AC 2008-1514: ASSESSING THE TRUE COST OF DELIVERING NANO-HYPE

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Abstract

Engineering and technology can have a massive impact on productivity and economic growth so it is important to track the likely course of new technologies as they grow from concept to maturity. Nowhere is this more important than in the case of nano-technologies. This broad category ranges from incremental CMOS developments to highly speculative new materials with novel functionality. However, roadmaps for strategic development need to be built on more than hype and promises. This paper describes a simple tool to measure the maturity of new technologies in many economic as well as technical domains. It ascribes one of ten stages of maturity to fourteen different parameters. A review of non-volatile memory technologies is used as a benchmark. The tool has been used to demonstrate technology evolution within academic courses and it has also been applied within short industry courses.

Project rationale and scope

The appeal of nanotechnology lies in the sheer breadth and potential impact of its applications. However, these features are also its greatest weakness. Hardly a week passes without some new nano-product or material being touted as the miracle solution that will drive the next wave of high-tech development [1]. The reality is that few of these claims will be realized in the form predicted. Even the developments that eventually succeed will have a tortuous and demanding evolution path. How does anyone make a balanced assessment of new technology that captures its novelty and the imagination of the innovators but at the same time acknowledges that realistic business criteria will also be applied? This paper describes a simple process to derive a measure of the maturity of new technologies in many economic as well as technical domains. It was initiated by a need to explain new technology in course work and has since been extended to research and development outcomes in several industry sectors.

Technology evolution rests on a brutally Darwinian process that is based on the interaction of engineering, economics and market opportunities. This makes any long term planning difficult yet there is every reason to believe that the scope and impact of technical change will be as profound in the next thirty years as it has been in the last thirty. However, it is difficult to find a balanced view of any emerging technology. The advocates obviously dwell on its strengths and sometimes their enthusiasm can drift into unsubstantiated hype and wishful thinking. At the other end of the spectrum, those involved with mature technologies are too busy managing products and cash flow in highly competitive global markets to be seriously concerned about a technology that may be a decade or more away.

A quantitative tool that measures the maturity of emerging technologies has a number of applications in the domain of Engineering Economics:

- It can determine risk in research and development (R & D) investment.
- It may be used for technology roadmap preparation and analysis.
- It shows where and when financial and market comparisons should be made.
- It demonstrates the wide range of factors needed for technology success and the vulnerability to a weakness in any one of them.
- It is a useful framework for student projects where some reasoned case has to be made for the likely evolution path.

Many parties have an interest in making objective assessments of the possible success of emerging technologies - from investors to students pondering their career direction. To make the task more tractable, cases that are judged individually on merit have been excluded. This avoids the minefield of research project funding, venture capital and peer-reviewed publications. Instead, this paper concentrates on cases where there is no single project advocate. The goal is to determine the maturity state and intrinsic merits of an emerging technology rather than measure the capacity of an individual or group to make it a success. To be successful as a distinct technology, it will have to rise far beyond the level of individual enthusiasms.

Background methodology

New technologies (of any kind) face three major hurdles before they can be considered a success in the business world.

1. If they offer a radically new application or market opportunity, there are too few customers to provide the revenue needed to support mature development. We may now feel smug when we read Ken Olsen's 1977 statement that, "there is no reason for any individual to have a computer in his home" [2]. However, in the context in which it was offered, he made a valid claim and the 30 years it took to move from lab curiosity to household item is still typical. This is the most risky category to predict success since every facet of the market is new.

2. If the new technology is a replacement for an existing product, for example a new memory or a replacement for CMOS logic, there is a cost target to be met. The great advantage is that many features of the market and its growth are known. However, until the new technology can approach the market cost-per-function, benchmark comparisons will be poor [3] and there will be a natural reluctance to move away from the familiar technology. The association of nano-$ with nanotechnology is uncomfortable but cannot be avoided.

3. International standards relating to quality, safety, environment, ethical applications and warranty have to evolve *and be met*. It is a long slow process to establish the required track record in these areas but if they are not met, the technology will not progress to successful maturity [4].

