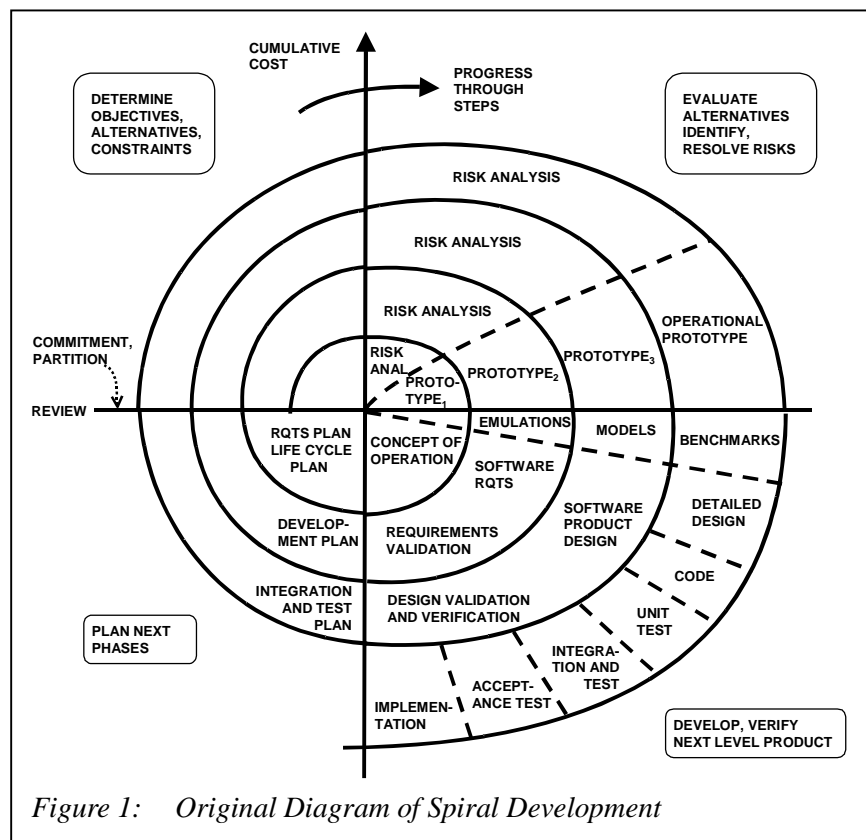


Understanding the Spiral Model as a Tool for Evolutionary Acquisition

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Since its original publication [Boehm 88], the spiral development model diagrammed in Figure 1 has been used successfully in many defense and commercial projects. To extend this base of success, the



Department of Defense (DoD) has recently rewritten the defense acquisition regulations to incorporate "evolutionary acquisition," an acquisition strategy designed to mesh well with spiral development. In particular, DoD Instruction 5000.2 subdivides acquisition [DoD 00]:

"There are two ... approaches, evolutionary and single step to full capability. An evolutionary approach is preferred. ... [In this] approach, the ultimate capability delivered to the user is divided into two or more blocks, with increasing increments of capability." (p. 20)

Here, a block corresponds to a single contract, although one contractor may be chosen for multiple blocks of a project. The text goes on to specify the use of spiral development within blocks:

"For both the evolutionary and single-step approaches, software development shall follow an iterative spiral development process in which continually expanding software versions are based on learning from earlier development." (p. 20)

Given this reliance of DoD on spiral development it is appropriate to define that method in depth. This paper does so. A follow-on article will address the relationships among spiral development, evolutionary acquisition, and the Integrated Capability Maturity Model (CMMI).

In anticipation of the DoD 5000 series, the USC Center for Software Engineering (CSE) and the CMU Software Engineering Institute (SEI) held workshops in February and September 2000. Their objectives were to identify a set of critical success factors and recommended approaches for spiral development and its application to evolutionary acquisition. Their results appear in two reports, [Hansen 00] and [Hansen 01] and are available on the workshop website <http://www.sei.cmu.edu/cbs/spiral2000>. The first author's presentation at the February workshop was converted to a report [Boehm 00b] and forms the basis for much of this paper. For details and further references, see that paper.

"Spiral Development" Definition and Context

We can begin with a high-level definition of the spiral development model:

The spiral development model is a *risk-driven process model* generator that is used to guide multi-stakeholder concurrent engineering of software-intensive systems. It has two main distinguishing features. One is a *cyclic* approach for incrementally growing a system's degree of definition and implementation while decreasing its degree of risk. The other is a set of *anchor point milestones* for ensuring stakeholder commitment to feasible and mutually satisfactory system solutions.

