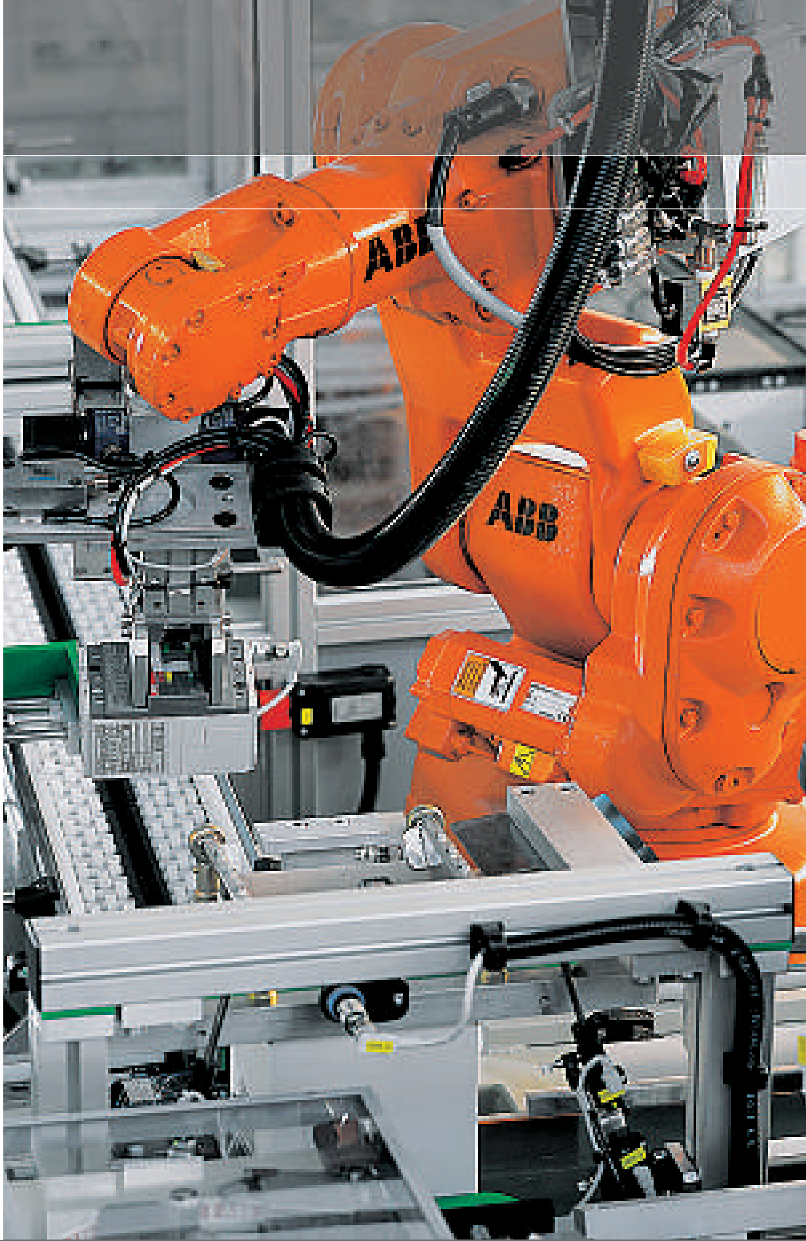

The science of manufacturing

Efficient manufacturing processes are based on fundamental factory physics laws

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Man has been "manufacturing" since he first walked the earth. Of course, manufacturing has evolved significantly since then and it keeps on evolving. New philosophies and buzzwords regularly appear that seem to be the answer to every manufacturing manager's prayer, only to be replaced later by better philosophies and cooler buzzwords.

While most of these do contain a certain element of truth, what is more important is that managers have a profound knowledge of the fundamental laws that govern manufacturing processes, in order to apply the appropriate tools and philosophies in a correct and balanced combination. In other words, there is a need to understand the "science of manufacturing".

What is meant by the "science of manufacturing"? In a nutshell, it refers to the fundamental physics of a specific manufacturing process; not only the details, but how the parts of a production line work together as a system. The Egyptians, for example, were skilled in applying the laws of physics when constructing the pyramids. However, as mass production – and therefore speed – were clearly not issues at the time, the Egyptians were not confronted with the flow dynamics that come into play when talking about the mass production of goods or continuous processes. For this, we need to fast-forward to the first industrial revolution.

