boom (see Figure 15).

The introduction of a bright, inexpensive and safe source of light allowed for a longer work day, night shifts, and more time for reading, education, entertainment, etc. The need for good illumination activated by this invention stimulated the development of electrical power and of the electrical industry in general.

But mass production of kerosene created a problem: What to do with the by-products, such as gasoline, that were unusable for generating light because they were explosive, or the heavy oil components containing complex hydrocarbons? Ultimately these by-products became inexpensive fuel for the growing automotive industry, as well as a rich source of raw material for the emerging chemical industry.

At the same time, the utilization of oil fuel instead of coal eliminated the most serious drawbacks to the expanding military and civil fleets (steam boat engines that burned coal required a lot of stoking).

**Figure 15. Kerosene lamp avalanche**



The kerosene lamp is a good illustration of a modest invention that activates an avalanche (“invention tornado”), namely, the industrial evolution. Other illustrations are the invention of typography, gunpowder, production of hay, cotton gin, personal computer, the Arpanet (which enabled the Internet), etc.

Chain reactions can be also very dangerous and often catastrophic. A typical example of a harmful tornado are the results of the September 11 terrorist attack.

The planes that hit the World Trade Center towers started an intense fire. Burning airplane fuel weakened the towers’ structural elements, causing certain floors to collapse. The weight of the upper floors impacted the lower floors, causing the towers themselves to collapse ... At the same time, the overall damage was not limited to the enormous number of casualties and loss of airplanes and property. The attack halted air transportation and caused huge losses for hotels, resorts and the tourism industry, resulting in the loss of numerous jobs and eventually multiplying the damage by hundreds, hurting the economy of the U.S. and, in turn, the world.<sup>43</sup>

### ***Homeostasis***

Unlike positive feedback, which causes avalanche-like chain reactions, in a negative feedback (or stabilizing loop) situation, an increase in outcome (for any reason) weakens

<sup>43</sup> For example, it caused the bankruptcy of the Swiss airline Sabena.

the system's process and reduces the outcome so the system can return to its original state. This effect was discovered in chemistry by Le Chatelier, who in 1884 proposed one of the central concepts of chemical equilibrium: *A change in one of the variables that describe a system at equilibrium produces a shift in the position of the equilibrium, counteracting the effect of this change.* In other words, Le Chatelier's principle states that any system in stable chemical equilibrium subjected to an external cause which tends to change its temperature, pressure, concentration, etc. can only undergo internal modifications that compensate for the external cause.

A similar effect in biology is called **homeostasis** – the ability of a live organism or cell to maintain internal equilibrium by adjusting its physiological process. Homeostasis can also be observed in social systems, when any group or organization established to perform a certain social or business function strives to ensure its survival under unfavorable conditions or influences.

In general, homeostasis can be described as a situation wherein a certain influence on an evolving system creates a system response that tries to compensate for this influence. In certain situations the response can be much stronger than what is necessary for compensation. In this case the excess can be directed to influence the origin long after the influence has stopped, or re-directed to a different subject altogether.

The phenomenon of homeostasis can explain why certain partial or incomplete actions can be more dangerous than no action at all. While in usual situations 50% of the desired result might be satisfactory, in a homeostatic system incomplete action can activate a strong resistance (counterforce) or create a vaccination effect that will protect the system homeostasis from further influence. Unlike biological systems, in which homeostasis provides protection from both death and excessive growth, social systems under favorable conditions can grow continuously, producing enormous empires, bureaucracies, political parties, scientific movements, etc. Such a situation, where changes are limited to one side only (preventing death) can be called *asymmetric* or *evolutionary homeostasis*.

### ***Evolutionary S-curves***

No avalanche-like process can last forever. Sooner or later it slows or even destroys the system in which it takes place. In technology, typical reasons for this slow-down are associated with resource exhaustion, in particular:

- Depletion or the growing cost of natural resources (coal, oil, water, etc.).
- Exhaustion of the potential of an idea or design; physical limits imposed by nature (e.g., the impossibility of increasing the speed of propeller-driven aircraft above 500 mph).
- Limitations imposed by a social system (rejection of nuclear power; other environmental issues).
- Absence or exhaustion of the market for a specific product.