The highlighted terms deserve further explanation:

Risks are situations or possible events that can cause a project to fail to meet its goals. They range in impact from trivial to fatal and in likelihood from certain to improbable. Since risk considerations dictate the path a development must take, it is important that those risks be cataloged candidly and completely. See the references for a taxonomy of risks [Carr 93] and a method for identifying them [Williams 99].

A *process model* answers two main questions:

- What should be done next?
- For how long should it continue?

Under the spiral model the answers to these questions are driven by risk considerations and vary from project to project and sometimes from one spiral cycle to the next. Each choice of answers generates a different process model.

The *cyclic* nature of the spiral model is illustrated in Figure 1. Rather than develop the completed product in one step, multiple cycles are performed with each taking steps calculated to reduce the most significant remaining risks.

Each *anchor point milestone* is a specific artifact or condition which must be attained at some point. The sequence of three anchor point milestones—"LCO", "LCA", and "ICO"—

is defined in Spiral Essential 5, below. These milestones impel the project toward completion and offer a means to compare progress between one project and another.

Many aspects of spiral development are omitted in the above definition. The remainder of this paper expands the definition by describing six *essential* aspects that every proper spiral process must exhibit. These Essentials are sketched in Figure 2. Each subsequent section describes a Spiral Essential, the critical-success-factor reasons why it is necessary, and the variant process models it allows. Examples are given. Other process models which are precluded by the Spiral Essential are described. Because these may seem to be instances of the spiral model, but lack necessary Essentials and thus risk failure, they are called "hazardous spiral look-alikes."

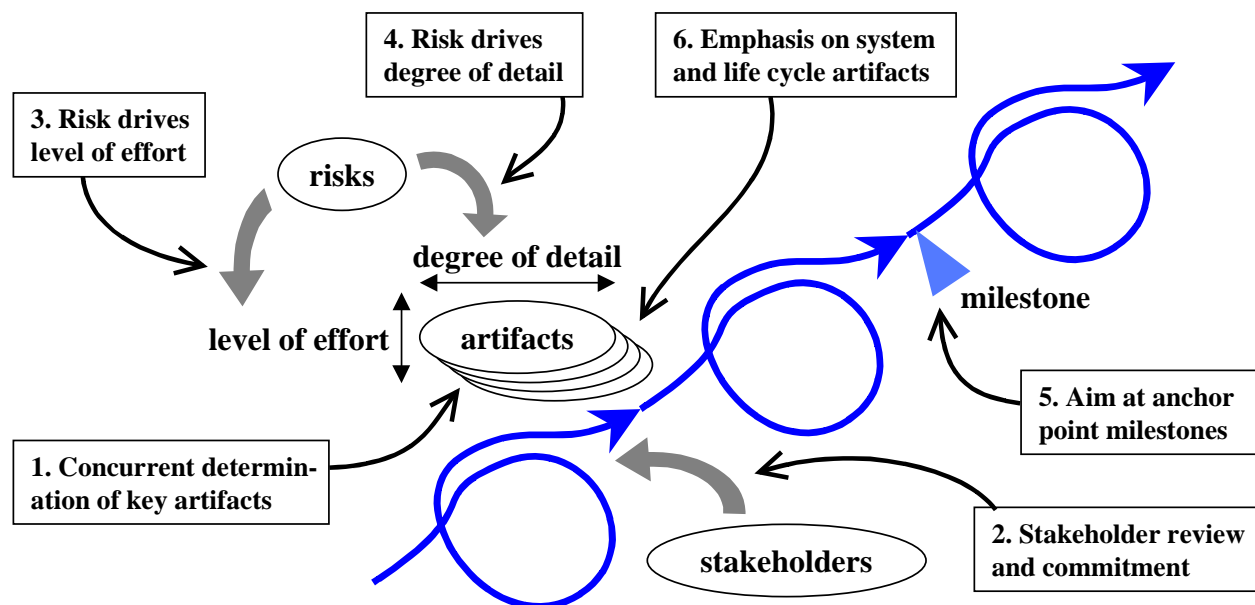


Figure 2: Pictorial sketch of the six spiral Essentials

Spiral Essential 1: Concurrent Determination of Key Artifacts (Operational Concept, Requirements, Plans, Design, Code)

For a successful spiral effort, it is vital to determine certain key artifacts concurrently and not sequentially. These key artifacts are the operational concept, the system and software requirements, the plans, the system and software architecture and design, and the code components including COTS, reused components, prototypes, success-critical components, and algorithms. Ignoring this Essential by sequentially determining the key artifacts will prematurely overconstrain the project, and often extinguish the possibility of developing a product satisfactory to the stakeholders.

