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An Overview of System Engineering at Sandia National Laboratories

April 23, 2007

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Sandia National Laboratories

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Outline

- Some definitions
- Elements of System Engineering at Sandia
- Sandia Initiatives in System Engineering

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System Engineering

A Definition at Sandia

- **System Engineering is an interdisciplinary science-based engineering approach to the design, development, qualification, and release of complex products - hardware and software - that, when followed, assures customer requirements will be satisfied throughout the product's lifecycle. Successful application of systems engineering rests on an understanding and application of scientific and engineering principles while explicitly considering the relevant contexts – geopolitical, socioeconomic, and technological– to which the product will be exposed throughout its lifecycle.**

System Engineering at Sandia

- **Systems Engineering (SE) is an interdisciplinary activity that ensures that the customers' needs are satisfied throughout a system's entire life cycle. The SNL Systems Engineering effort provides requirements definition, design integration, coordination of activities across the NNSA complex, technical guidance for DoD deployment and maintenance operations, and support for stockpile surveillance.**

- **Breakout of Weapons SE Areas**
  1. **Research/Technology Maturation and Transfer**
  2. **Weapon Requirements**
  3. **Weapon Architecture and Design**
  4. **Weapon Certification**
  5. **Technical Management**
  6. **Weapon Production, Maintenance, and Support**

System Engineering Core Competencies

- Customer Support
- Requirements Engineering
- System Design
- System Integration
- System Analysis
- Validation and Verification
- Logistics and Operations
- Technical Management
- Information Management
- Coordination
- Leadership
- Systems Engineering Ownership

Key Elements of "Excellence in Engineering"

- **Conduct engineering as a creative, but disciplined process, according to defined plans and official, documented procedures**
- **Exercise critical thinking in every aspect of our work (*Assertion ➔ Challenge ➔ Conclusion)***
- **Exploit advances in technologies to improve products and processes *(Innovation)***
- **Confident, capable staff**

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"Excellence in Engineering" through Systems Engineering

A consistent approach to Systems Engineering will help achieve a goal of Engineering Excellence. Commonality and formality in approach to SE that will ultimately provide:

- Our **customers** with an improved interface, confidence in our solid methodology and an improved final product;
- Our **leadership** team with consistency in defining and managing our portfolio of work; and
- Our **engineers** with a simplified day-to-day SE job.

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Outline

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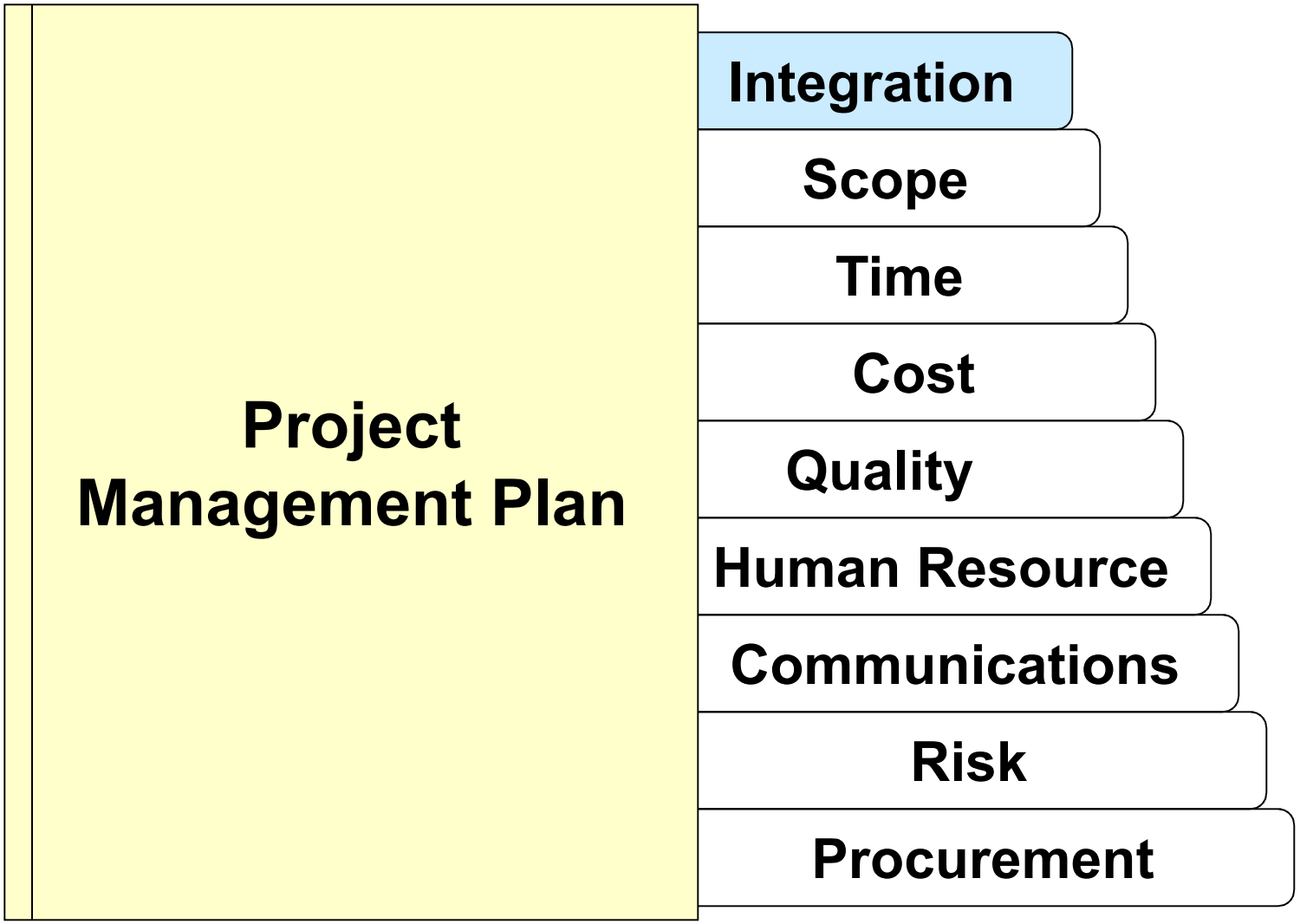
Key Elements of System Engineering



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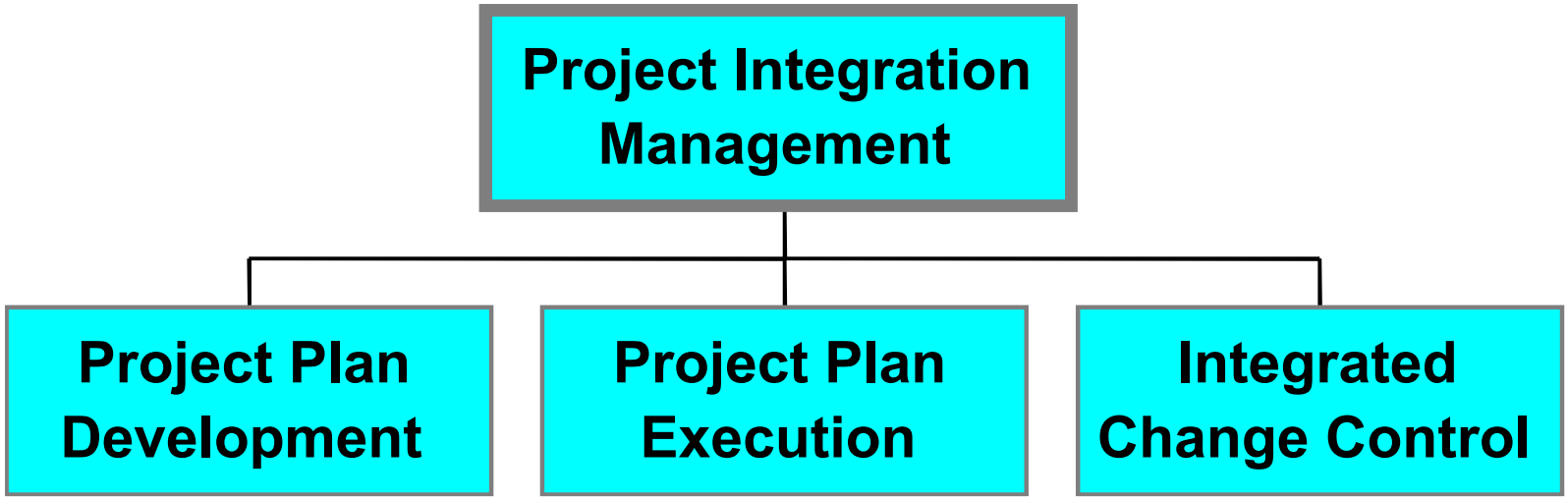
Project Integration Management

- *"Processes required to ensure that the various elements of the project are properly coordinated" - PMI PMBOK Guide*



Plan the Work and Work the Plan

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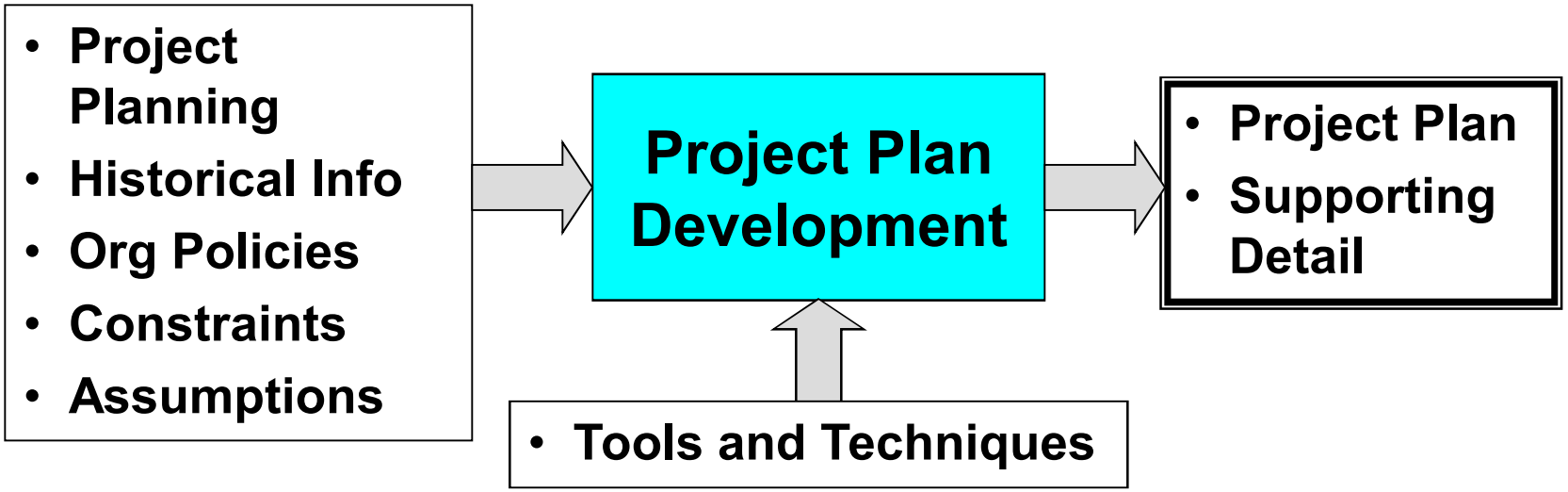
Project Plan Development



References:

- *"A Guide to the Project Management Body of Knowledge,PMBOK Guide – 3rd Edition,"* 2004, Project Management Institute (PMI), ISBN 1-930669-45-X
- *"Project Management, A Systems Approach to Planning, Scheduling, and Controlling,"* Fifth Edition, Harold Kerzner, Ph.D., ISBN 0-422-01907-6
- "What Every Engineer Should Know About Project Management," A. M. Ruskin and W. Eugene Estes, ISBN 0-8247-89534-9