These three constraints are a formidable 'catch-22' that is rarely featured in technical papers and even less in degree programs. However, most of today's high-impact technologies had to overcome similar challenges [5]. The important message for students and technology executives alike is that innovation does not stop when the papers describing the original concept have been published. The typical evolution path starts with speculative funding (from government or private sources) and later proceeds to revenue and market-based support providing key conditions have been met. Unfortunately, there is a time gap between these funding regimes and it appears to be growing. It has been called 'The Valley of Death' [6] and is often one of the most severe bottlenecks in technology development. On the other hand, if an embryonic product or new technology can cross the Valley of Death, that becomes an important early indicator for further success.

The concept of an all-embracing metric to measure performance or maturity is well known. Four examples serve to illustrate the variety of background applications we have examined.

a. The Technology Readiness Index or Level (TRI or TRL) was developed by NASA more than 20 years ago [7]. It is widely used by the defense industry. There are 9 levels with brief descriptions in figure 1.

	Level	Features
	1	Basic principles observed & reported
Explore	2	Concepts or applications formulated
	3	Lab studies to validate concepts
	4	Components or sub-systems in lab form
Examine	5	Show components in relevant environment
	6	Prototype product in relevant environment
	7	System prototype in operational environment
Exploit	8	System technology qualified
	9	Technology has successful mission operations

Figure 1. Technology Readiness Levels

The TRI is important because it is accepted for risk identification and analysis. The levels are defined in great detail in the DOD literature but they can also be summarized concisely and usefully as shown in figure 1. The limitation of the TRI is that it was designed to assess components and cannot handle the diversity of concepts and expectations involved in determination of a whole new technology. It was the starting point for the work described in this paper.

b. The risk attaching to new products and systems may be represented using conventions that are standard project management practice. The parameters considered are probability, severity, screening and mitigation options. The first two are usually represented on a grid as shown in figure 2 [8]. A typical representation of values of probability and severity for 8 different project risks (A through G) is shown in figure 2. Risk F could be a vital sub-assembly that has a single source and that supplier is having financial problems. A decision to continue to use that supplier would require a sound monitoring and mitigation plan. Risk B could be a complementary case where the regular supplier may be having financial difficulties but there are others who could be used if needed.

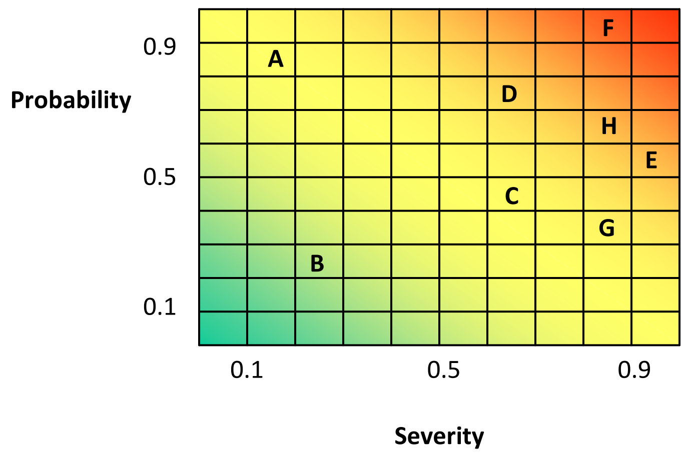

Figure 2. Project risk representation

Although the risk parameter values are highly subjective, the process has the advantage of documenting opinions that are used for decision-making. This is an important attribute of all assessment processes. Project contract conditions invariably require substantial documentation but it means a lot more in retrospect if it is structured within a clear and simple format as shown in figure 2.

c. The maturity or capability in a production process is represented by a number of industry-standard metrics. For hardware, it takes the form of a capability index (C_{pk}) that is based on process variation. For software, it is a staged process that uses CMMI criteria. In both cases, the goal is to achieve a predictably robust product.

d. When techniques a, b or c are not applicable, status can be determined by systematic interactive questioning and analysis. Examples are the Myers-Briggs personality test and tax preparation software. By posing a structured series of questions, a determination can be made of the status of a complex scenario. At a more fundamental pedagogical level, this is a variant of the Socratic dialog that is familiar and effective.