Until the middle of the 18th century, goods were mostly produced one piece at a time by skilled craftsmen. Then several inventions helped bring about what is termed the industrial revolution, when extensive mechanization of production systems resulted in a shift from home-based hand manufacturing to larger-scale factory production. The most important of these inventions was the steam engine (James Watt). The use of steam power not only allowed the localization of industrial operations without being constrained by the availability of water power, but it also provided cheaper power, enabling lower production costs, and lower prices.

Another invention came around the turn of the century (1799–1801) from the gunsmith Eli Whitney. He introduced the concept of interchangeable parts to enable products to be assembled and repaired quickly without having to rely entirely on the craftsmanship of skilled individuals. Uniformity was also achieved by having machines with jigs that made each separate part of a gun. It is clear that the foundations of the assembly line were laid early in the 19th century.

Other important innovations included those in transportation (the railways) and communications (telegraphs) which were instrumental in providing the necessary distribution mechanisms for goods and information.

The modern integrated industrial enterprise started to take shape in what is called the second industrial revolution. All elements for mass production and distribution were now in place.

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The advent of mass production

The one person who will forever be associated with the advent of mass producing standardized goods using dedicated machines and moving assembly lines is Henry Ford. The moving assembly line was introduced in his car factory in 1913. The implementation of conveyors eliminated the extra handling and waiting between each station. Ford brought to life the thoughts expressed by Frederick Winslow Taylor in "The Principles of Scientific Management" in 1911 in that he created a continuous flow by "taking the work to the man" instead of "taking the man to the work". This was basically the birth of lean production in which one of the main focal points is waste elimination. This was later copied and perfected by Taiichi Ohno and his team at Toyota.

In hindsight, however, the introduction of the conveyor seemed somewhat overshadowed by Ford's recognition of the strategic importance of speed. He saw that a fast process has a positive impact on throughput and inventories and would therefore enable him to keep his costs lower than those of his competitors.

Discovering the nature of variation

While Henry Ford reduced product variability to an absolute minimum (only black cars were manufactured) in his efforts to achieve production speed and drive down overall costs, there were others who concentrated on "fine-tuning" the process as a way of improving product reliability. For example, the engineers at Western Electric's Bell Laboratories experimented with various process adjustments in an attempt to improve the quality of their transmission systems, with little or no success. The statistician Walter A. Shewhart eventually concluded that any adjustments made to a process to correct fluctuations that are within the level of the random variation will only increase the variation in the process and thus degrade the performance. In other words, using intuition and best intentions – or trial and error – is like navigating through unknown territory without a compass and map. His findings led to the birth of Statistical

Generator assembly in Baden, Switzerland, 1895

Process Control (SPC)[1] practices, which were later adapted and further developed by two former Western Electric employees, Dr W. Edwards Deming and Dr Joseph M. Juran.

Shewhart's work, published in 1931 under the title of "Economic Control of Quality of Manufactured Product", was a major scientific contribution to the entire manufacturing discipline.

The modern quality tools of today, such as Six Sigma Textbox 1, are directly derived from these findings.

The reductionist versus the systems approach

In his efforts to develop manufacturing management practices, Frederick Winslow Taylor divided the production system into separate simpler parts – reductionism – with the aim of improving each of them to maximize efficiency. He developed jigs, fixtures and other devices to support his goals of standardizing best practices, thus earning him the title of "the father of industrial engineering".
This reductionist approach is excellent when analyzing individual activities that make up the production of a part or an assembly. However, improving overall efficiency should not focus on improving each individual component of the process, but rather on how the components interact with one another and other sub-systems to form the complete production process. Performance optimization is then achieved based on the overall goals of the system.

A production system, like most real-life systems, consists of dependent events and variation. Because things

Textbox 1 Managing variation – the quality perspective

A modern manufacturing process often uses sophisticated technologies to supervise and monitor productivity and quality. These are essential, especially in a manufacturing world where managers and operators continuously seek to improve process performance.

Many different parameters must be controlled to bring about an efficient process that produces a product of exceptional quality. Accordingly, modern approaches and tools – such as Six Sigma, Design of Experiments (DOE), and SPC[1] – are required.