Variants: Within the constraints of this Essential, variation is possible in the product and process internals of the concurrent engineering activity. For a low technology, interoperability-critical system, the initial spiral products will be requirements-intensive. For a high-technology, more standalone system, the initial spiral products will be prototype-code-intensive. Also, the Essential does not dictate the number of

mini-cycles (e.g., individual prototypes for COTS, algorithm, or user-interface risks) within a given spiral cycle.

Example: One-Second Response Time

Examples of failure due to omission of this Essential are: premature commitments to hardware platforms, incompatible combinations of COTS components, and requirements whose achievability has not been validated. For instance, in the early 1980s, a large government organization contracted with TRW to develop an ambitious information system for more than a thousand users. This system was to be distributed across a campus and offer powerful query and analysis access to a large and dynamic database. Based largely on user need surveys and an oversimplified high-level performance analysis, TRW and the customer fixed into the contract a requirement for a system response time of less than one second.

Two thousand pages of requirements later, the software architects found that subsecond performance could only be provided via a highly customized design that attempted to cache data and anticipate query patterns so as to be able to respond to each user within one second. The resulting hardware architecture had more than 25 super-minicomputers busy caching data according to algorithms whose actual performance defied easy analysis. Estimated cost: \$100 million, see the upper arc in Figure 2.

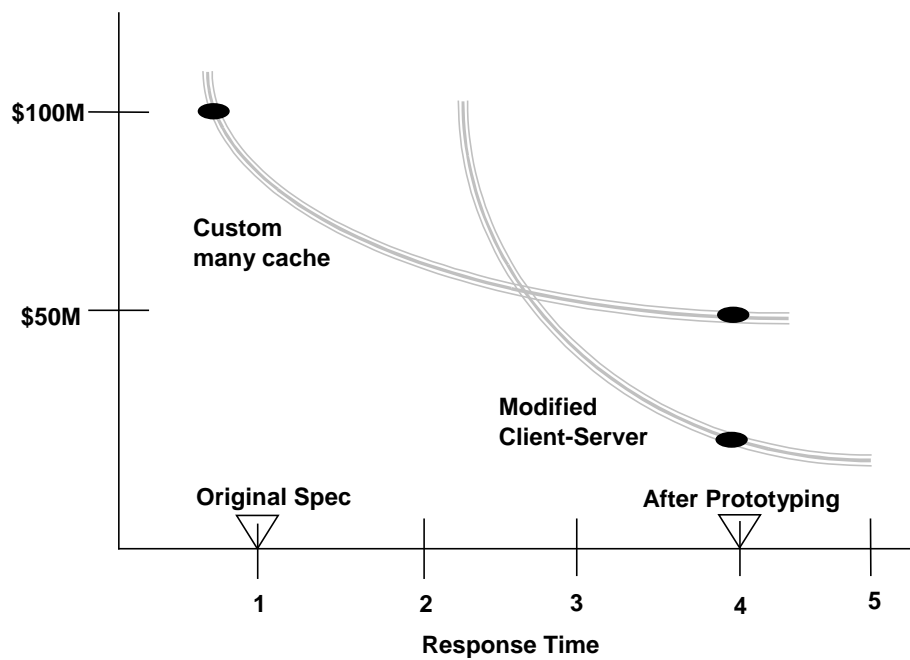


Figure 2: Two System Designs: Cost vs. Response Time

Faced with an exorbitant cost, the customer and developer decided to develop and user-test a prototype. The results showed that a four-second response time would satisfy users 90 percent of the time. This lower performance could be achieved with a modified client-server architecture, cutting development costs to \$30 million as shown by the lower arc in the Figure [Boehm 00a]. Thus, the premature specification of a one-second response time introduced the risk of an overly expensive system.

Hazardous Spiral Look-Alike: Violation of Waterfall Assumptions

Essential 1 excludes the use of an incremental sequence of waterfall developments in the common case where there is a high risk of violating the assumptions underlying the waterfall model. These assumptions are that the requirements are pre-specifiable, unchanging, and satisfactory to all stakeholders, and that a well-understood architecture can meet these requirements. These assumptions must be met by a project if the waterfall model is to succeed. If all are true, then it is a project risk not to specify the requirements: the spiral-dictated risk analysis results in a waterfall approach for this project. If any assumption is false, then a waterfall approach will commit the project to troublesome assumptions and requirements mismatches. Here are typical cases that violate waterfall assumptions:

Requirements are not generally denumerable for new user-interactive systems, because of the IKIWISI syndrome. When asked for their required screen layout for a new decision-support system, users will generally say, “I can’t tell you, but I’ll know it when I see it (IKIWISI).” In such cases, a concurrent prototyping/requirements/architecture approach is necessary.