What these techniques have in common is that they break a complex topic down into several parameters that can be assessed independently. An extended version of this process has been developed to determine technology maturity. The novelty in this case is to extend the scope and to apply the resulting model to new applications to meet under-served needs.

Methodology

The goal was to create a tool that will give an objective numerical measure of the maturity of a technology. The first step was to compile an extended list of the factors that must be present for any technology to be accepted and widely used. Good coverage of all features can be obtained with fourteen such parameters. Collectively they are called the Nanotechnology Readiness Parameters (NRPs):

1. Validity of the science base
2. Intellectual property
3. Technology maturity level (above but with a #10 added)
4. Unique tools and processes
5. Manufacturability
6. Qualification procedures
7. Environment, safety and liability
8. Standards
9. Supplier readiness
10. Market readiness
11. Price expectations
12. A capable workforce
13. Educational support
14. Functional competitors

The general evolution path is that in its early stages, a new technology borrows heavily from existing (successful) technologies. Then as it matures and gains acceptance, the parameters become more specific. An obvious example is parameter #4: Unique tools and processes. Early stage development and prototyping use whatever tools are available. As the technology matures and revenue-generating products are produced, unique tools are created to provide the performance and control features that optimize capabilities of the new technology. Unique tools (hardware or software) are easily recognized in publications and company literature so their development can be easily tracked as a good measure of technology progress.

The maturity of each NRP is measured using a numerical scale from 1 to 10. Low numbers characterize an early stage of development. It is still a quasi-subjective process but it is easy to compare current capabilities of any technology against a list of maturity criteria. It is also a long list with 14 x 10 criteria. Some examples of numerical values for maturity of a few NRPs will serve to demonstrate the process.

1. Validity of the science base

1 = Observation only, no specific theory or theoretical prediction capability.
4 = Theoretical framework for a few major parameters.
10 = Uniform representation in textbooks.

2. Intellectual property

3 = Disclosures only.
6 = Field is well covered and IP has been challenged
9 = IP is securely established and licensing is prevalent.

5. Manufacturability

3 = Lab process with little documentation and data (< 10 GB).
6 = Routine process on pilot line with statistical data.
9 = Dedicated production with full statistical validation.

10. Market readiness

2 = Research prototypes seed product roadmaps
5 = Trials in selected products and applications
8 = Market star – fastest growing and > 20% segment market share.

14. Functional competitors

7 = Competing products available in volume from at least 2 suppliers.
8 = Volume products from >3 suppliers.
9 = Commodity item (sold mostly on price).
10 = Transition to end-of-life management companies.

A value for each parameter can be assigned very quickly by comparison with the ten levels in each NRP template. Each level requires a description that is distinct from its neighbors and can be supported by evidence. The capability of a technology is usually easier to define in terms of the products it can deliver so many parameters have product-related metrics.

Most development work on the assessment tool has been applied to nano-electronic functions. The consumer market gives a good demonstration of how products move through their life cycle in a year or less showing the familiar bell-shaped revenue curve. However, the underlying components and technologies can last for many product generations. They show the classical S-curve but there is an additional feature that makes prediction difficult. As one technology matures, it is replaced by a more advanced version. Thus there are many generations of maturity for the same basic technology. This is reflected in different maturity scores. For example, consider the CMOS logic used in the processors in current desktop computers. It scores 9 for Technology Maturity, but 8 for Manufacturability (complexity still lots of room for development) and 7 for Functional Competitors (only available from Intel and AMD). By comparison, the simpler microcontroller families that use older embedded processors score 9 or 10 for all three parameters. This is a good example of technology persistence.