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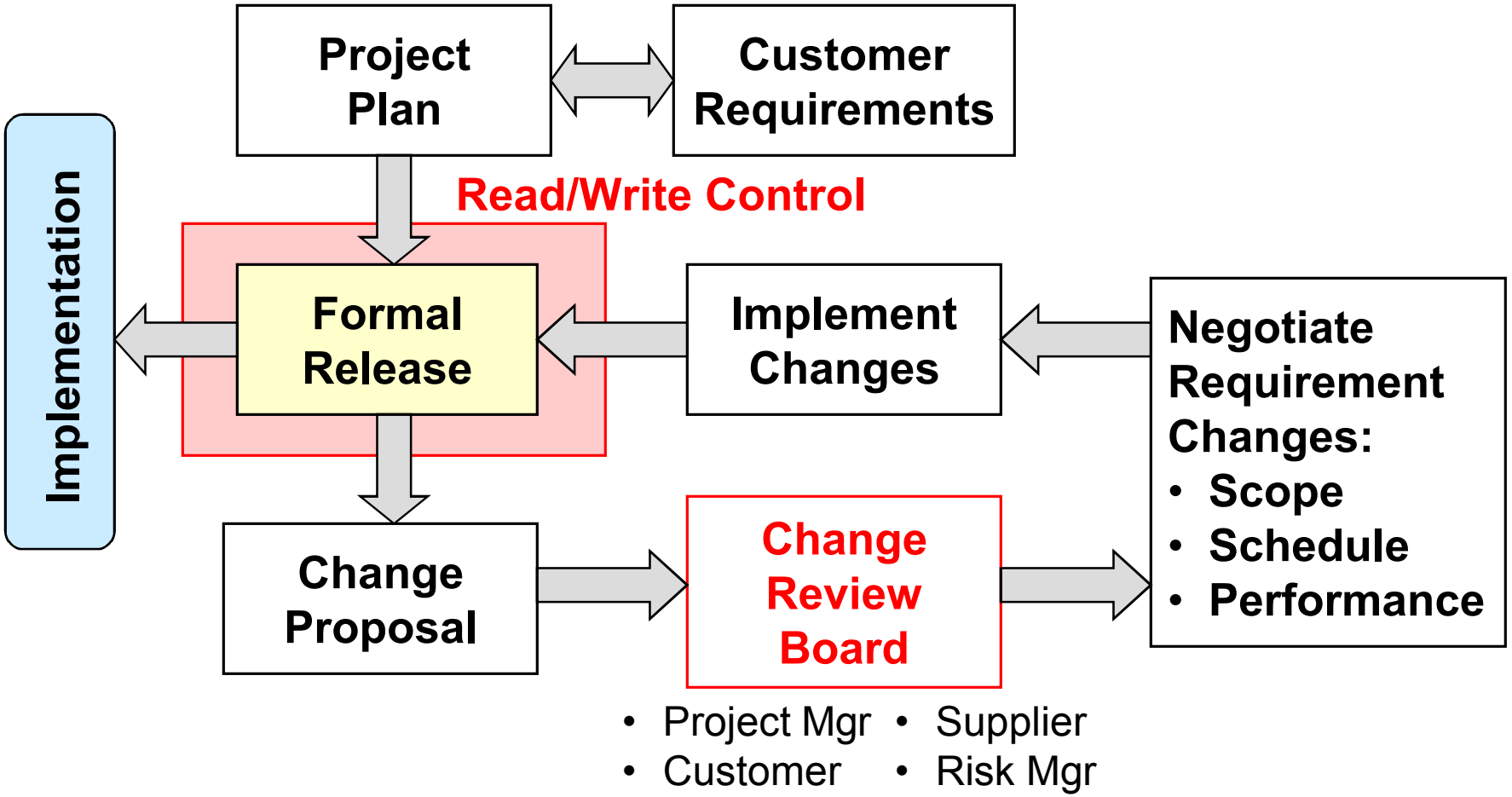
Integrated Change Control



Change proposal must have proper justification.

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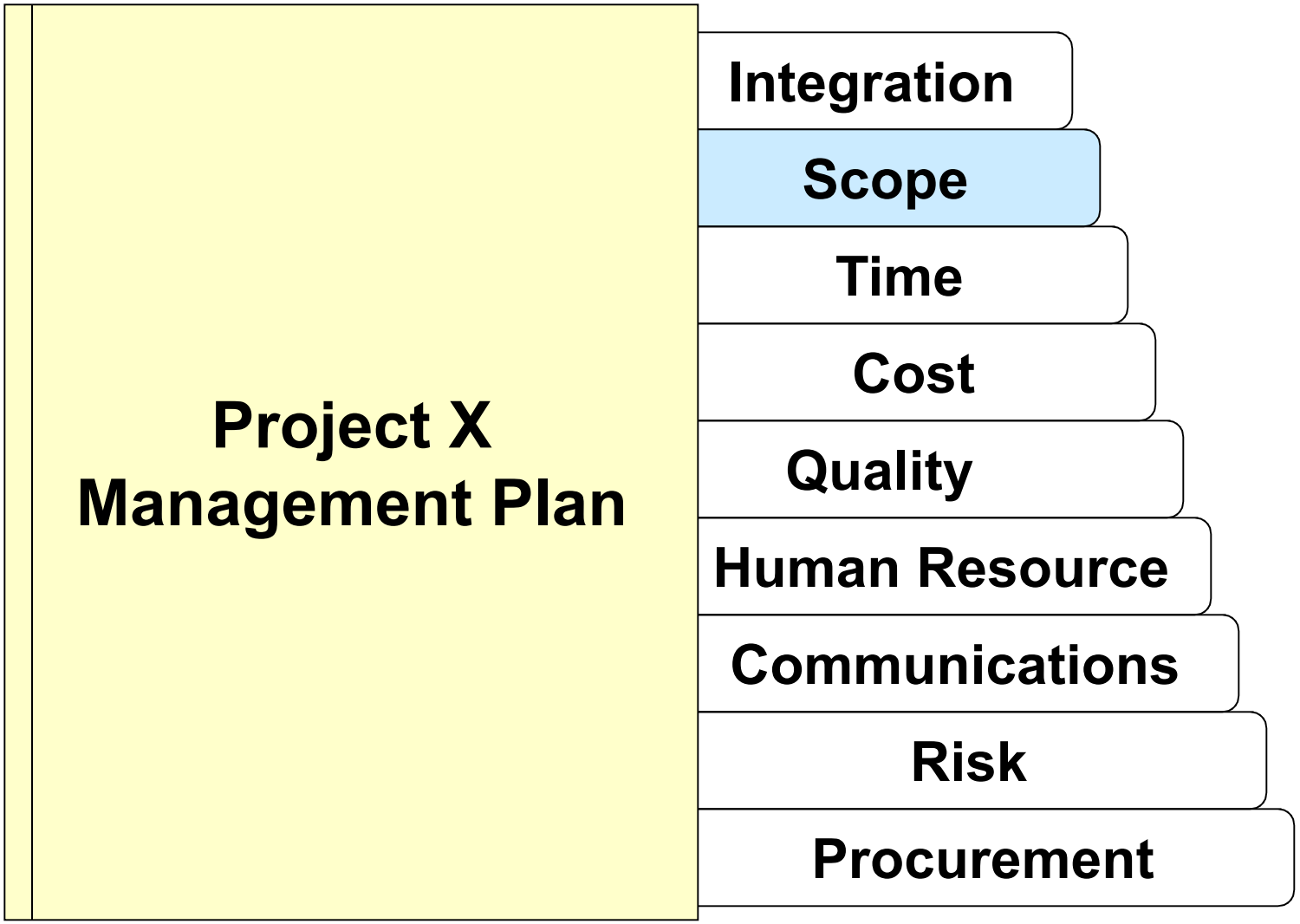
Lessons Learned

- Develop the plan with all project members to get buy-in, commitment, and correct assumptions
- Develop a plan to the detail necessary to manage the project
- Do not let the plan become the project
- Must baseline the plan and maintain configuration control
- Good information management and communication is essential
- A successful project requires a manager with strong leadership and communication skills

Key Elements of System Engineering



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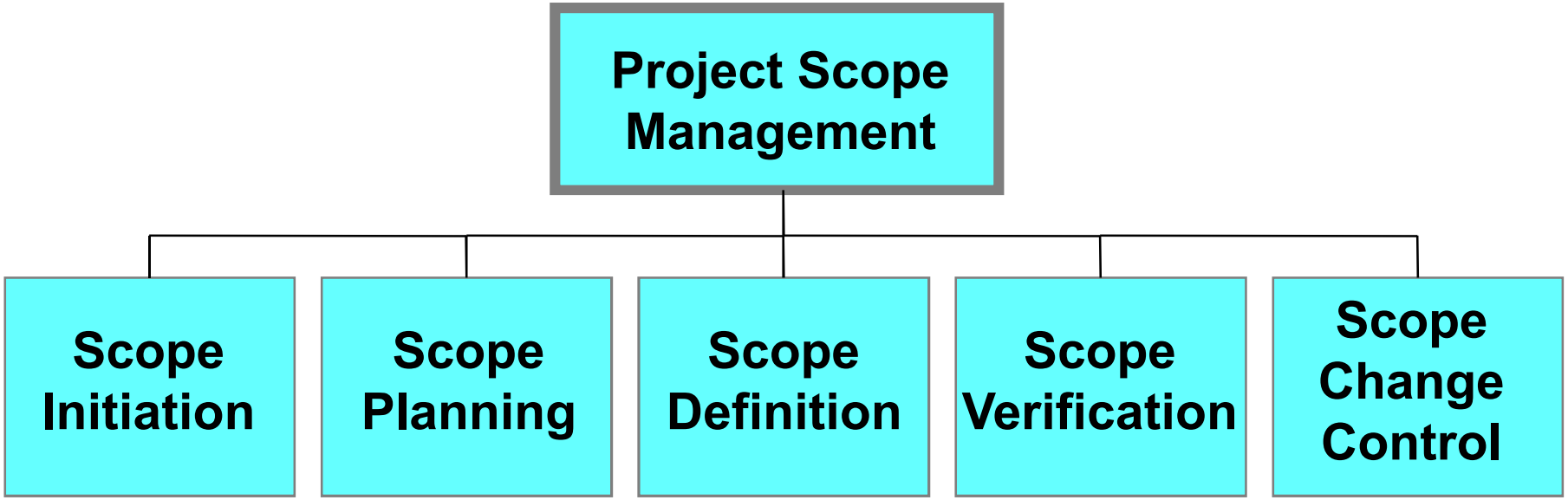
Scope Management

- *"Processes required to ensure that the project includes all the work required, and only the work required, to complete the project successfully" - PMI PMBOK Guide*



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Scope Initiation

- Project Selection Methods
  - Benefits and Impacts
  - Strategic Plan fit
- Project Charter
  - Formal recognition of the project
  - Business need identified and product description
- Project Manager Identified/Assigned
  - Proper authority delegated by management
- Constraints and Assumptions
  - Input to Risk Identification

Need criteria to accept or walk away from a project.