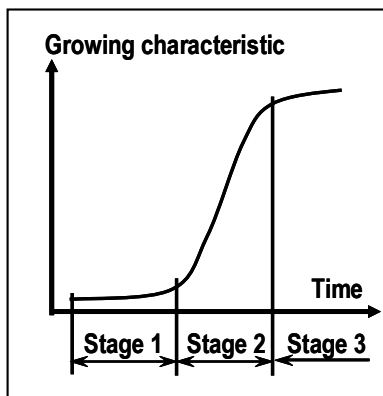
In certain cases, system evolution stops because the harmful effects associated with the system grow faster than the benefits; for example, increases in aircraft speed and transition to supersonic commercial planes almost stopped because of the noise produced at high r speeds.

Often, a combination of several reasons is possible; for example, the growth in oil tanker capacity was fairly high in the 1970s and 1980s; it slowed down later due to the unacceptable dangers associated with possible accidents, the technical problems associated with handling super-large tankers in ports, etc.

Mathematically, the rapid growth followed by the slowing and eventual stop in system evolution can be described by an S-curve.

S-curve evolution was first discovered in the 1890s, when the behavior of a colony of microbes and other biological objects was being studied. It was later shown that the evolution of numerous systems of different types (technologies, hurricanes, empires, etc.) can be depicted on an S-curve (see Figure 16).<sup>44</sup>

**Figure 16. S-curve**

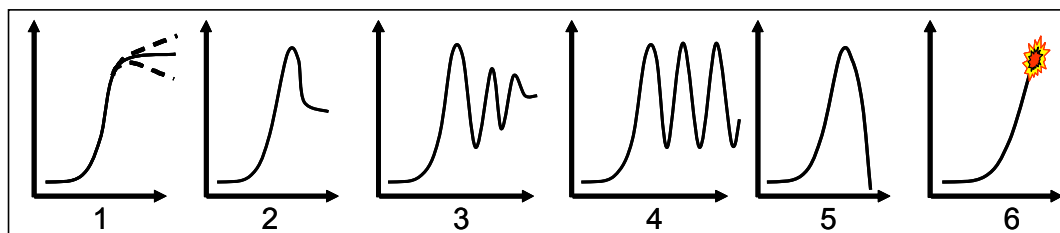


An S-curve is produced by the interaction of two processes:

- The ignition and rapid growth of a chain reaction based on positive feedback (reinforcing loop) in a non-linear system.
- The gradual weakening of a chain reaction due to exhaustion of the resources necessary for it to “burn,” or the emergence of negative (stabilizing) feedback (homeostatic effect).

There are several scenarios that can stop exponential growth (Figure 17):

**Figure 17. Growth scenarios**



<sup>44</sup> G. S. Altshuller, *Creativity as an Exact Science*, trans. Anthony Williams (Gordon and Breach Science Publishers, 1984).

1. Slowing of exponential growth, transition to a stable or slowly changing (either up or down) process.
2. Dramatic drop after achieving a certain maximum, then stabilization (or slow changes) at the reduced level.
3. Dramatic drop as in 2 above, followed by a damping oscillation that eventually transforms the process into a linear process.
4. Transition to continuous oscillations.
5. Rapid demise
6. Collapse

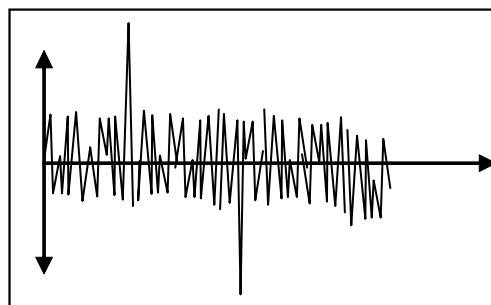
## Self-organization

### *Dissipative structures*

As mentioned earlier, only complex non-linear systems in an unbalanced position can evolve. To continue evolving, a flow of energy and/or substances should pass through the system, producing certain gradients in temperature, concentration, pressure, etc., which in turn produce forces capable of changing the system's structure in space (shape changes) or in time (oscillations, pulses, etc.). These structures are called *synergistic* or *dissipative* structures. The process of establishing dissipative structures has certain features:

- Dissipative structures emerge within a certain range of energy/substance flows: too low a level has no effect on the system; too high a level results in chaotic change or destruction.
- A new structure typically emerges in the system's center and slowly propagates to its periphery, supplanting existing structures.
- Several centers for the new organization are possible; in some cases they can compete, absorb one another, merge, or synchronize. The strongest center can impose its structure on the others. It is also possible that different centers will interact to create complex borderlines, including fractals (Figure 18), honeycomb or cellular structures.