Inconstant requirements are well illustrated by electronic commerce projects, where the volatility of technology and the marketplace is high. The time it takes to write detailed requirements is not a good investment of the scarce time-to-market available when it is likely the requirements will change more than once downstream.

The architecture and its implications were the downfall of the one-second response time example.

Spiral Essential 2: Each Cycle Does Objectives, Constraints, Alternatives, Risks, Review, Commitment to Proceed

Spiral Essential 2 identifies the activities that need to be done in each spiral cycle. These include consideration of critical-stakeholder objectives and constraints; elaboration and evaluation of project and process alternatives for achieving the objectives subject to the constraints; identification and resolution of risks attendant on choices of alternative solutions; and stakeholders’ review and commitment to proceed based on satisfaction of their critical objectives and constraints. If all of these are not considered, the project may be prematurely committed to alternatives that are either unacceptable to key stakeholders or overly risky.

Variants: Spiral Essential 2 does not mandate particular generic choices of risk resolution techniques, although guidelines are available [Boehm 89]. Nor does this Essential mandate particular levels of effort for the activities performed during each cycle. Levels must be balanced between the risks of learning too little and the risks of wasting time and effort gathering marginally useful information.

Example: Windows-Only COTS

Ignoring Essential 2 can lead to wasted effort in elaborating an alternative that could have been shown earlier to be unsatisfactory. One of the current USC digital library projects is developing a web-based viewer for oversized artifacts (e.g., newspapers, large images). The initial prototype featured a tremendously powerful and high-speed viewing capability, based on a COTS product called ER Mapper. The initial project review approved selection of this COTS product, even though it only ran well on Windows platforms, and the Library had significant Macintosh and UNIX user communities. This

decision was based on initial indications that Mac and UNIX versions of ER Mapper would be available "soon." These indications proved unreliable, however, and the anticipated delay became quite lengthy. So after wasting considerable effort on ER Mapper, it was dropped in favor of a less powerful but fully portable COTS product, Mr. SID. The excess effort could have been avoided had the review team included stakeholders from the Mac and UNIX communities on campus who would have done the necessary investigations earlier.

Hazardous Spiral Look-Alike: Excluding Key Stakeholders

Essential 2 excludes the process model of organizing the project into sequential phases or cycles in which key stakeholders are excluded. These omissions are likely to cause critical risks to go undetected. Examples are excluding developers from system definition, excluding users from system construction, or excluding system maintainers from either definition or construction. Excluding developer participation in early cycles can lead to project commitments based on unrealistic assumptions about developer capabilities. Excluding users or maintainers from development cycles can lead to win-lose situations, which generally devolve into lose-lose situations.

Spiral Essential 3: Level of Effort Driven by Risk Considerations

Spiral Essential 3 dictates the use of risk considerations to answer the difficult questions of how-much-is-enough of a given activity. How much is enough of domain engineering? prototyping? testing? configuration management? and so on. The recommended approach is to evaluate Risk Exposure (RE), which is computed as Probability (Loss) • Size (Loss). There is risk of project error RE_{error} from doing too little effort and project delay RE_{delay} from doing too much. Ideally, the effort expended will be that which minimizes the sum $RE_{\text{error}} + RE_{\text{delay}}$. This approach applies to most activities that are undertaken in a spiral development.

Variants to be considered include the choice of methods used to pursue activities (e.g., MBASE/WinWin, Rational RUP, JAD, QFD, ESP) and the degree of detail of artifacts produced in each cycle. Another variant is an organization's choice of particular methods for risk assessment and management.

Example: Pre-Ship Testing

Risk considerations can help determine "how much testing is enough" before shipping a product. The more testing that is done, the lower becomes RE_{error} due to defects, as discovered defects reduce both the size of loss due to defects and the probability that undiscovered defects still remain. However, the more time spent testing, the higher is RE_{delay} from losses due to both competitors entering the market and decreased profitability on the remaining market share.