One important adjustment of the assessment data has been made. The later stages of technology maturity depend on market success to generate the revenue for continued development. This implies many billions of dollars and is far beyond the capacity of government or venture capital agencies. Some type of non-linear scale is therefore in order to give more weight to the later stages of maturity. A simple expedient was adopted to use the square of the maturity rating value. Thus a level 6 on the readiness list for a parameter registers as 36 on the maturity measure. The parameters have not been weighted relative to each other. That is a more subjective process but it could be easily done in a later version of the tool.

Use case – New memory technology

Published material on any new technology tends to be patchy. It is usually narrow in scope and written by specialists for specialists. It can also have little competitive commercial value if it is to be made freely available. These factors conspire to make it difficult to make a realistic assessment of the standing of an emerging technology. The path to success is dominated more by the weakest features and these are rarely displayed openly. However, there is evidence – if the right questions are posed.

As an example, consider the case of non-volatile memory technology. It is a good example of an emerging nano-technology that is not too exotic but still offers new applications and market opportunities. Currently, the field is dominated by flash memory. Flash comes in two varieties – NAND and NOR. NAND has overtaken NOR in sales but for the purposes of this evaluation, they are very similar in terms of their maturity. Flash memory has reached the competitive level where it has become a commodity. In other words, it is bought on price/byte or the color of the package, not the brand or erase time. There is also the market expectation that every six months, we shall get twice as much memory for the typical $40 cost. Commodity status implies level 9 for market maturity.

Flash memory sets an intimidating standard for any competitors. Unless an application emerges with new performance requirements (but there is no evidence to show that is likely to happen), the benchmark will continue to be cost. Unfortunately, low unit cost is a feature of products made using only the most mature technologies so competitors face a stiff challenge. However, flash memory does have technology limits. Increased packing density (and hence lower cost) means smaller memory cells. If the lateral dimensions are reduced, the vertical dimensions of transistors have to be reduced too [9]. This is difficult for the case of flash where the storage mechanism depends on charge transport through an insulator. The physics of the process sets a minimum value for the thickness of the critical dielectric layer. This should put an end to the shrink process that has driven flash development [10]. It should also open the way to alternative memory technologies that do not suffer from the constraints of the flash memory mechanism.

Although this reasoning for the proximate demise of flash memory is valid, it has a glaring deficiency that is a challenge for all technology maturity assessment efforts. It does not give enough weight to the dynamics of development. Timescales are critical. Well-developed technologies usually have enough resources to find marginally better solutions and hold off debilitating constraints for longer than expected. Their would-be replacements, on the other hand, are invariably under-funded and it invariably takes longer to overcome their constraints than their advocates predict. For the case of flash memory, its demise has been only two years away for at least the past five years. Further analysis is limited by a lack of contextual data. The performance and limitations of state-of-the-art memory cells are closely held proprietary information so future progress has to be inferred from secondary features such as investment in next-generation wafer fab plants.

There are three acknowledged contenders to replace flash memory.

1. Magneto-resistive random access memory (MRAM) [11] is the latest in a long line of developments that have attempted to adapt successful serial access magnetic disk storage technology to a solid state format that is compatible with read-write-erase circuitry and X-Y grid access. MRAM structures have been in the pilot-plant evaluation phase for about 5 years but no serious products have yet emerged.

2. Phase-change memory (Ph-CRAM) also has a long history. It was a competitor for the first versions of flash more than twenty five years ago [12] and has recently emerged from a long hibernation as a contender. Like MRAM, it is a solid state version of a technology that is used in recordable disks where the shape of an energy pulse determines whether a small region of a compound semiconductor is amorphous or crystalline. In the disk case, the two states have different reflectivity. For the solid state cell, it is resistance difference that is detected.

3. Programmable Metallization Cell (PMC) memory also has a long history [13]. In this case, the change in state is caused by driving a filament of metal ions through a solid electrolyte. Unlike the other contenders, the filament can be reduced to atomic dimensions so it suffers from none of the technology constraints of the others. However, development is also less mature and has not yet reached the stage where early product specifications are being touted.