Of these, Six Sigma has earned itself a very good reputation. It is a disciplined, data-driven approach and methodology for eliminating defects in any process. To achieve six sigma level, a process must not produce more than 3.4 defects per million opportunities.

To enable a full understanding of the processes and to make continuous improvements, the implementation of Six Sigma requires the gathering, displaying and analysis of process data.

The statistical representation of Six Sigma describes quantitatively how a process is performing. The statistical and problem-solving tools are similar to other modern quality improvement strategies. However, Six Sigma emphasizes the application of these tools in a methodical and systematic fashion that leads to breakthrough improvements with dramatic and measurable bottom-line impact.

Six Sigma's measurement-based strategy focuses on process improvement through the application of improvement projects. This is accomplished through the use of a Six Sigma basic road map, DMAIC. The DMAIC – Define, Measure, Analyze, Improve, and Control – process is an improvement system for existing processes that fall below specification and which require incremental improvement.

To achieve the above-mentioned goals, Six Sigma uses many different statistical tools. However, the application of the SPC technique – and its associated control charts 1 – is the primary tool needed to achieve process variation.

SPC is a methodology for charting a process and quickly determining when a process is "out of control" (eg, a special cause variation is present). The process is then investigated using one or more of the process improvement tools (Pareto, DOE, Cause and Effect Diagram [C&ED], Failure Mode and Effect Analysis [FMEA]) to determine the root cause of this "out of control" condition. When the root cause is determined, a strategy is identified to correct it. The effectiveness of any changes can be verified using SPC 2.

The variation can be partitioned into two components: natural process variation, frequently called common cause or system variation (the naturally occurring fluctuation or variation inherent in all processes); and special cause variation (typically caused by a particular problem or extraordinary occurrence in the system/process).

Six Sigma methodology is a widely used in discrete and continuous manufacturing processes. ABB has experienced the far reaching benefits of Six Sigma and SPC in terms of quality improvement and profits

Within the company's research organization, an SPC system dedicated to monitoring and analyzing discrete manufacturing processes has been developed. A proven technique has been modernized, allowing ease of installation and effectiveness of decision support. It is currently being deployed, together with ABB's manufacturing execution system (MES), and is strengthened by the recent launch of a specific initiative within the group's Operational Excellence Program, which promotes the use of SPC systems in discrete manufacturing processes.

do not happen in isolation, a systems approach is needed when deciding how to best leverage performance. This is the single most important message from some of the great thinkers in the 20th century, which include W. Edwards Deming, Jay Forrester, Peter Senge and Eli Goldratt.

A good example of a system with variable and dependent events is a motorway at rush-hour. Each moving car is an event that is dependent on the movement of the other cars. The variables are different reaction times, driver skills, individual car performance, and tire and weather conditions. An increase in the number of cars will, at some point, create congestion, thus causing the flow to decrease. A "rubber band effect" is also created and is amplified along the congested queues. Drivers are forced to constantly adjust to deal with the erratic movement of the traffic.

The key to managing production is about understanding variation and its effects on the production and supply system as a whole.

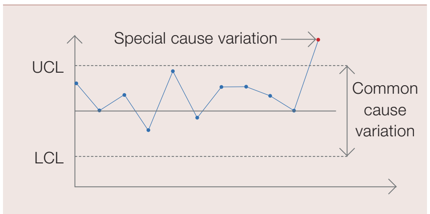
The same effect can be seen in production lines. With too many jobs on the shop floor, the flow is interrupted and the end result is poor overall productivity. This is where the reductionist approach clashes with the system approach. When striving for high local efficiencies in each sub-process, more jobs must be released to the shop floor than is optimal for a fast flow. The result will be excess Work-In-Progress (WIP), long throughput times and higher costs, not to mention reduced overall efficiency. This is another example of where intuition and best intentions without profound knowledge of fundamental relationships could lead to problems.

The most severe "rubber band effect" is usually seen in long Supply Chains, and is more commonly known as the "bullwhip effect". Increased delay in information and material transfer causes fluctuations in stock and availability. It would seem that the key to managing production is about understanding variation and its effects on the production and supply system as a whole.