**Figure 18. Fractals**



### ***Sporadic spikes***

Sporadic spikes or an interruption in stability are characterized by spikes of high activity that replace relatively quiet or low-level activity. There is no specific pattern to the range of intervals between spikes, their magnitude, etc. These spikes can be observed in many different areas such as biological evolution, social and market processes, hydrodynamics, seismology, etc.

### ***Flicker noise***

Flicker (or pink) noise is observed in different complex systems, both natural and man-made). Its origin is related to the fact that complex systems (unlike simple ones) do not have their own inherent frequencies. The substantial portion of the system's energy is associated with fairly slowly-changing processes, often with an oscillation period greater than the lifetime of the system. This means that no matter how long we accumulate information about a certain system, there can always be processes that haven't yet manifested but might surprise us sooner or later. The existence of flicker noise signals makes huge fluctuations in the system possible, indicating an inherent inclination to catastrophe. That is, the system is always close to a bifurcation point.

### ***Self-organized criticality***

The theory of self-organized criticality is a modern study in the area of non-linear systems that proves that, in certain systems, crises are inevitable. As it evolves, a complex non-linear system moves to the next bifurcation point and eventually loses stability. In an unstable situation, any haphazard event can start an avalanche in an unpredictable place or at an unpredictable time, resulting in unpredictable consequences that can dramatically change the original system. Typical examples are:

- An aging individual or technological system is increasingly prone to illnesses and accidents.
- An aging organization tends to accumulate conflicts and “bureaucratic pork” such as superfluous employees (or sometimes entire departments), overly-complicated hierarchies, etc., which prevent the organization from functioning normally. Young newcomers joining the organization typically try to create change, but face strong resistance from “old style” employees. If the controlled structural changes are not periodically held, a crisis is inevitable.

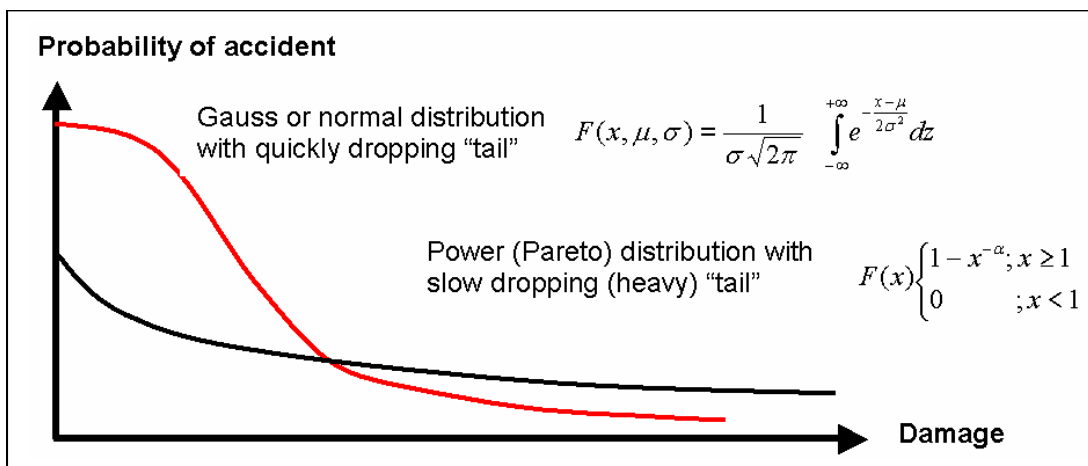
An unpleasant derivative of the theory of self-organizing criticality is that eliminating one potential danger (a possible bifurcation point) often increases the probability of another undesirable event. For example, an analysis of the work of various security groups has shown that, where resources are insufficient, attempts to protect certain vulnerable points force attackers to move to other zones, producing only geographical changes rather than improving overall safety. Under certain combinations of events, breaches of security might become even more dangerous. In other words, attempts to delay the crisis might be successful, but the attacking forces can regroup, strengthen, and strike in another unexpected place ... One possible conclusion is the following: if the situation is not good

and there are not enough resources for restructuring, it is better to do nothing to prevent widespread problems.

**Power function catastrophes**

It has recently been proven that major accidents and catastrophes associated with substantial damage and large casualties do not comply with the usual probability patterns of normal (Gaussian) distribution. The actual statistics for such catastrophes are described by the power (or Pareto) function. These functions have a “heavy tail distribution”<sup>45</sup> as shown in Figure 19.

**Figure 19. Damage/probability functions**



The difference in the two distribution curves is critical. In the normal distribution function, events with the highest damage are rare or negligible, thus they receive little consideration. In the power function distribution, the probability of these highly-damaging events becomes higher and thus cannot be ignored.