The assessment tool was applied to flash and its three non-volatile memory contenders. The ratings reflect status that can be substantiated from open-source data. For the contenders, there may well be additional proprietary information that could move the rating up. However, the upward shift would be by one level at most and would not apply to every parameter.

The ratings for the four memory cases are shown in the table below. The first column of data is the simple summation of the 14 maturity ratings. The second is the sum of the squares so the maximum value is ($14 * 10^2 = 1400$). The third column is the scaled score expressed as a percentage of the maximum.

	Raw score(/140)	Scaled score (/1400)	Scaled score (%)
Flash	114	962	69
MRAM	71	387	28
Ph-CRAM	58	252	18
PMC	52	206	15

The implications of the non-linear scaling are clear – and realistic. The maturity gap between flash memory and its competitors is at least as great as the scaled scores imply.

Although flash memory is a well-established technology, its score of 69% indicates that it still has some way to go. This is typical of technologies that are approaching their peak. Even if the cell packing density on flash memory does not increase much in future, there will be more embedded and stacked-die developments that will drive new markets for many years to come.

Overall scores have very limited use. They can serve to show when technologies are too immature to justify extravagant claims. Conversely, by the time a technology gets above 50%, it should have its own generic tracking data from industry-wide associations such as the Semiconductor Industry Association (SIA) or market analysts. Overall market growth can be predicted from general economic indicators so the technology growth questions are more concerned with what it takes to win market share.

The individual maturity scores are shown in figure 3. They are more useful in that they provide insight into the features where a new technology may have a significant strength or weakness.

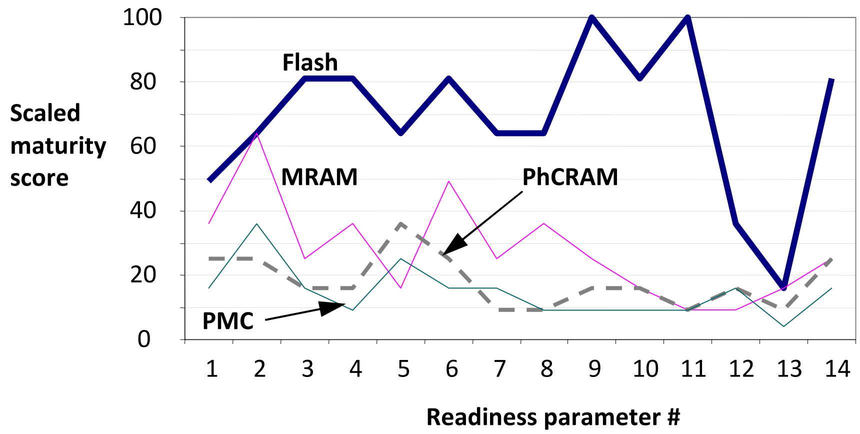

Figure 3. Memory maturity measures

All four technology contenders have been given low ratings for parameters 12 and 13 – existence of a capable workforce and educational support. The implications are considered in the next section.

Application within an educational program

The idea of having a maturity assessment tool started with a course need for a balanced view of future technology development. The authors have used it in four ways:

- As a simple instructor-led explanation of what's involved in taking new product concepts through the evolutionary life cycle. It demonstrates that market success has many facets. Working through the assessment process is a very systematic way to show the interaction of technical, business and personnel requirements and to provide pointers to further study.

- As a framework for individual or team activities to research the readiness parameters and find evidence to support the assessment. This involves significant learning and critical thinking within a constructive framework. However, it also demonstrates the difficulties in garnering non-explicit conclusions from a mass of published results.

- As a simple way to consider the viability of new technologies for a future career. At present, almost all career advice available to students is retrospective. It assumes that past business and technology trends will continue. A quick glance at the changes in industry over the past decade will show that is rarely true so students need their own appraisal process.