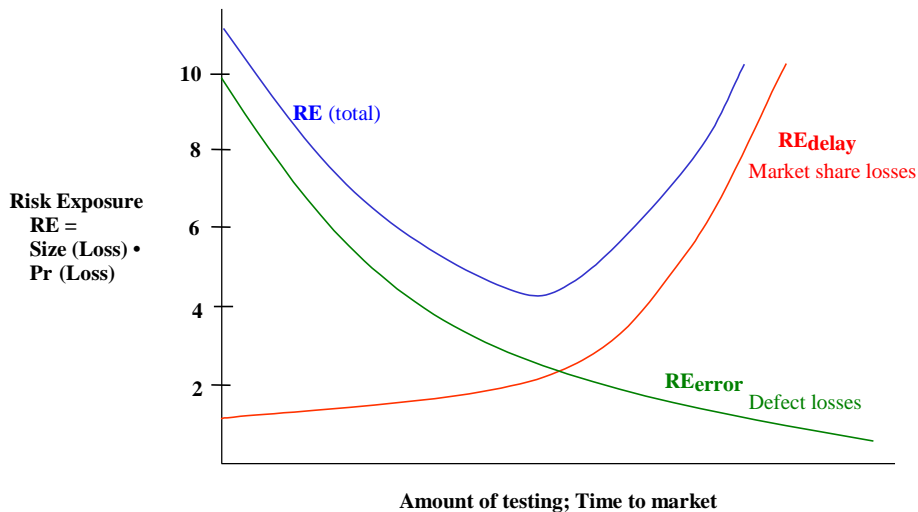


Figure 3: Pre-Ship Test Risk Exposure

As shown in Figure 3, the sum of these risk exposures achieves a minimum at some intermediate level of testing. The location of this minimum-risk point in time will vary by type of organization. For example, it will be considerably shorter for a “dot.com” company than it will for a safety-critical product such as a nuclear power plant. Calculating the risk exposures also requires an organization to accumulate a fair amount of calibrated experience on the probabilities and size of losses as functions of test duration and delay in market entry.

Hazardous Spiral Look-Alikes: Risk Insensitivity

Hazardous spiral model look-alikes excluded by Essential 3 are

- risk-insensitive evolutionary development (e.g., neglecting scalability risks)
- risk-insensitive incremental development (e.g., suboptimizing during increment 1 with an ad hoc architecture which must be dropped or heavily reworked to accommodate future increments)
- impeccable spiral plans with no commitment to managing the risks identified.

Spiral Essential 4: Degree of Detail Driven by Risk Considerations

Where Essential 3 circumscribes efforts, Essential 4 circumscribes the results of those efforts; it dictates that risk considerations determine the degree of detail of artifacts. This means, for example, that the traditional ideal of a complete, consistent, traceable, testable requirements specification is not a good idea for certain product components, such as a graphic user interface (GUI) or COTS interface. Here, the risk of precisely specifying screen layouts in advance of development involves a high probability of locking an awkward user interface into the development contract, while the risk of not specifying screen layouts is low, given the general availability of flexible GUI-builder tools. Even aiming for full consistency and testability can be risky, as it creates a pressure to prematurely specify decisions that would better be deferred (e.g., the form and content of exception reports). However, some risk patterns make it very important to have precise specifications, such as the risks of safety-critical interface mismatches between hardware and software components, or between a prime contractor’s and a subcontractor’s software.

This guideline shows when it is risky to over-specify and under-specify software features:

- If it's risky to not specify precisely, DO specify
(e.g., hardware-software interface, prime-subcontractor interface)
- If it's risky to specify precisely, DO NOT specify
(e.g., GUI layout, COTS behavior)

Variants: Unconstrained by Essential 4 are the choices of representations for artifacts (SA/SD, UML, MBASE, formal specs, programming languages, ...).

Example: Risk of Precise Specification

One editor specification required that every operation be available through a button on the window. As a result, the space available for viewing and editing became unusably small. The developer was precluded from moving some operations to menus because the GUI layout had been specified precisely at an early step. (Of course, given too much freedom programmers can develop very bad GUIs. Stakeholder review is necessary to avoid such problems.)

Hazardous Spiral Look-Alikes: Insistence on Complete Specifications

Is it hazardous to undertake a spiral development project wherein complete specifications are pre-specified for *all* aspects. Aspects such as those described in the example should be left to be further defined during project exploratory phases.

Spiral Essential 5: Use Anchor Point Milestones: LCO, LCA, IOC

A major difficulty of the original spiral model was its lack of intermediate milestones to serve as commitment points and progress checkpoints. This difficulty has been remedied by the development of a set of anchor point milestones:

LCO - Life Cycle Objectives - what should the system accomplish

LCA - Life Cycle Architecture - what is the structure of the system

IOC - Initial Operating Capability - the first released version

(The artifacts for each are provided by an electronic process guide [Mehta 99].)