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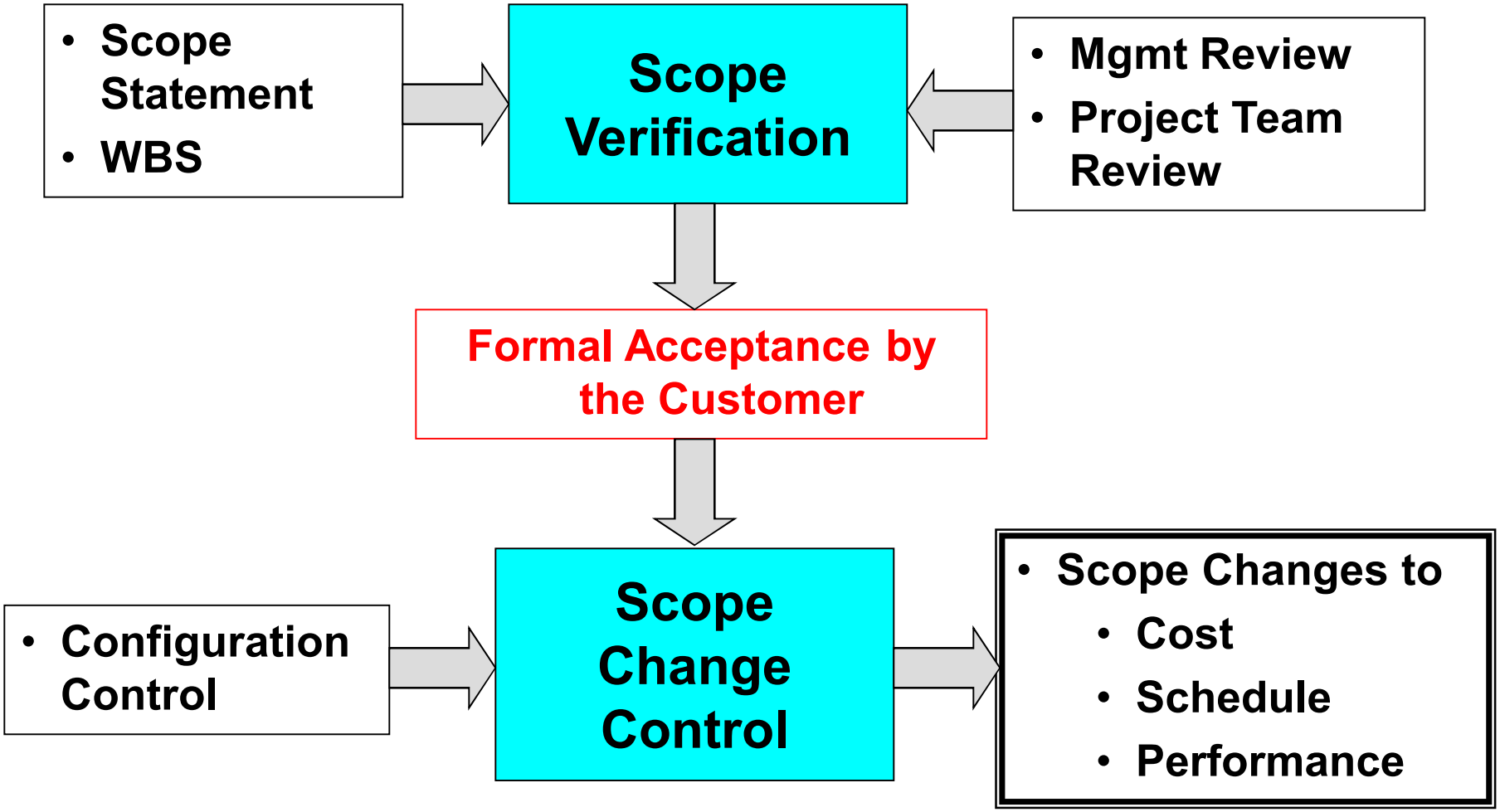
Scope Definition

Developing a Work Breakdown Structure (WBS)

- Decompose the project deliverables into smaller components until the work elements are defined at a level of detail to manage the project
  - Top-down initiated to define major deliverables
  - Bottoms-up for necessary detail to meet deliverables

Identifies the work necessary to deliver the product.

Scope Verification & Change Control



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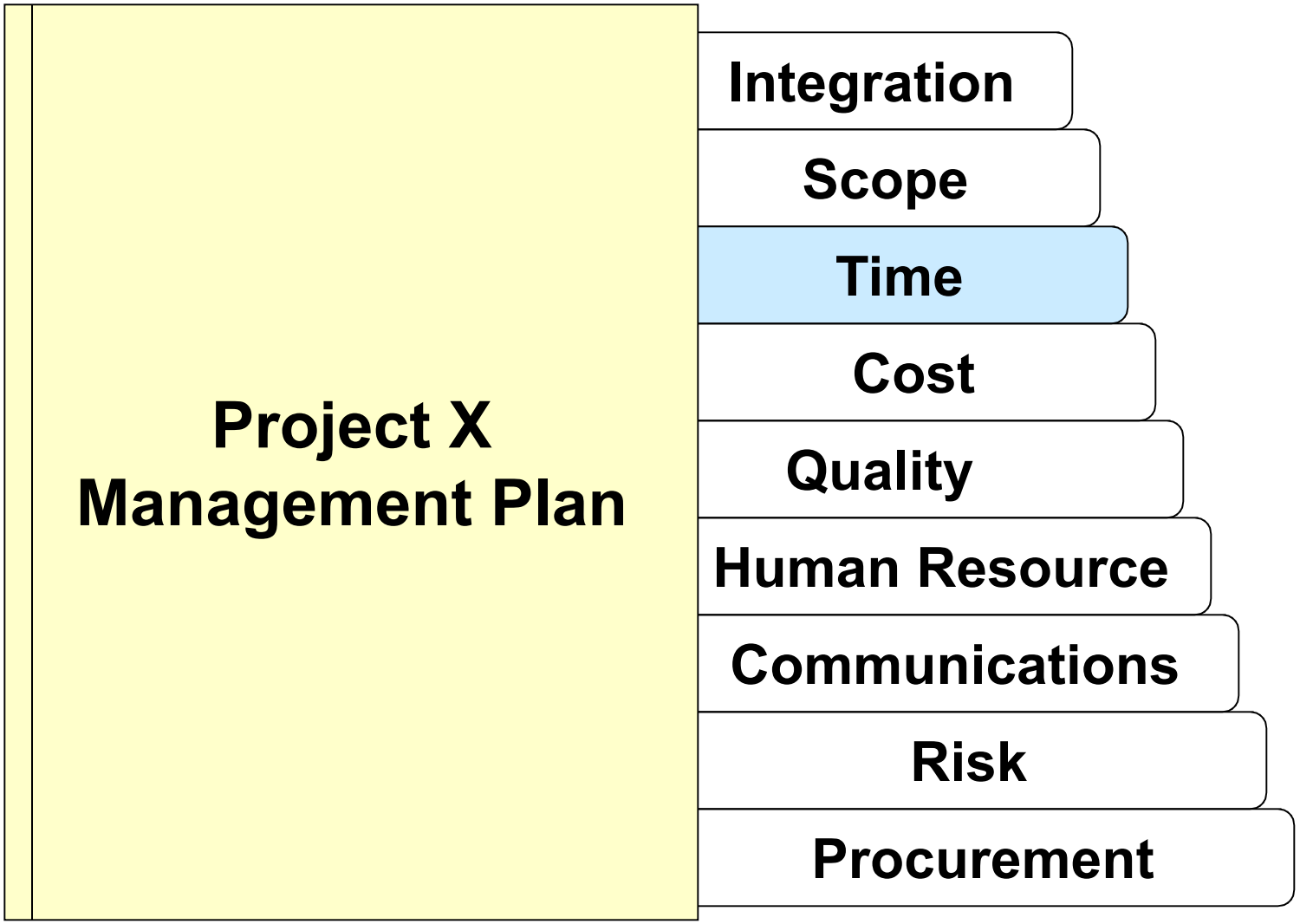
Lessons Learned

- Project manager must be given proper authority and be recognized by the project team
- Generate a WBS with the detail necessary to develop a plan that can be used to manage the project
- Formal customer and supplier agreement on scope and configuration control will minimize future conflicts

Key Elements of System Engineering



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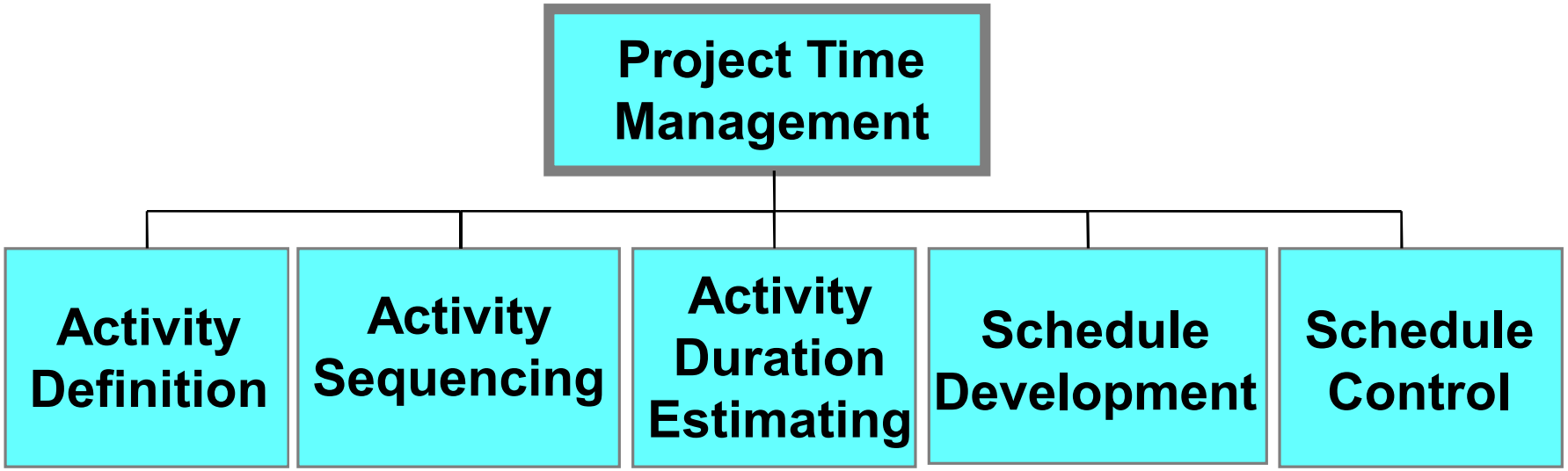
Project Time Management

- *"Processes required to ensure timely completion of the project" - PMI PMBOK Guide*