The power function (“heavy tail”) distribution curves are the result of chain reactions that are ignited by relatively insignificant events (which statistically have a sound probability) and cause an avalanche-like growth in damage. The probability of this course of events is relatively high because modern systems are rich in the energy and other resources that could become dangerous (fuel, hazardous chemicals, high concentration of people in certain places).<sup>46</sup> World statistics show that the number of powerful catastrophes in our increasingly complicated world is growing, as are the levels of the resulting damage.

<sup>45</sup> P. Embrechts, Kluppelberg and Mikosch, *Modeling Extremal Events for Insurance and Finance* (Berlin: Springer-Verlag, 1997), 645.

<sup>46</sup> Compare the damage produced by two events with the same probability: lightning striking a lone tree and lightning striking a warehouse stocked with explosives.

## Fractals

Fractals<sup>47</sup> were introduced by Benoit Mandelbrot<sup>48</sup> in 1975. In his book *The Fractal Geometry of Nature* he gives a simple explanation of a fractal. According to his concept, the length of the shoreline of the British Islands depends on the length of the measuring tool. For example, the least accurate measurement will be made using a ruler one kilometer long – such a ruler can't following the shoreline of a bay or cape less than 100 meters long. If a smaller ruler (one meter long, for example) is used, the measured length will be much greater. With a ruler one millimeter long, every little stone along the shoreline can be included, increasing the length many times over. According to this concept the real length could, theoretically, be infinite.

The main feature of a fractal is that it consists of parts that look like miniature copies (though not necessarily exact copies) of the whole. It has been shown that evolutionary processes and self-organization processes result in the emergence of fractals. From the mathematical point of view, a tree leaf or biological population could be described as a stochastic fractal – a particular combination of random and deterministic events.

With respect to the evolution of an organization or of society, a fractal nature means that a certain congruence in structure and functionality exists on different levels of an organization. In these terms, effective control of evolution of human civilization on its highest level requires effective management at the lower levels – countries, districts, enterprises ... even to families and individuals.

Fractals are responsible for the existence of patterns in the evolution of systems having different natures, of a certain repeatability of events that inspired the expression “there is nothing new under the sun” – life goes in cycles or spirals with many repetitions. The fractal nature of evolving systems allows evolutionary patterns to be revealed and purposefully applied for the purpose of controlling evolution; however, we cannot reduce these processes to exact mathematical formulas because there will always a place for chance, creativity, individuality ...

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<sup>47</sup> From the Latin *fractus* – segmented, split, broken.

<sup>48</sup> Benoit B. Mandelbrot, *The Fractal Geometry of Nature* (New York: W. H. Freeman & Company, 1982).