The focus of the LCO review is to ensure that at least one architecture choice is viable from a business perspective. The focus of the LCA review is to commit to a single detailed definition of the project. The project must have either eliminated all significant risks or put in place an acceptable risk-management plan. The LCA milestone is particularly important, as its pass/fail criteria enable stakeholders to hold up projects attempting to proceed into evolutionary or incremental development without a life cycle architecture. Each milestone is a stakeholder commitment point: at LCO the stakeholders commit to support architecting; at LCA they commit to support initial deployment; at IOC they commit to support operations. Together the anchor point milestones avoid analysis paralysis, unrealistic expectations, requirements creep, architectural drift, COTS shortfalls and incompatibilities, unsustainable architectures, traumatic cutovers, and useless systems.

Variants: One appropriate variant of Essential 5 is the number of spiral cycles between anchor points. Another possible variant is to merge anchor points. In particular, a project using a mature and appropriately scalable fourth generation language (4GL) or product line framework will have already determined its architecture by its LCO milestone, enabling the LCO and LCA milestones to be merged.

Example: Stud Poker Analogy

A valuable aspect of the spiral model is its ability to support incremental commitment of corporate resources rather than requiring a large outlay of resources to the project before its success prospects are well understood. Funding a spiral development can thus be likened to the game of stud poker. In that game, you put a couple of chips in the pot and receive two cards, one hidden and one exposed. If your cards don't promise a winning outcome, you can drop out without a great loss. This corresponds to cancelling a project at or before LCO. If your two cards are both aces, you will probably bet on your prospects aggressively (or less so if you see aces among other players' exposed cards). Dropping out of the second or third round of betting corresponds to cancelling at or before LCA. In any case, based on information available, you can decide during each round whether it's worth putting more chips in the pot to buy more information or whether it's better not to pursue this particular deal or project.

Hazardous Look-Alike: Evolutionary Development without Life Cycle Architecture

The LCO and LCA milestones' pass-fail criteria emphasize that the system's architecture must support not just the initial increment's requirements, but also the system's evolutionary life-cycle requirements. This avoids the hazardous spiral look-alike of an initial increment optimized to provide an impressive early system demonstration or limited release, but not architected to support full-system requirements for security, fault-tolerance, or scalability to large workloads. Other important considerations for LCA are that the initial release be good enough to ensure continued key stakeholder participation, that the user organizations are sufficiently flexible to adapt to the pace of system evolution, and that legacy-system replacement be well thought out. Ignoring these aspects lead to other hazardous spiral look-alike processes.

Spiral Essential 6: Emphasis on System and Life Cycle Activities and Artifacts

Spiral Essential 6 emphasizes that spiral development of software-intensive systems needs to focus not just on software construction aspects, but also on overall system and life cycle concerns. Will the product satisfy its stakeholders? Meet cost and performance goals? Integrate with existing business practices? Adapt to changes in the customer organization's environment? Software developers are particularly apt to fall into the oft-cited trap: "If your best tool is a hammer, the world you see is collection of nails." Writing code may be a developer's forte, but it stands in importance to the project as do nails to a house.

Variants: The model's use of risk considerations to drive solutions makes it possible to tailor each spiral cycle to whatever mix of software and hardware, choice of capabilities, or degree of productization is appropriate.

Example: "Order Processing"

A good example of failure to consider the whole system occurred with the Scientific American order processing system sketched in Figure 4 [Boehm 81]. Scientific American had hoped that computerizing the functions being performed on tabulator-machines would reduce its subscription processing costs, errors, and delays. Rather than analyze the sources of these problems, the software house jumped in and focused on the part of the problem having a software solution. The result was a batch-processing

computer system whose long delays put extra strain on the clerical portion of the system that had been the major source of costs, errors, and delays in the first place. The software people looked for the part of the problem with a software solution (their “nail”), pounded it in with their software hammer, and left Scientific American worse off than when they started.