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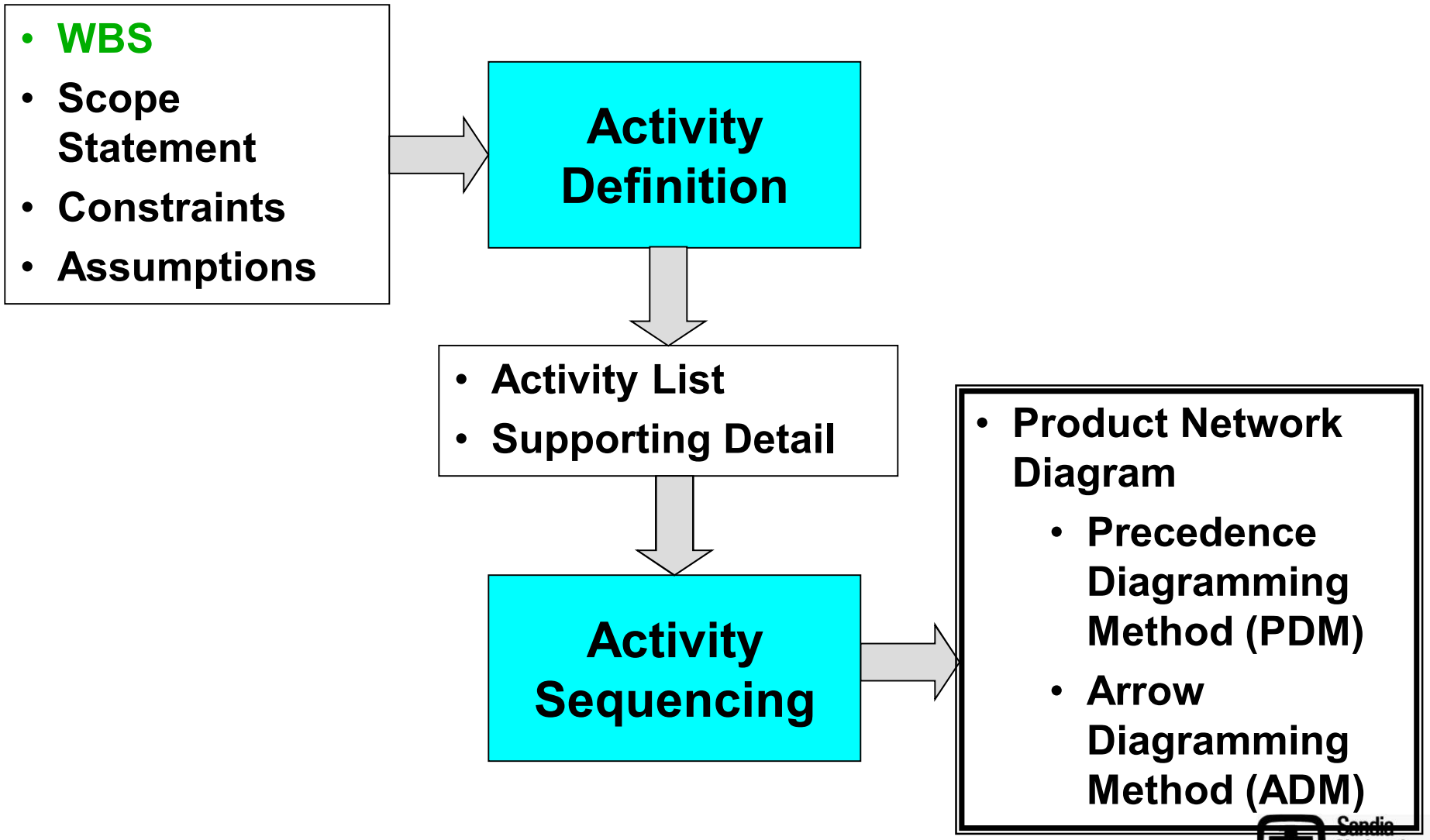
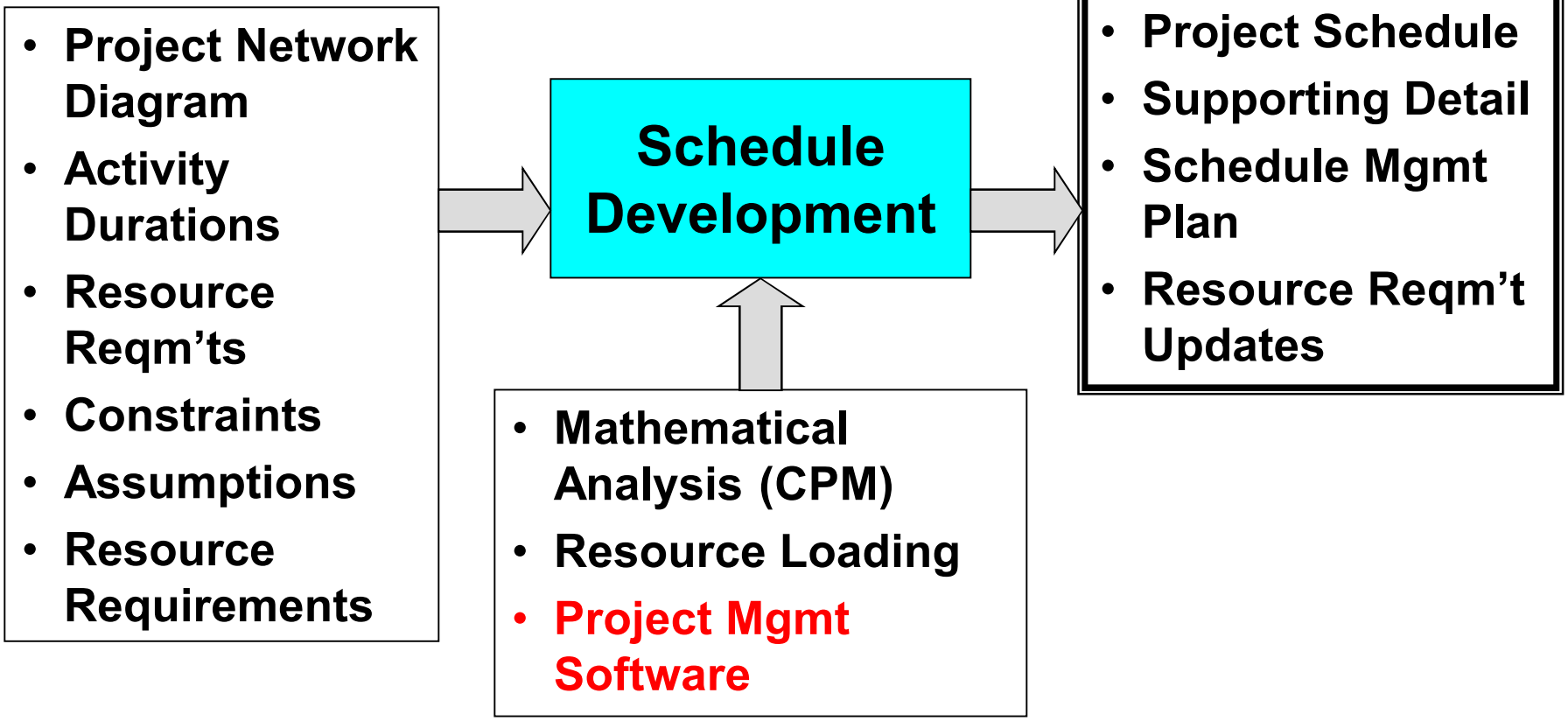
Activity Definition & Sequencing

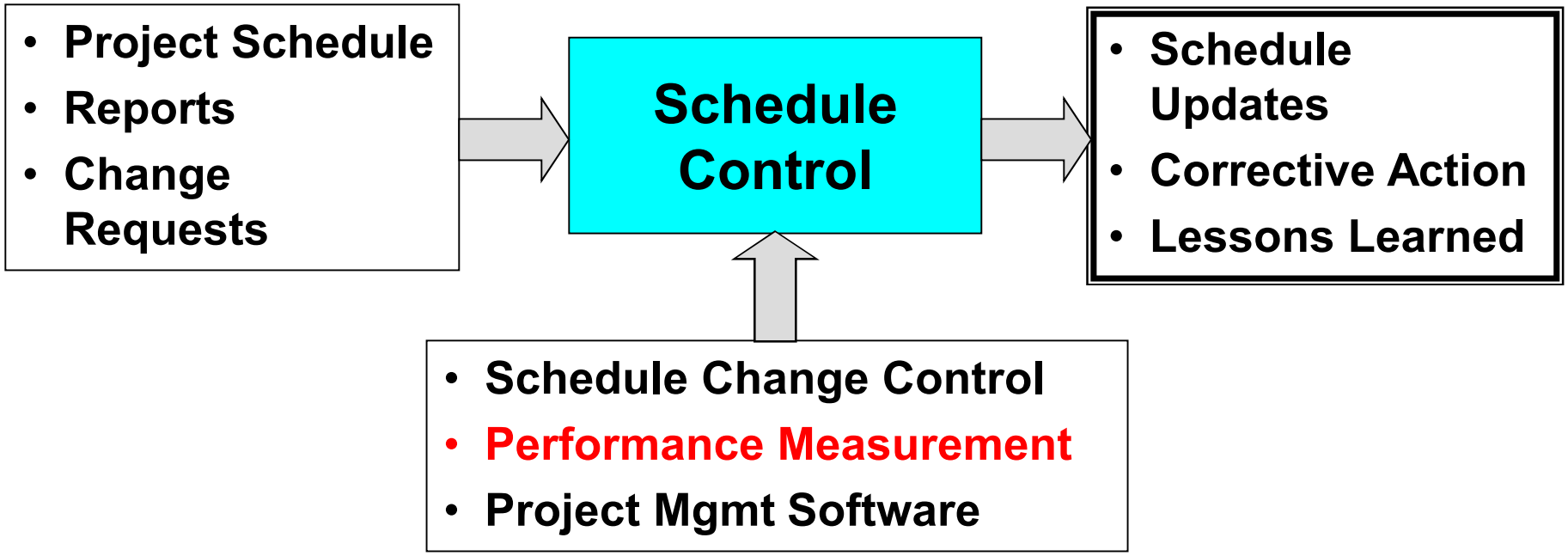


Schedule Development



Easy to let PM software overwhelm the project.

Schedule Control



Need timely notification on impending schedule slips.

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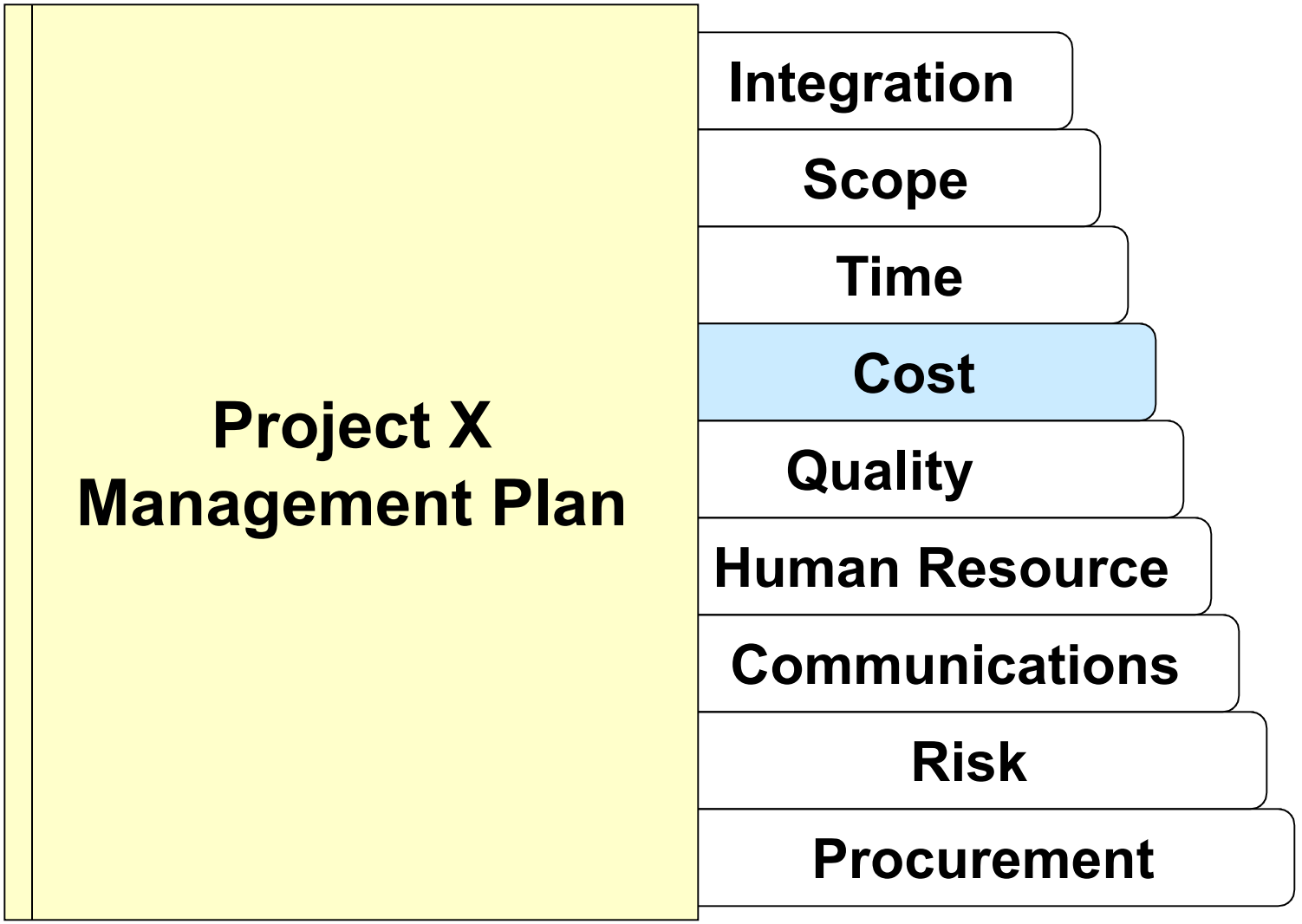
Lessons Learned