## Appendices

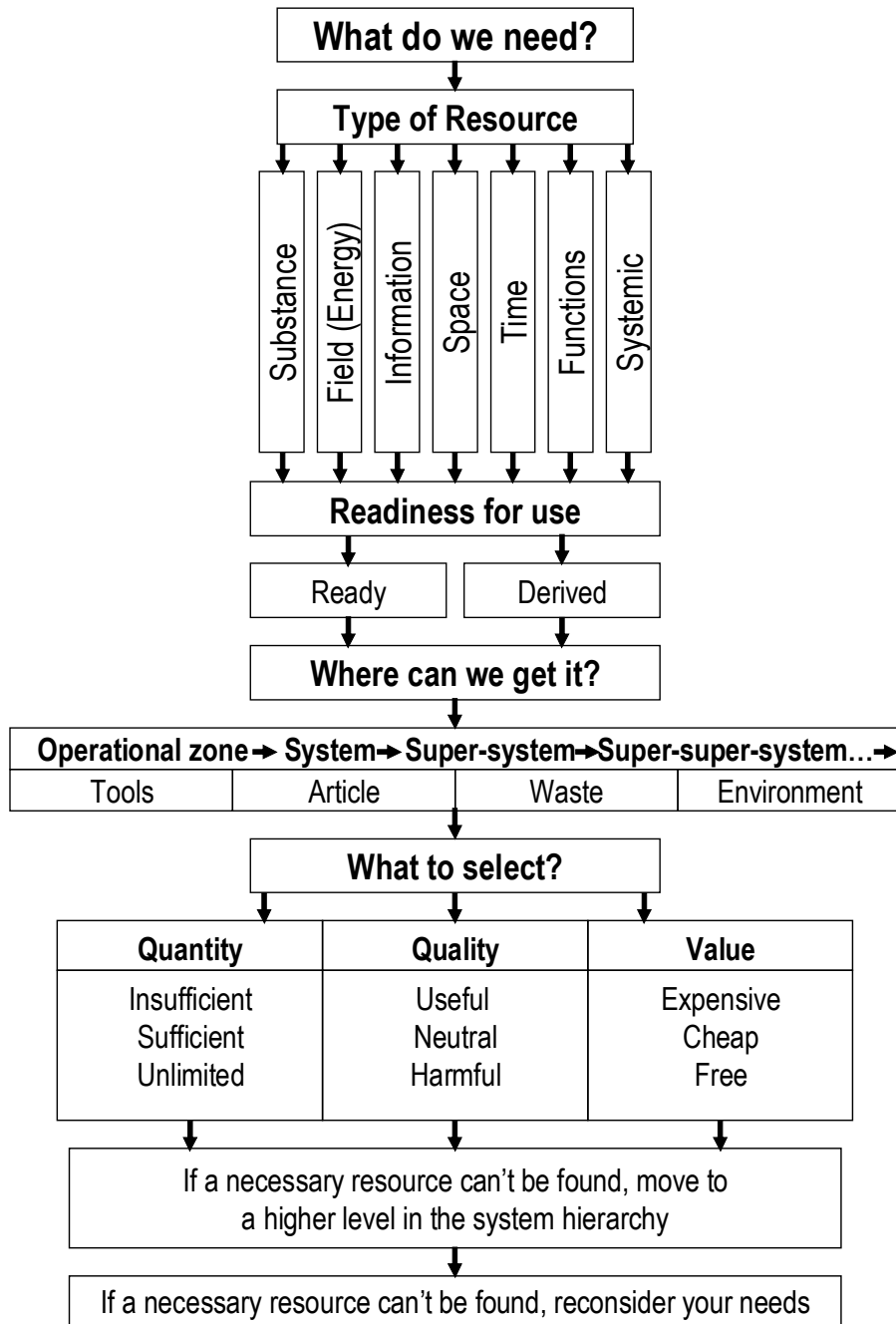
### Appendix 1. Hidden resources in product development

Characteristics of a resource	Signs that a resource exists	Reasons the resource exists	Ways to detect a resource
1. Excessive specification requirements	Incomplete utilization of product capabilities. Wide product utilization in conditions beyond the product specification.	Shortage of objective information about real customer needs and working conditions. Absence of economical consideration of excessive features. Excessive assurance.	Analysis of the conditions of the product's use, and of experience in its use. Revealing the real requirements for a product.
2. Excessive parameters for the product compared to the specification requirements (strength, reliability, power, precision, etc.)	Significant excess in parameters compared to competing products. Absence of problems (failures, recalls) during mass production.	Over-cautiousness of producers and designers. Absence of elaborated design calculations. Insufficient consideration of economic criteria.	Comparisons with competing or similar products. Analysis of product performance. Calculations confirming the correct selection of parameters.
3. Excessive conservatism of design and/or technological solutions in products that are new or have existed for a long time.	Discrepancy between the level of product performance compared to existing world standards. Obvious violations of patterns and lines of technological evolution.	Insufficient study of scientific and technical information, especially patent information. Lack of innovation skills. Psychological inertia, fear of the new. Absence of revisions in design and technology over a long time period.	Comparison with competing products. Analysis of the product's evolution. Verification of the possibilities for modifying the product using new, enabling technologies.
4. Unforeseen harmful interaction between the parts of a product, between the product and other related products, or between the product and the environment.	Failure with unknown root causes manifested after testing or in the process of operation.	Insufficient study of scientific and technical information. Absence of a systematic approach to product development.	Systematic approach to various kinds of interaction (mechanical, chemical, electrical, etc.) and combinations of these. AFD Failure Analysis approach.
5. Incomplete, poorly developed design and/or technological process.	Excessive amount of modifications to the design and manufacturing process, suggestions for improvement, compromises. High rate of failures and claim reports. Presence of bottlenecks	Missing stages in the process of product development. Lack of attention on the part of developers to the testing and operation of the product. Lack of communication between company	Analysis of design and technological modifications, useful suggestions, production bottle necks, warranty problems, etc.