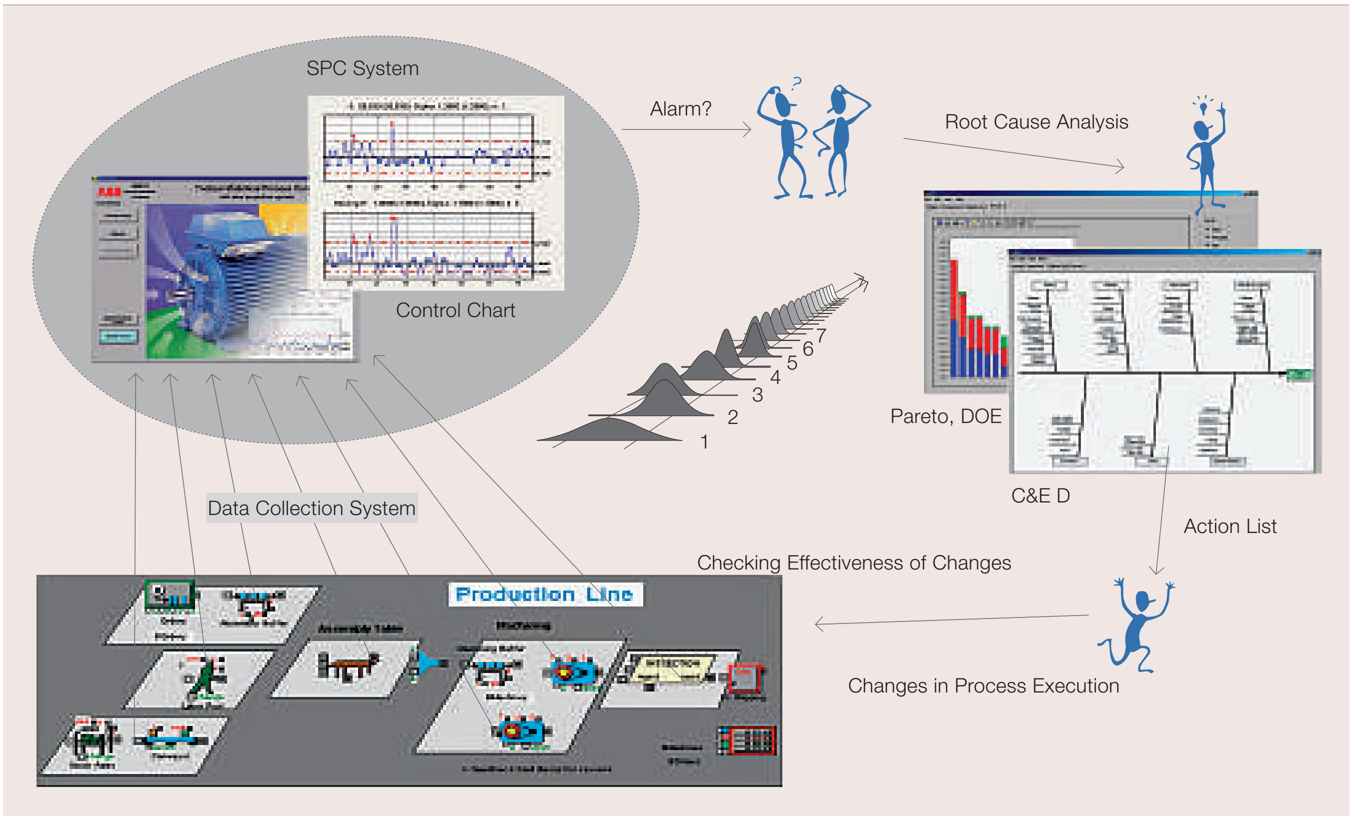
Managing variation – the flow perspective

One of the most fundamental laws of manufacturing implies that increasing variability always decreases the performance of a production system. This implies that by reducing variability, manufacturing processes become easier to manage and improve. Henry Ford and the famous Toyota Production System certainly thought along these lines. However what they seemingly failed to consider is that systems with a great degree of variation do

1 Control chart – common and special cause variation



2 Continuous reduction of variation – SPC basic road map



Manufacturing trends

have the potential to improve if smart ways of managing such variation are found.