- Estimated most likely activity duration is usually not accurate so everyone adds slack to their activity
- Critical Path Analysis does not high-light critical or known high-risk activities that also require attention
- Engineers tend to put too much detail into their plans to manage appropriately
- Fixed end-point delivery dates require cost and performance tradeoffs

Key Elements of System Engineering



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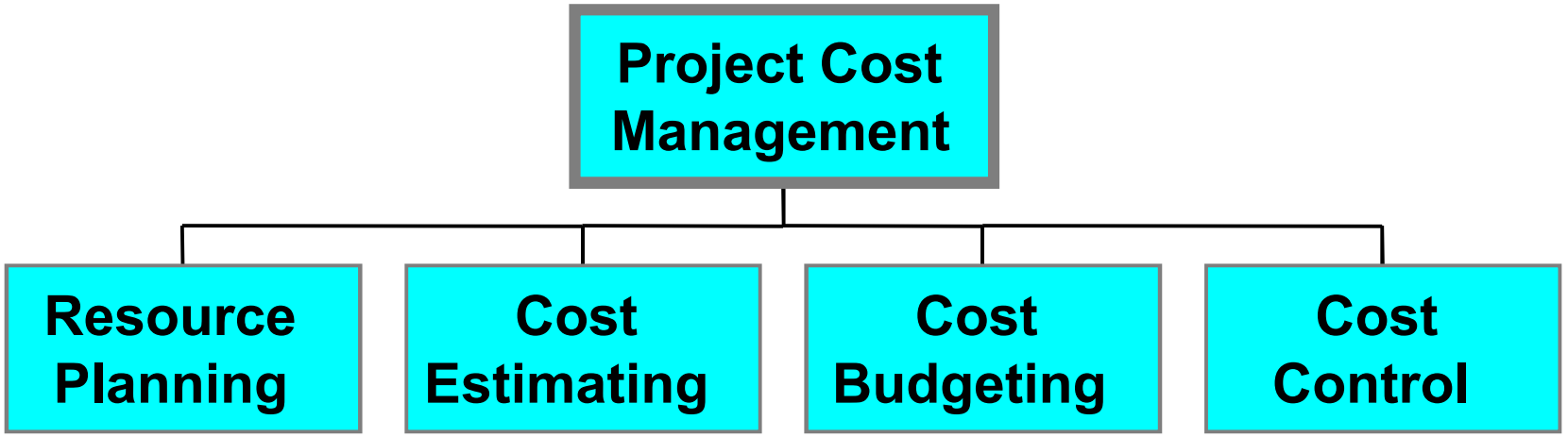
Project Cost Management

- *"Processes required to ensure that the project is completed within the approved budget" -*
  PMI PMBOK Guide



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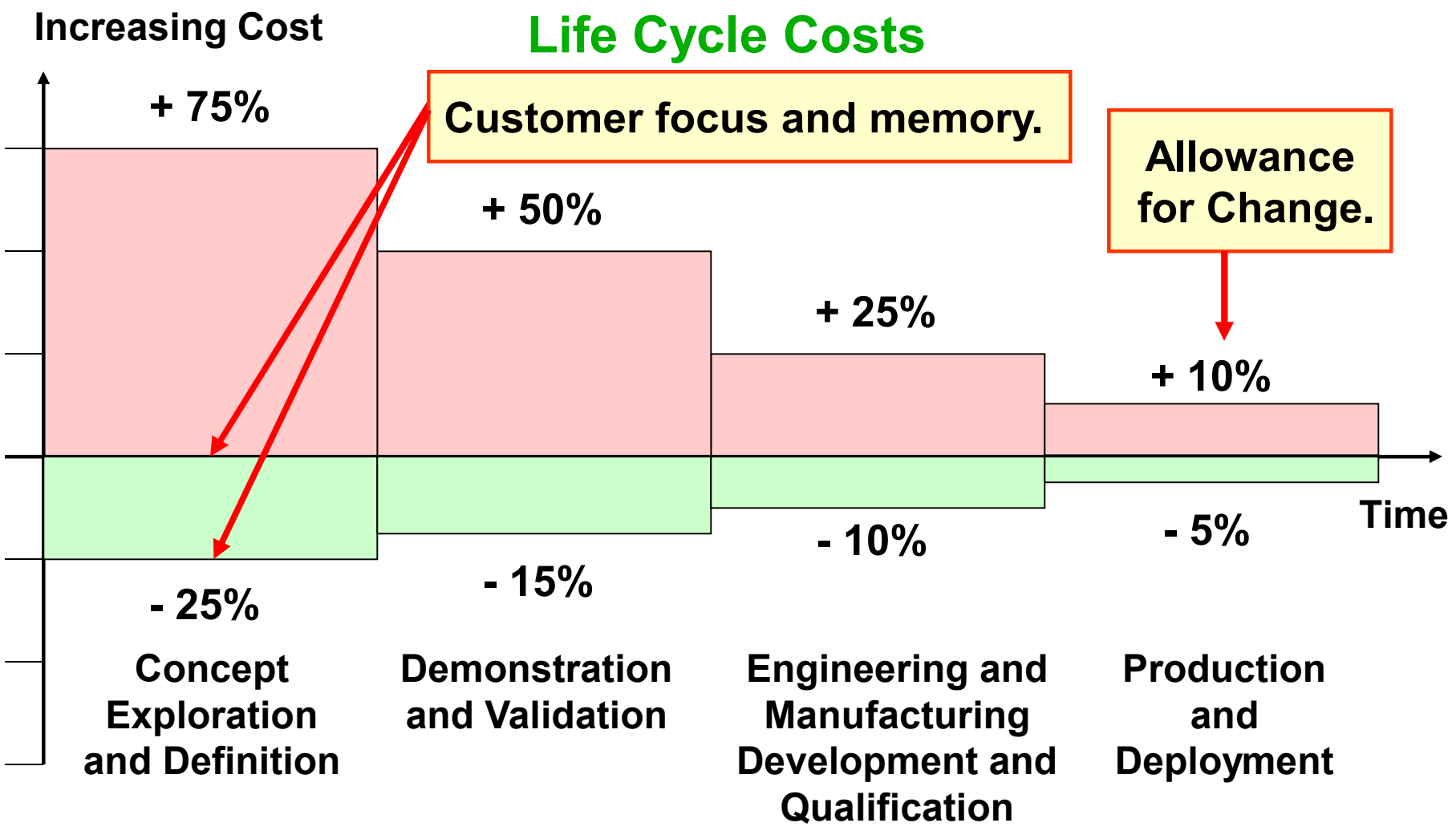
Cost Estimating



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Types of Cost Estimating

- **Rough Order of Magnitude (ROM): - 30% to +50%**
  - Used during project formation for initial evaluation
  - No detailed engineering definition
  - Based on experience, capacity, and level of effort

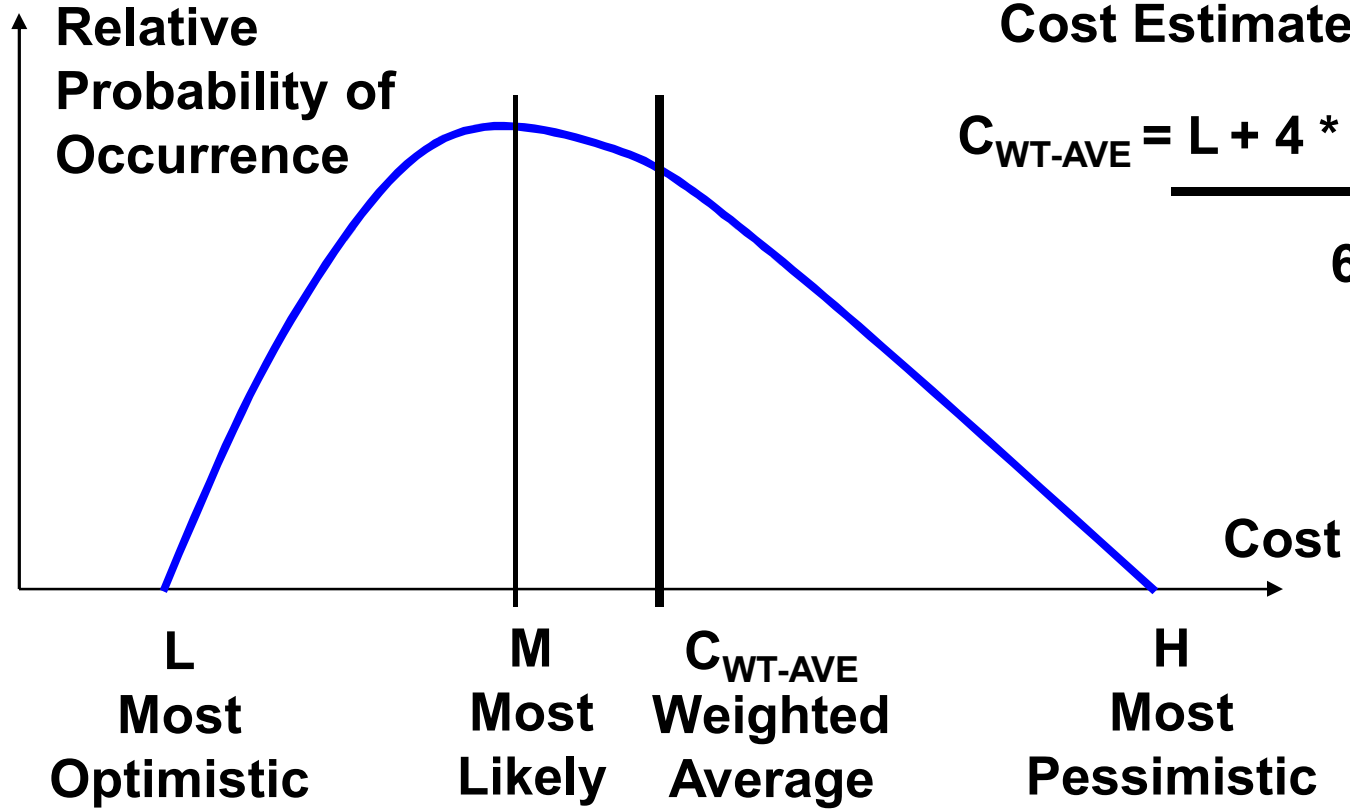
- **Budget: -15% to +25%**
  - Used to establish required funds and for project approval
  - Prepared from preliminary project plan and design definition
  - Based on estimates for labor, testing, material and equipment

- **Definitive: -5% to +10%**
  - Used for bid proposals and scope changes
  - Prepared from mature project plan and design definition
  - Based on higher resolution for labor, testing, material and equipment

Cost Estimating Methods

- Top-Down or Analogous
  - Quick approach and low fidelity
  - Compare to previous experience
- Bottom-Up
  - Rigorous approach and high fidelity (WBS based)
  - Utilize experience from work force
- Parametric Modeling
  - Use project parameters in a mathematical model
  - More accurate with a good data base
  - Good for sensitivity analyses
- Activity Based
  - Accounts for activities that drive indirect costs
  - Provides more accurate manufacturing cost drivers