- As a risk assessment tool in short courses for industry executives. The structure and wide scope of the assessment criteria generate quick results from experienced participants. Examples from different companies can be compared; the outcomes are very similar for all high-tech industry activities.

One of the most significant attributes of successful engineering executives is that they have the ability to break complex problems down into simpler, more tractable tasks [14]. Strangely, this basic exercise in systematic analysis is rarely taught as a deliberate process in technical courses. Of course, its outcomes are evident in the structure of every course but students often miss incidental messages. Conducting a technology maturity analysis is a simple but thorough way of spelling out the steps to market success. Courses usually do well at explaining the concepts behind a technology but that is only the beginning. In a competitive world, the concerns about US competitiveness [15] will continue to be valid if the educational process does not hasten the progression of new technology along the path to maturity.

The assessment process has been incorporated into courses from freshman to graduate levels. One example will serve to illustrate the utility of the process. A junior-level class had a task to examine the One Laptop per Child (OLPC) project [16]. With such a wide-ranging task, the students initially found it difficult to move beyond a description of the published OLPC implementation plan. By applying the assessment tool, the class very quickly progressed in five independent dimensions:

- Define the intended mature state in quantitative and observable terms.

- Fill in the steps between today's technology and the mature version using the 14 categories as parallel development paths.

- Identify which paths are incremental and which need new solutions, especially unproven nano-technologies.

- Search for information to justify their ratings. This was an important move into explicit searches. It was much more productive than sorting through a million Google hits on the general topic.

- Add up the financial implications of all the development stages to determine a realistic cost to deliver the intended result.

It is interesting to observe the student response to the tool. Initially, there is caution and some trepidation when they see the scale of the task and so many terms they barely understand. That quickly turns to satisfaction that it is so easy to use and make good progress. Then the implications of finding and defending evidence hit home. The response to that challenge is a good discriminator between those who simply wish to complete the course and those who have realized that they are really doing a career planning activity and effort invested now is a precursor for job satisfaction to come. From a faculty viewpoint, it is a useful integrative activity that hits many ABET outcomes at once.

Conclusions

One of the most important outcomes from any application of the assessment tool is the emphasis it gives to the development-time domain. All too often, technology development is viewed as an obvious and automatic process that just happens at its own pace. The non-volatile memory example shows very harshly how new technologies require massive and unique advantages if they are to compete for funding and market space with a more mature established technology. Any delay in meeting development targets means that the success criteria have risen. The alternative – waiting for the leader to become obsolete – can take a very long time.

The initial applications of the tool to nano-electronic products pointed towards a single set of 10 levels for each of the 14 readiness criteria. Examples are given above. However, as the scope has been extended to energy, aerospace and nano-materials cases, some changes are necessary. The 14 NRPs are still valid – though they may justify unequal weightings. However, it is more realistic to create new maturity scales appropriate to the application. This is not as troublesome as it might seem. Examples for maturity 1 and 10 can be easily defined for each criterion and then the intervening levels can be formulated. The process of thinking systematically about what constitutes a continuous evolution path is the real benefit from the activity.

From an academic perspective, it seemed reasonable to include readiness parameters that defined whether there is a capable workforce available to service new technology (#12) and the capacity of the academic sector to grow, sustain and update that workforce (#13). The outcomes for all technologies assessed to date are not flattering. Academic course content is a lagging measure of technology maturity. Typical undergraduate courses deal with technology that was mature 20 or more years ago. The most significant application of this assessment tool may be to serve as a framework to update and reconfigure degree programs to make a better showing in readiness parameters 12 and 13.

The assessment tool has made students more aware of the detailed and demanding process that has to be followed if a fascinating idea is to transition quickly from a lab curiosity to a revenue-generating product. The process has a direct impact on their future careers and the skills they should seek to acquire through their degree program [17]. The assessment tool provides an easy-to-use map for technology development. The maturity assessment process provides a simple way to quantify what has to be done and how it can be measured. It can be applied both to incremental technology and to the most radical nano-technology concepts.

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