Managing variation – concepts

It was only towards the end of the 20th century that industry started to exploit the potential of producing a variety of end products from a common set of standardized parts. Two manufacturing paths are therefore available – either reduce variation or manage it 3. ABB developed the concept of Common Pull Production Practices (CP3)[1] to address both these aspects at the same time. CP3 focuses on the way production is controlled, how materials and information flow through a factory, and the way in which suppliers' processes are integrated into such a factory. Lean Manufacturing[1] and the Theory of Constraints (TOC)[1] are the underlying philosophies behind these practices.

In pull production, customer orders trigger production as opposed to a system that produces parts or pieces to a predetermined schedule. This makes the manufacturing process more coherent.

A key role in the CP3 concept is the introduction of Pull with WIP control, which is based on another fundamental manufacturing relationship, "Little's Law" Textbox 2:

WIP[1] = Production rate (PR)[1] × Throughput time (TPT)[1]

There are numerous other laws or relationships that govern manufacturing operations, many of which – Table 1 [2] – are related to those mentioned above. Understanding these fundamental factory physics laws is a "must" for efficient manufacturing management.

At the beginning of the 20th century, electric motors began to replace steam engines as the main source of power for machinery. BBC alternating current motors for one-, two- and three-phase current played an important part in this development

Textbox 2 Little's Law

Little's Law states that at any given production rate the average production throughput time is directly proportional to the amount of WIP. There are several important ramifications of this statement including:

- Firstly, if the throughput time is increased, more WIP is needed to achieve the same output. It is clear that queue times added to Enterprise Resource Planning (ERP)[1] systems to compensate for day-to-day cycle time variation, is one of the root causes of excess WIP in many plants.
- Secondly, it indicates that speed in production can be attained by limiting the number of jobs released to the shop floor. By simply "capping" WIP, flow speed can be significantly increased.

Little's Law can be seen as the "Ohm's Law" of manufacturing:

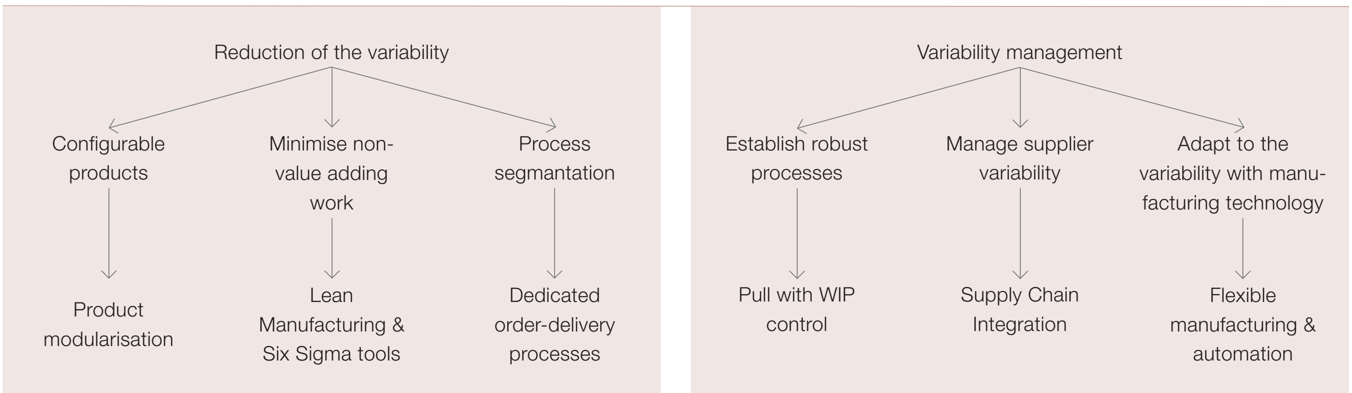
- If $R = \frac{V}{I}$, then $TPT = \frac{WIP}{PR}$ where: TPT represents the time required – **resistance** – for one product to flow through production.
- WIP represents the production **potential** in the system waiting to be completed.
- PR represents the **rate** of production flow.

Footnote

[1] See glossary an page 74. For TOC, see page 25.

[2] Adapted from "Factory Physics", Hopp and Spearman, 2000 2nd edition.

3 A set of options are indicated that either strive to reduce or manage variation



Understanding the manufacturing environment

It is important to understand each individual manufacturing environment. The variation and nature of interaction between activities differs depending on the environment. Let's first look at the process structure 4:

Table 1 A set of factory physics laws and fundamental relationships

Law (Variability):
Increasing variability always degrades the performance of a production system.