Cost Range Estimating



Cost Estimate

$$C_{WT\text{-}AVE} = \frac{L + 4 * M + H}{6}$$

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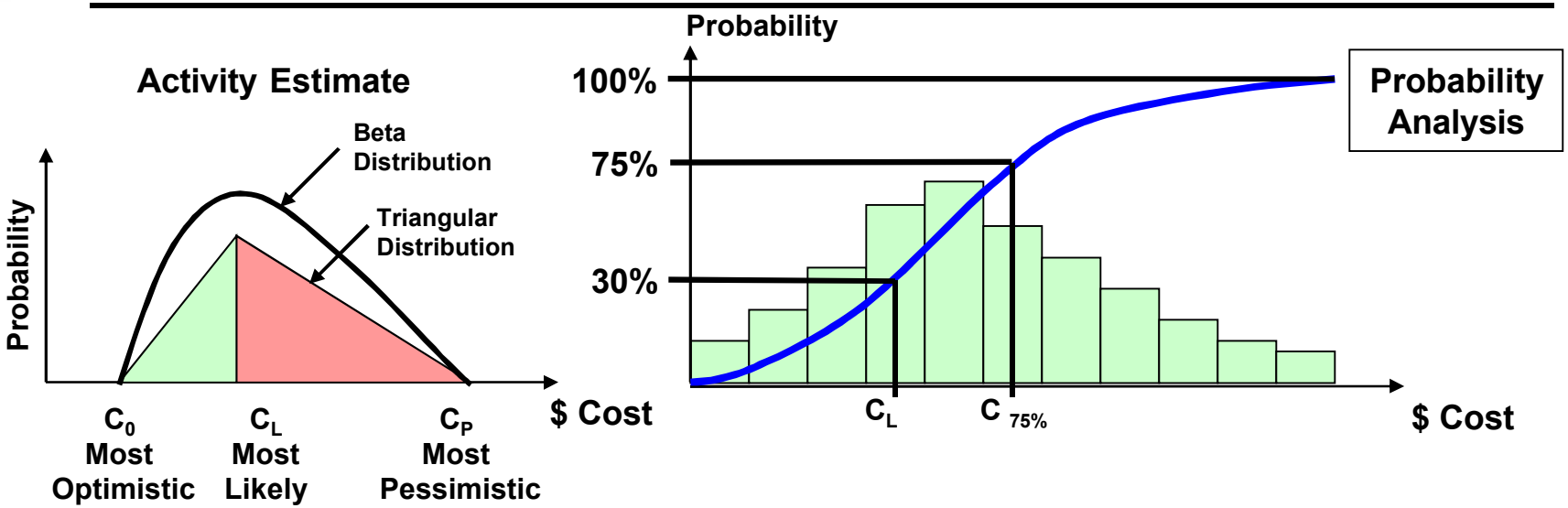
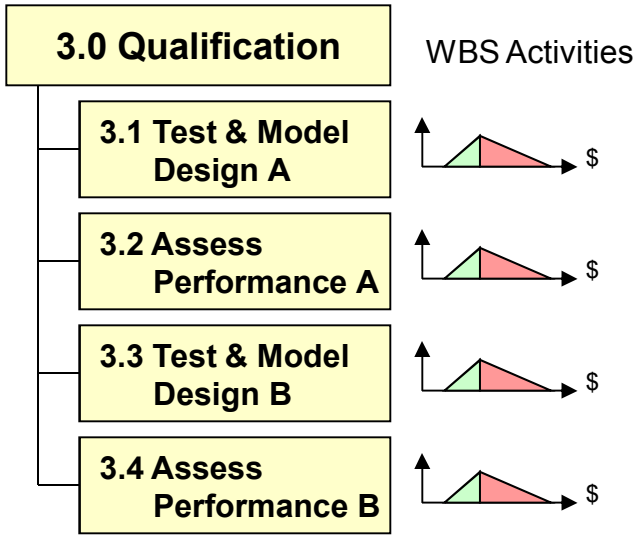
Monte Carlo Cost Simulation





Simulation can help contingency planning.

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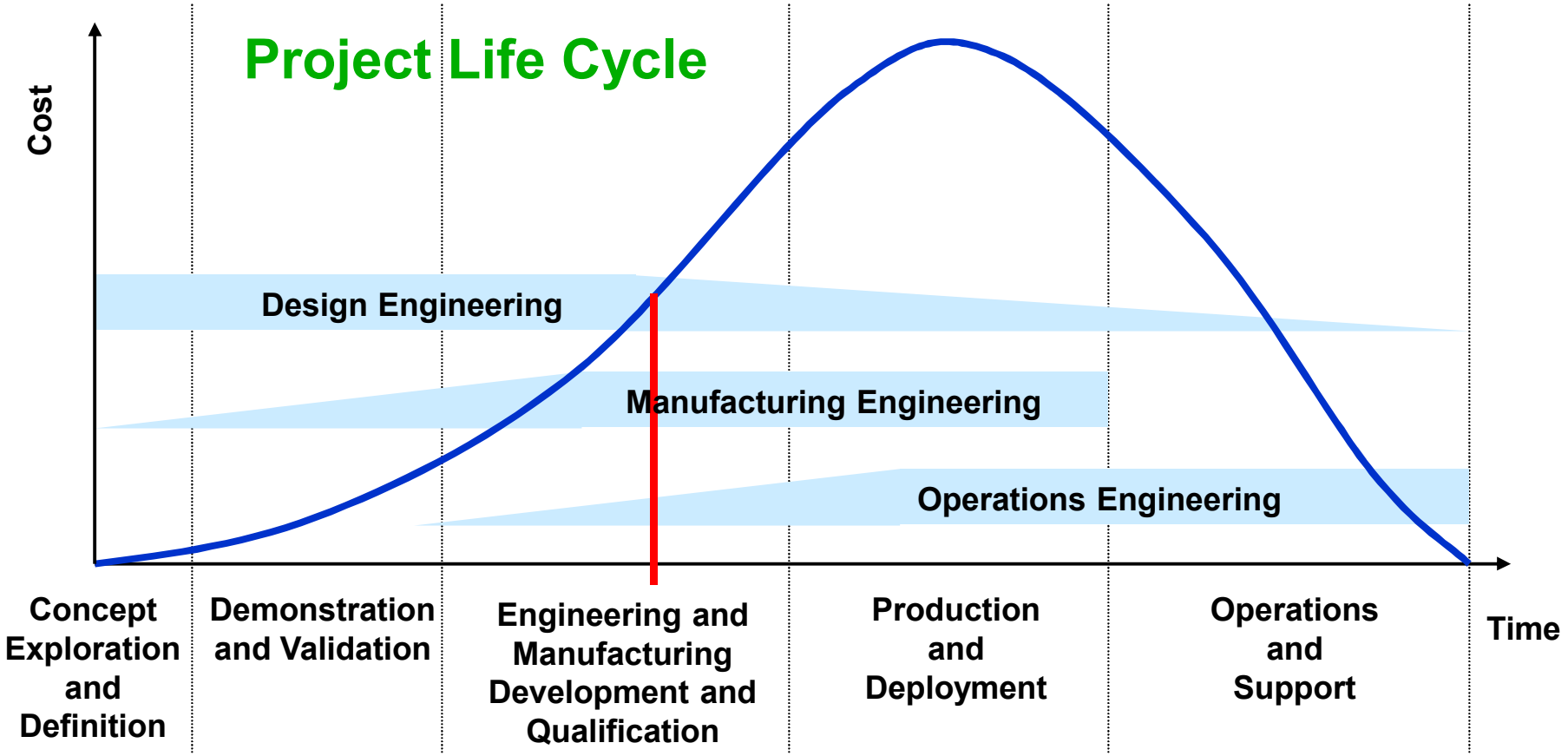
Project Cost



~ 80% of the total project cost is locked in during the design phase.

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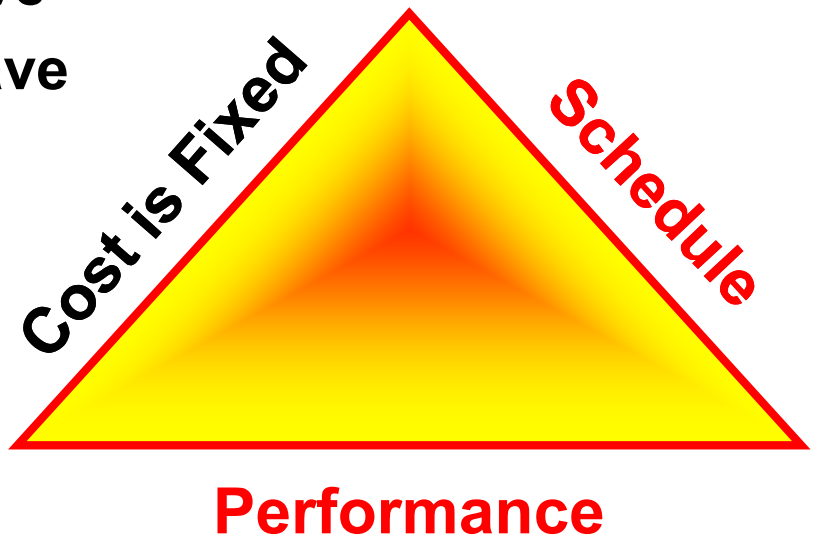
Cost as An Independent Variable

- CAIV is being used to control costs by forcing tradeoffs with performance and schedule
- Aggressive cost targets are set early
- Performance priorities are established
  - Must Have
  - Like to Have
  - Wish to Have



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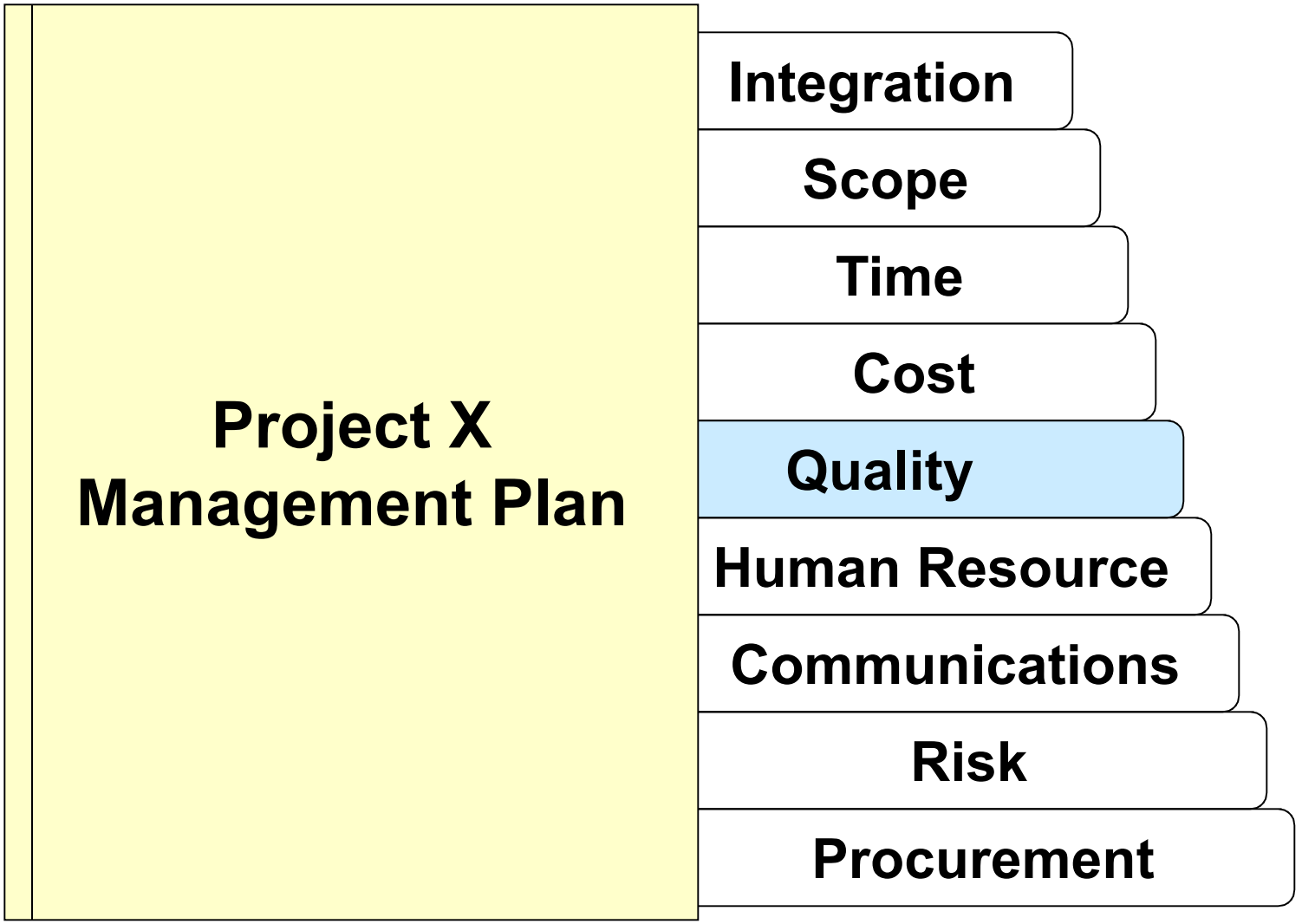
Lessons Learned