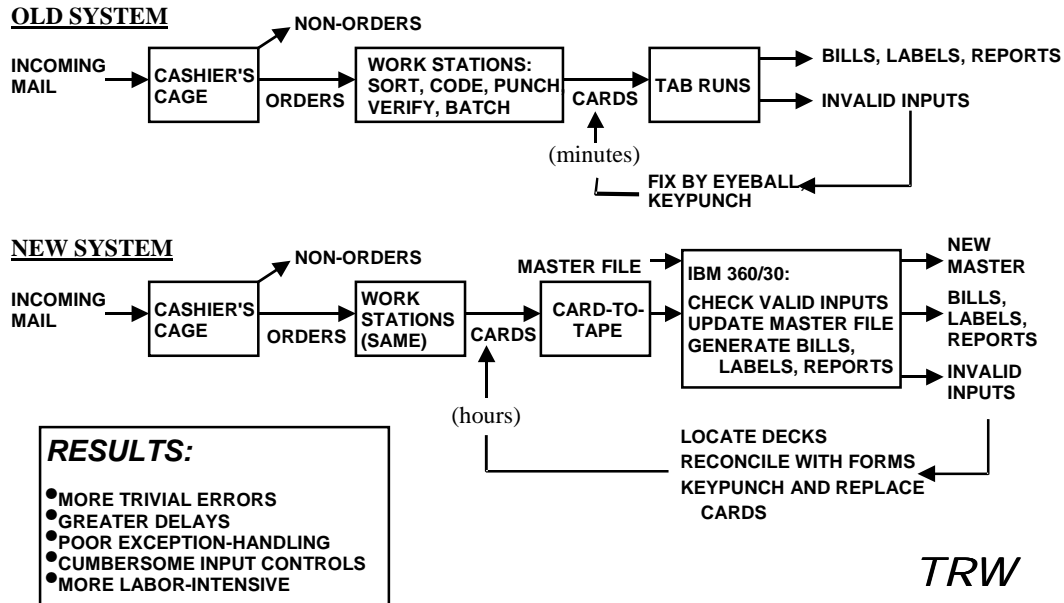


Figure 4: Scientific American Order Processing

This kind of outcome would have resulted even if the software automating the tabulator-machine functions had been developed in a risk-driven cyclic approach. However, its Life Cycle Objectives milestone package would have failed its feasibility review, as it had no system-level business case demonstrating that the development of the software would lead to the desired reduction in costs, errors, and delays. Had a thorough business case analysis been done, it would have identified the need to re-engineer the clerical business processes as well as to automate the manual tab runs.

Hazardous Spiral Look-Alikes: Logic-Only OO Designs

Models excluded by Essential 6 include most published object-oriented analysis and design (OOA&D) methods, which are usually presented as abstract logical exercises independent of system performance or economic concerns. For example, in a recent survey of 16 OOA&D books, only six listed the word “performance” in their index, and only two listed “cost.”

Using the Spiral Model for Evolutionary Acquisition

Both the February and September workshops had working groups on the relationships between spiral development and evolutionary acquisition. A primary conclusion was that the relationships differ across two major DoD acquisition sectors:

- Information systems, such as C4ISR systems, logistics systems, and management systems, in which spiral and evolutionary models coincide well.

- Software-intensive embedded hardware-software systems, in which the software aspects best follow a spiral approach, but the hardware aspects need to follow a more sequential approach to accommodate lead times for production facilities, production subcontracts, and long-lead critical-component orders.

Even for embedded systems, however, spiral approaches can be helpful for synchronizing hardware and software processes, and for determining when to apply an evolutionary, incremental, or single-step acquisition strategy. For example, Xerox's Time-to-Market process uses the spiral anchor point milestones as hardware-software synchronization points for its printer business line [Hantos 00]. Rehtin and Maier adopt a similar approach in their book, the Art of Systems Architecting [Rehtin 96].

A good example of the use of a risk-driven spiral approach to determine a preferred software/system acquisition strategy was originally developed for DoD's MIL-STD-498, and subsequently incorporated in IEEE/EIA 12207 [IEEE/EIA 98]. This approach distinguishes among single-step (once-through or waterfall), incremental, and evolutionary acquisition processes as shown in Table 1. Thus, evolutionary acquisition avoids defining all requirements first, and proceeds in multiple development cycles, some of which involve distribution and usage of initial and intermediate operational capabilities.

Table 1. Evolutionary Acquisition Distinctions [IEEE/EIA 98]

Development strategy	Define all requirements first?	Multiple development cycles?	Distribute interim software?
Once-Through (Waterfall)	Yes	No	No
Incremental (Preplanned Product Improvement)	Yes	Yes	Maybe
Evolutionary	No	Yes	Yes

Table 2 shows how a spiral risk analysis is performed during early integrated product and process definition cycles to select the most appropriate acquisition process for a system. The example shown in Table 2 is for a fairly large, high-technology C4ISR system. For such a system, the high risks of poorly-understood requirements and rapid technology changes push the decision away from once-through or incremental acquisition, while the needs for an early capability and for user feedback on full requirements push the decision toward evolutionary acquisition. If the system had been a small, lower-technology embedded system where all capabilities are needed at first delivery, the risk and opportunity factors would push the decision away from evolutionary and incremental acquisition toward once-through or single-step acquisition.