Corollary (Variability placement):
In a production line where releases are independent of completions, variability early in a routing increases cycle time more than equivalent variability later in the routing.

Law (Variability Buffering):
Variability in a production system will be buffered by some combination of inventory, capacity and time.

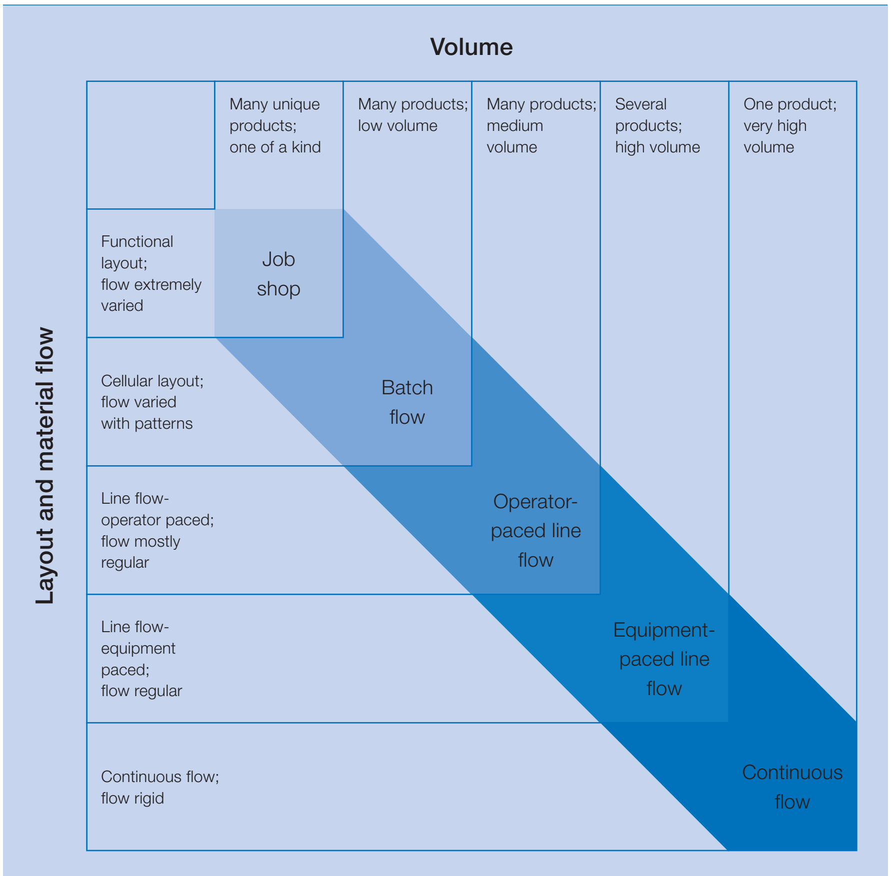
Corollary (Buffer flexibility):
Flexibility reduces the amount of variability buffering required in a production system.

Law (Capacity):
In steady state, all plants will release work at an average rate that is less than the average capacity.

Law (Utilization):
If a station increases utilization without making any other changes, average WIP and throughput time will increase in a highly non-linear fashion.

Law (Assembly Operations):
The performance of an assembly station is degraded by increasing any of the following:
- Number of components being assembled
- Variability of component arrivals
- Lack of coordination between component arrivals

4 The Product process matrix
(source: J Miltenburg, 1995: "How to formulate and implement a winning plan")



Environments located in the upper-left part have a much higher degree of variation than those in the lower right. The diagram also shows that "new" products initially produced in small amounts tend to position themselves in the upper-left part. After a successful product launch, and when initial systemic production defects have been ironed out, these products have the potential to move towards the lower-right corner.

This picture only presents one viewpoint. There are several others. The main lesson, however, is that each manufacturing environment is unique. The first step is to understand the fundamental physics of the specific manufacturing process, and especially how the parts work together as a system with special attention to the nature of variation within it. Without that understanding, any intuitive action might even make system performance worse.

If the challenges of variation are addressed with the right tools, process performance can be significantly improved. With CP3, excellent results are possible within six months. By mastering fundamental factory physics and extending this understanding to cover cross-enterprise collaboration, even more can be achieved. But that's another story.

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