- Bottoms-up cost estimates are conservative
- Top-down cost estimates are optimistic
- Estimated most likely costs are usually not accurate so everyone hides contingency
- Always generate a management reserve or contingency
- Indirect or burden loads are a moving target
- Baseline the budget against scope ASAP
- Earned Value Analysis requires work activity based costing – Hard to apply to level-of-effort work
- Cost escalation will terminate a project quicker than not meeting schedule or performance

Key Elements of System Engineering



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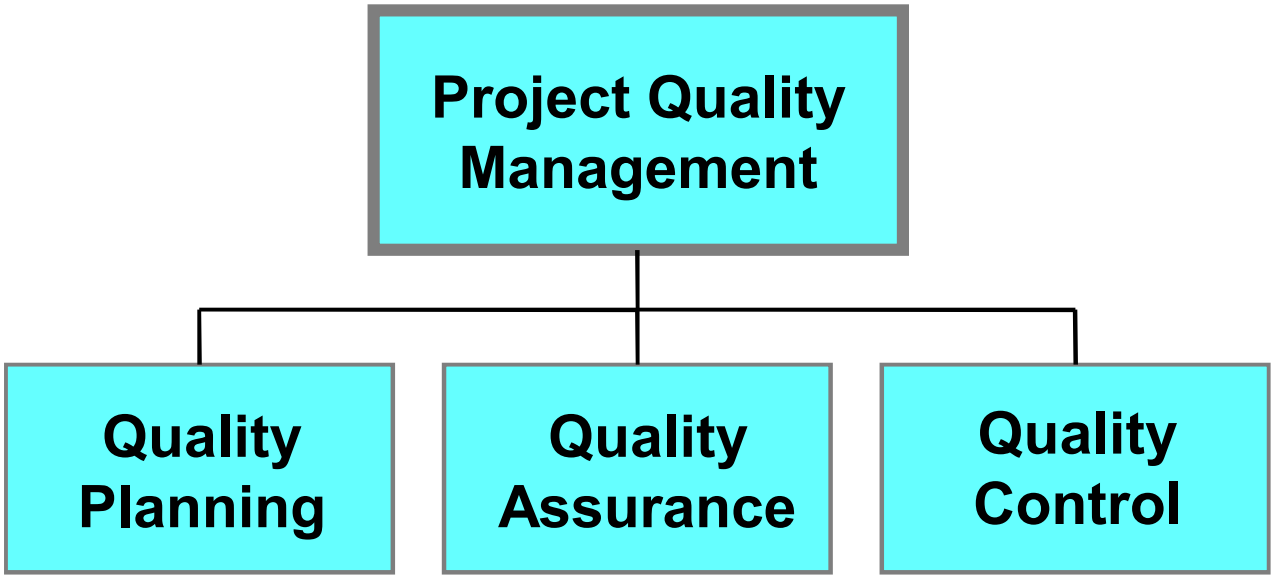
Project Quality Management

- *"Processes required to ensure that the project will satisfy the needs for which it is undertaken" -*
  PMI PMBOK Guide



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Quality Planning

Quality is meeting customer requirements and expectations for cost, schedule and performance

- Quality Criteria
  - ISO9000
  - Internal Quality Policy and Procedures
  - Customer Quality Criteria
  - Standards and Government Regulations
- Quality Implementation
  - Philip B. Crosby
  - W. Edwards Deming
  - J. M. Juran
  - G. Taguchi
  - J. Lomak

- Six Sigma
- Zero Defects
- Quality Circles
- Lean Manufacturing
- Continuous Improvement Process (Kaizen)

Quality Principles

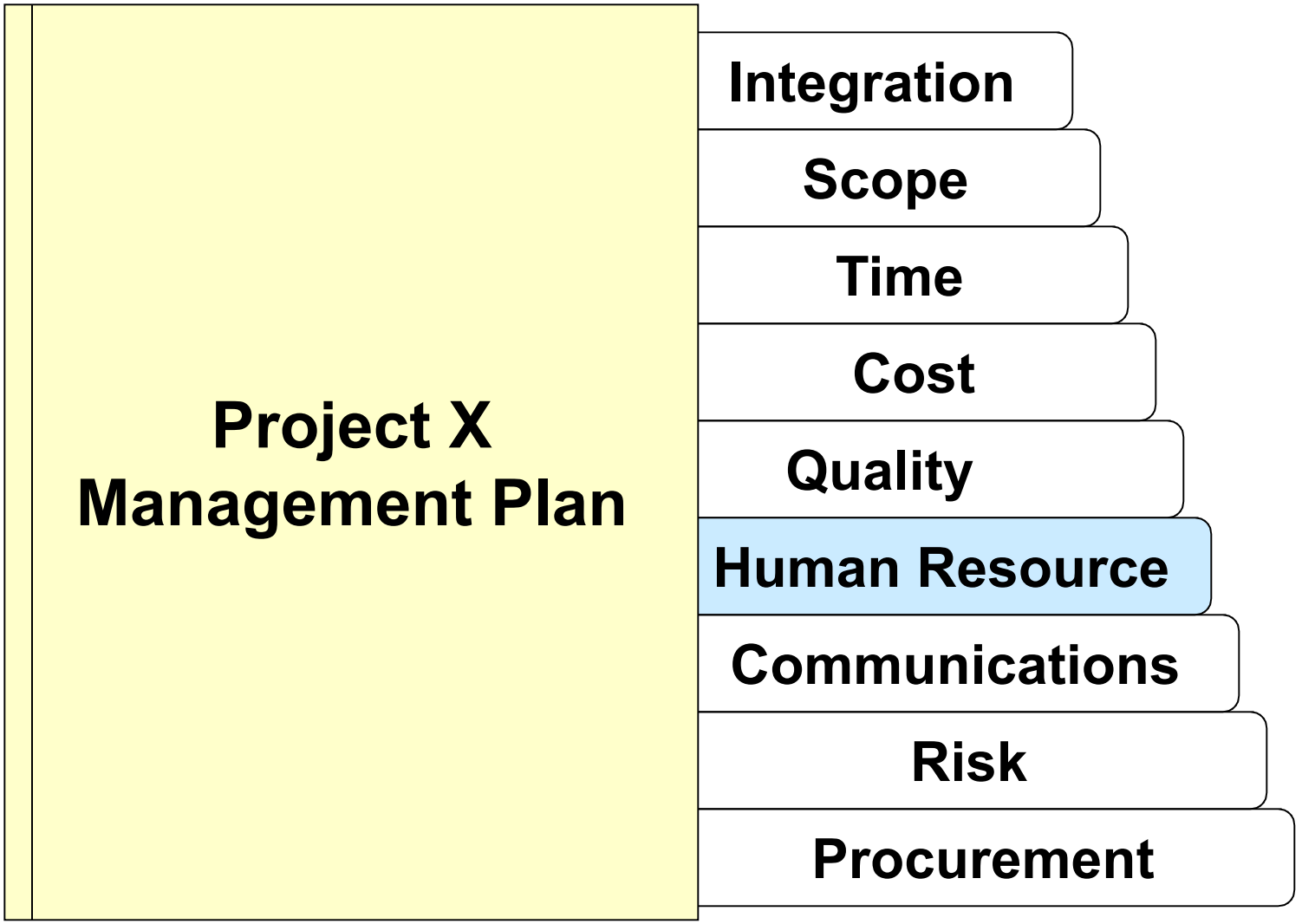
- If it is not documented, it does not exist
  - Need physical evidence
- If it cannot be measured or tested it is not a requirement
  - SMART Requirements =
    Specific / Measurable / Achievable / Relevant / with Time frames
- Strive to exceed expectations
  - Expectations are personal perceptions based on past experiences and anticipated outcomes
  - Important to know and understand your customer
- Focus on prevention rather than correction

Excellence doesn't just happen; it's a decision you make every day.
Author Unknown

Lessons Learned

- You should not have to prepare for a quality audit
- Quality plans must be easy to implement
- Project team has to be trained on quality implementation
- Hard to avoid the compliance mentality
- Self assessments can identify areas for improvement

Key Elements of System Engineering



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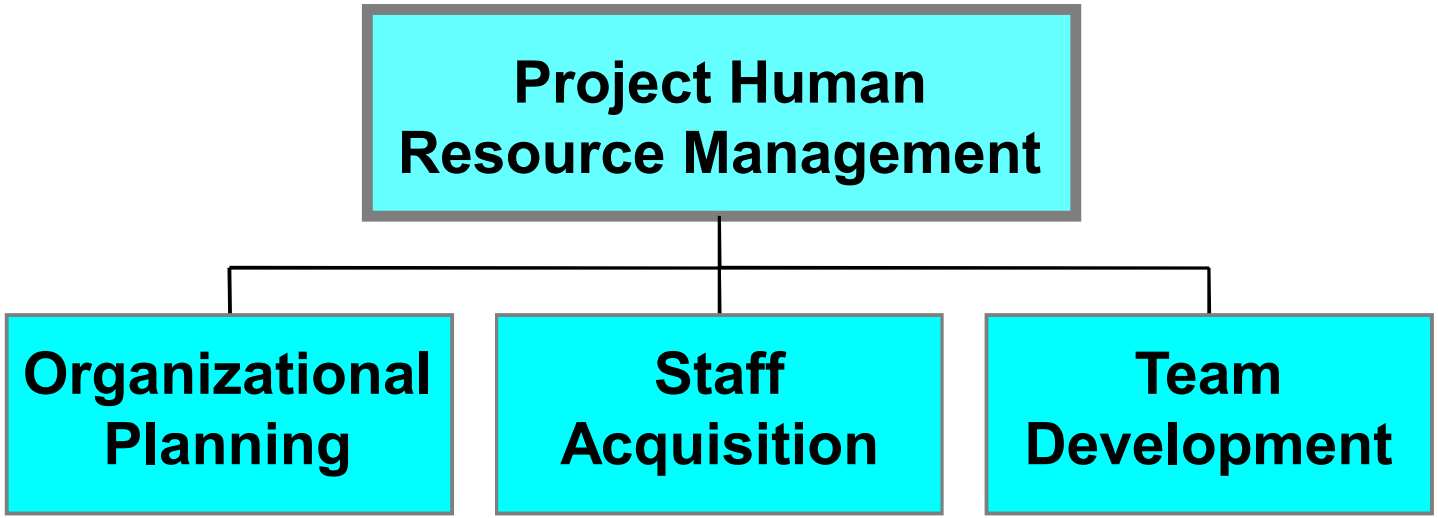
Project Human Resource Management

- *"Processes required to make the most effective use of the people involved with the project" -*
  PMI PMBOK Guide



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Hiring or Selecting Staff

- **Key attributes to look for in a candidate:**
  - **Technical and programmatic background**
  - **Experience base – successes and failures**
  - **Track record for meeting deliverables – execute**
  - **Communication skills (written / verbal / non-verbal) and style**
  - **Ability to work in a team environment – player or leader**
  - **Commitment or dedication – work ethic**
  - **Passion for excellence**
  - **Attitude – enthusiasm or energy**
  - **Willingness to change**
  - **Critical thinking – intellectual curiosity**
  - **Maturity – presence or self-esteem**
  - **Integrity – admit weaknesses and mistakes**
  - **Critical references – *Would they rehire the individual?***