Table 2. *Spiral Risk Analysis for Process Selection [IEEE/EIA 98]*

Risk Item (Reasons against this strategy)	Risk Level	Opportunity Item (Reasons to use this strategy)	Opp. Level
Once-Through Acquisition			
Requirements are not well understood	H	User prefers all capabilities at first delivery	M
Rapid changes in technology anticipated - may change the requirements	H	User prefers to phase out old system all at once	L
System too large to do all at once	M		
Limited staff or budget available now	M		
Incremental Acquisition			
Requirements are not well understood	H	Early capability is needed	H
User prefers all capabilities at first delivery	M	System breaks naturally into increments	M
Rapid changes in technology anticipated - may change the requirements	H	Funding/staffing will be incremental	H
Evolutionary Acquisition			
User prefers all capabilities at first delivery	M	System breaks naturally into increments	M
		Early capability is needed	H
		Funding/staffing will be incremental	H
		User feedback and monitoring of technology changes is needed to understand full requirements	H

Summary

This paper has defined the spiral development model as a risk-driven process model generator with cyclic process execution and a set of three anchor point milestones. The definition was sharpened by presenting a set of six "essential" attributes; that is, six attributes which every spiral development process must incorporate. These Essentials are summarized in Table 3. Omission of any one of the Essentials gives rise to a process model which is cyclic or iterative, but is not an example of spiral development. Such a model is called a "hazardous spiral look-alikes." Each was described and pilloried as part of describing the Essential it violates.

Spiral development works fairly seamlessly with evolutionary acquisition of information systems. For evolutionary acquisition of software-intensive embedded hardware-software systems, a mix of spiral and sequential processes is often needed. Even here, however, the spiral anchor points and risk-driven process selection approach are useful for determining how best to synchronize the hardware and software processes.

Table 3: Summary

Spiral Model Essential Element		
<u>Why essential</u>	<u>Variants</u>	<u>Hazardous look-alikes</u>
1. Concurrent determination of key artifacts		
Avoids premature sequential commitments to system requirements, design, COTS, combination of cost / schedule / performance	Relative amount of each artifact developed in each cycle Number of concurrent mini-cycles in each cycle	Incremental sequential waterfalls with significant COTS, user interface, or technology risks
2. Each cycle does objectives, constraints, alternatives, risks, review, and commitment to proceed		
Avoids commitment to stakeholder-unacceptable or overly risky alternatives Avoids wasted effort in elaborating unsatisfactory alternatives	Choice of risk resolution techniques: prototyping, simulation, modeling, benchmarking, reference checking, etc. Level of effort on each activity within each cycle	Sequential spiral phases with key stakeholders excluded from phases
3. Level of effort driven by risk considerations		
Determines "how much is enough" of each activity: domain engineering, prototyping, testing, CM, etc. Avoids overkill or belated risk resolution	Choice of methods used to pursue activities: MBASE/WinWin, Rational RUP, JAD, QFD, ESP, ... Degree of detail of artifacts produced in each cycle	Risk-insensitive evolutionary or incremental development. Impeccable spiral plan with no commitment to managing risks
4. Degree of detail driven by risk considerations		
Determines "how much is enough" of each artifact (OCD, Requirements, Design, Code, Plans) in each cycle Avoids overkill or belated risk resolution	Choice of artifact representations (SA/SD, UML, MBASE, formal specs, programming languages, etc.)	Insistence on complete specifications for COTS, user interface, or deferred-decision situations
5. Use of anchor point milestones: LCO, LCA, IOC		
Avoids analysis paralysis, unrealistic expectations, requirements creep, architectural drift, COTS shortfalls and incompatibilities, unsustainable architectures, traumatic cutovers, and useless systems	Number of spiral cycles or increments between anchor points Situation-specific merging of anchor point milestones	Evolutionary development with no life-cycle architecture
6. Emphasis on system and life cycle activities and artifacts		
Avoids premature suboptimization on hardware, software, or development considerations	Relative amount in each cycle of <ul style="list-style-type: none"> •hardware vs. software •capability •productization (alpha, beta, shrink-wrap, etc.) 	Purely logical object-oriented methods with operational, performance, or cost risks

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