	<p>in the manufacturing process, deviations from work schedules, complicated technological map.</p> <p>Low equipment utilization factor.</p>	<p>departments responsible for R&amp;D, production, design, etc.</p>	
<p>6. Poor coordination between separate parts of the product.</p>	<p>Separate design of parts of a complex object, lack of capitalization on super-effects produced by integrating parts.</p> <p>Presence of design elements that carry out only connecting, coordinating functions.</p> <p>Presence of harmful interactions between parts of the product.</p>	<p>Absence of fruitful coordination between the subdivisions developing different parts of the product.</p>	<p>Analysis of connections and interaction between the units and parts of the product.</p>
<p>7. Presence of elements (units, parts, etc.) that do not perform useful functions.</p>	<p>Absence of modifications in the drawings of parts connected to the modified parts.</p>	<p>Modifications of product parts without coordinating with the modifications of other parts (non-systematic approach to modifications).</p>	<p>Analysis of product modifications.</p>
<p>8. Groundlessness of certain secondary design solutions while the basic solutions are well-grounded.</p>	<p>Excessive labor or material consumption of some parts that is not justified by performance.</p> <p>Failure of auxiliary parts during their operation.</p>	<p>Insufficient attention to secondary elements.</p> <p>Forced, temporary solutions that have remained in the production documentation despite the disappearance of the reasons for these solutions.</p>	<p>Analysis of separate product elements.</p> <p>Estimation of element cost versus value from the point of their accordance with their functions.</p> <p>Comparison to parts with the same functions in other devices.</p>
<p>9. Poor design solutions that do not prevent the product from functioning but increase its cost; these shortcomings are easy to eliminate.</p>	<p>Excessive safety margins, presence (intentionally) of parts that are too heavy, extra treatments, excessively high purity and precision, extra coatings, etc.</p> <p>Design overburdened by excessive number of ancillary parts, elements (fasteners, holes, slots, etc.).</p> <p>Availability of a variety of performing units of the same in the same plant.</p>	<p>Resources for the later improvements.</p>	<p>Systematic analysis of the product.</p>

10. Insufficient level of product unification and standardization. Limitation to standardization by simple parts, fasteners, and so on.	Unification of several standard product sizes in the case when every size is mass produced separately.	Insufficient attention and formal attitude to the unification issue. Absence of fruitful contacts between different design subdivisions.	Comparative analysis of ancillary parts and elements, the same units designed by various design subdivisions. Comparative analysis of various standard sizes of the product.
11. Excessive level of product unification and standardization.	Excessive heaviness or obvious fragility of life-size products. Absence in drawing details at the 1:1 scale.	A formal attitude to the issue of unification.	Analysis of the quantity of manufacturing unified parts and utilizing them.
12. Errors and shortcomings in the design, caused by psychological factors: Conflicting requirements due to scale (up or down) design drawings. Excessive weight or complexity of a part due to it symmetric or rectangular shape. Discrepancy between product shape and the materials utilized.	Unnecessary symmetry of parts from a functional or technological point of view, an even number of attachment points, ribs, etc. Manufacturing of different product parts (mechanical, electrical, electronic) by the same specialist.	Due to peculiarities of human perception, the parts drawn to scale up seem less straight than in reality, and vice versa: the parts, drawn to scale down, seem more durable. The habit of designers to "see" the product as a drawing. Subconscious desire to make a part suitable for drawings rather than performance. Psychological inertia.	Study of life-size details. Making of simple models and drawings at the 1:1 scale. Control of reiterating design elements. Analysis of the product by a team of specialists knowledgeable in various areas and from various subdivisions of the company.
13. Low level of product adaptability to manufacturing.	High rejection and reclamations rate, bottlenecks in manufacturing process, unevenness of work, complicated technology, low level of utilization of equipment, high rate of manual labor.	Absence of fruitful contacts between design and manufacturing subdivisions. Weakness of tool supply. Manufacturing of products that were designed to be used in a different technological process (e.g., for another company).	Comparison of specified (as stated in the documents) and actual manufacturing processes. Analysis of technological deviations. Comparative analysis of manufacturing of various products.
14. Production is difficult to automate.	Substantial number of manual operations, complex shapes of parts, complex tooling.	Attempts to automate production of product designed for manual manufacturing, no design adaptation to automated production.	Element analysis of parts. Analysis of tooling.
15. Product design and/or technology does not fit the manufacturing process type.	Higher than usual rate of manual operations.	Product designed for small-scale production comes into high demand; no design adaptation to mass production.	Analysis of product's design history and dynamics of growth in production.

## Appendix 2. Algorithm for revealing resources



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