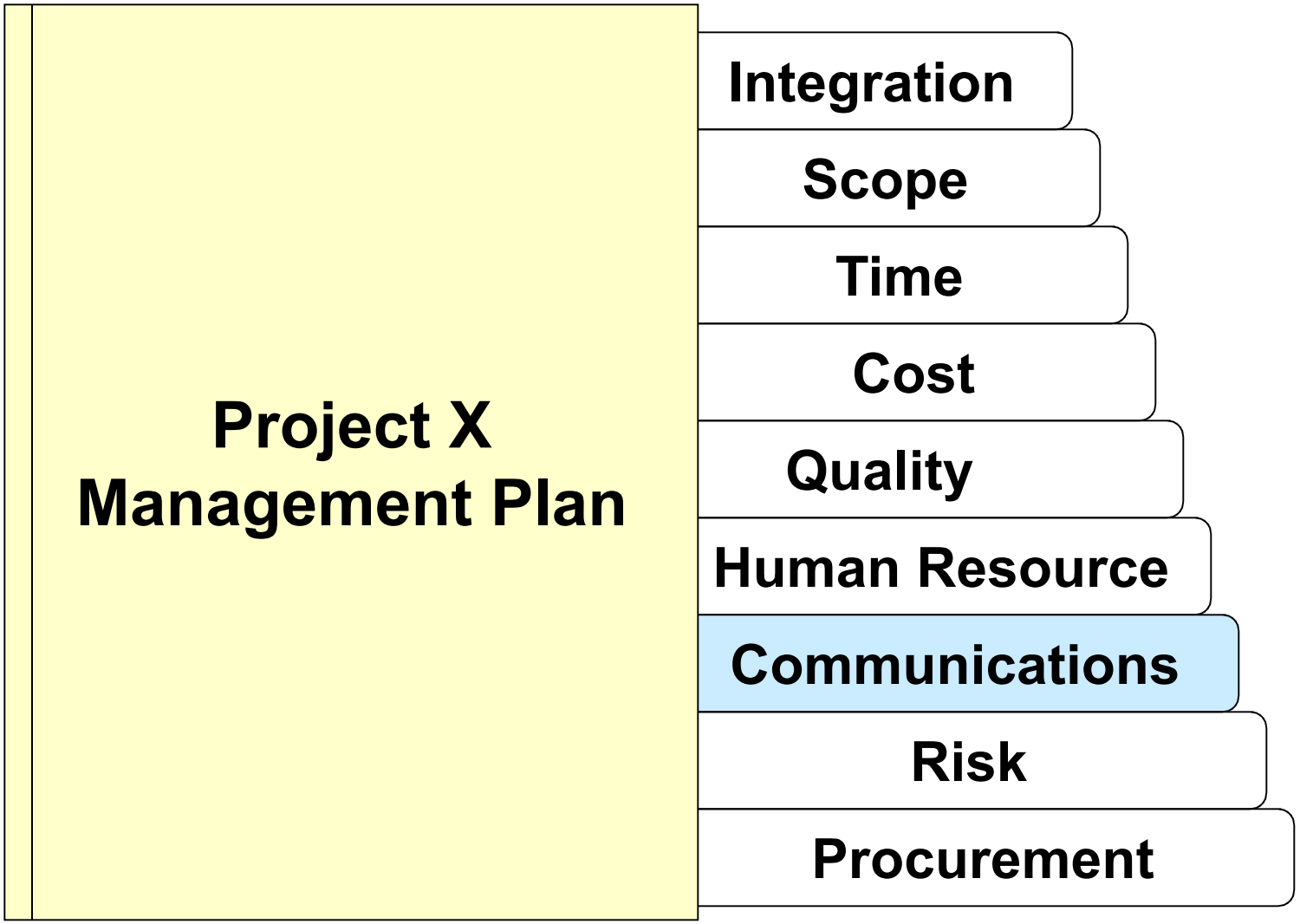
Surround yourself with the best people possible.

Decision Making Styles

- **Autocratic or Dictatorial**
  - Solicits little or no information from the team
  - Decision made independently by project manager
- **Consultive Autocrat**
  - Solicits extensive information from the team
  - Substantive decision authority retained by project manager
- **Consensus**
  - Initiates team discussion and information exchange
  - Encourages a team decision
- **Shareholder *(poor leadership)***
  - Little or no team discussion or information exchange
  - Team is given ultimate decision authority

Good project manager will use the appropriate decision style for the situation.

Key Elements of System Engineering



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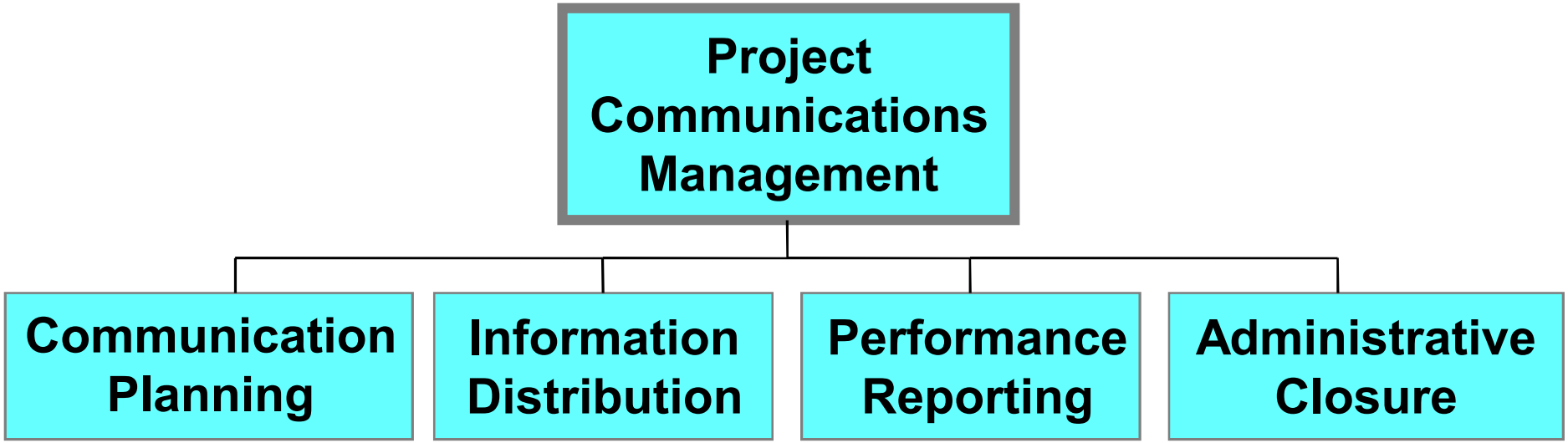
Project Communication Management

- *"Processes required to ensure timely and appropriate generation, collection, dissemination, storage, and ultimate disposition of project information" - PMI PMBOK Guide*



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Communications Planning

Communication Management Plan

Who:
- **Distribution Structure**
  - Internal, Suppliers, Stakeholders/Customers
- **Need-to-Know**
  - Proprietary or Classified Info

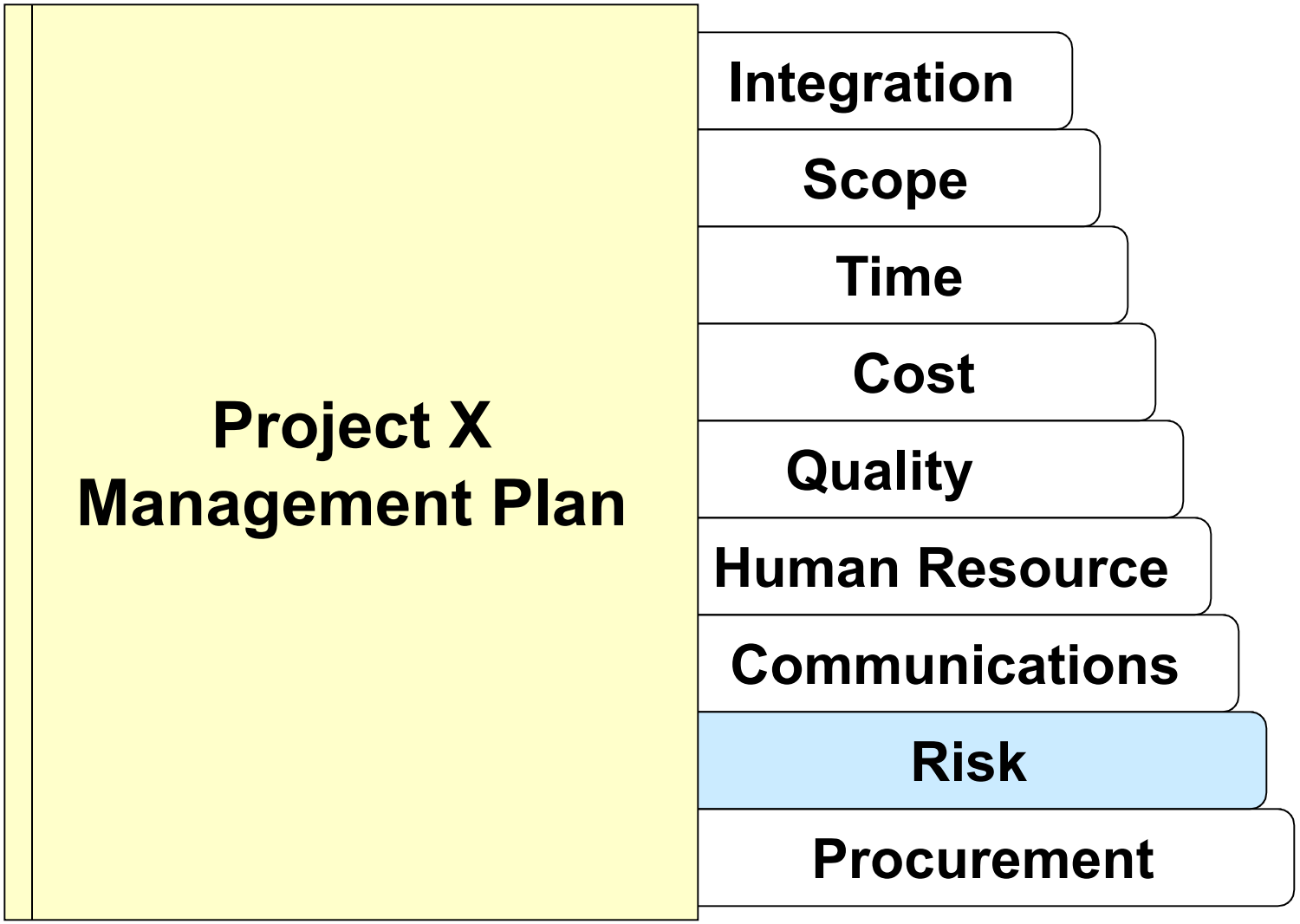
When:
- **Schedules - Project Calendar**
  - Meetings, Status Reports

How:
- **Collection Process**
- **Filing Structure and Retrieval Process**
- **Information Distribution**
- **Information Technology System**
- **Access Control for Need-to-Know**

Reviews

- **Formal Design Reviews**
  - Customer Requirements
  - Conceptual Design
  - Baseline Design
  - Final Design
  - Production Readiness
- **Peer Reviews**
- **Programmatic Reviews**
  - Earned Value Analysis
  - Variance Analysis
  - Budget Status/Trends
  - Schedule Status/Trends
- **Customer Tech Reviews**
  - Performance Status
- **Test Reviews**
  - Test/Facility Readiness
  - Pre- and Post-Test Analysis
- **Management Reviews**
- **Risk Reviews**
  - Consequence & Impact Analysis
  - Trigger Points
  - Mitigation Plans

Key Elements of System Engineering



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What is Risk?

"Project *Risk* is an uncertain event or condition that, if it occurs, has a positive or negative effect on a project objective."

"Guide to the Project Management Body of Knowledge," 2000 Edition, Project Management Institute

"*Risk* is a measure of the probability and consequence of not achieving a defined project goal."

"Project Management - A Systems Approach to Planning, Scheduling, and Controlling,"
Harold Kerzner, Ph.D., Van Nostrand Reinhold, Fifth Edition, 1995

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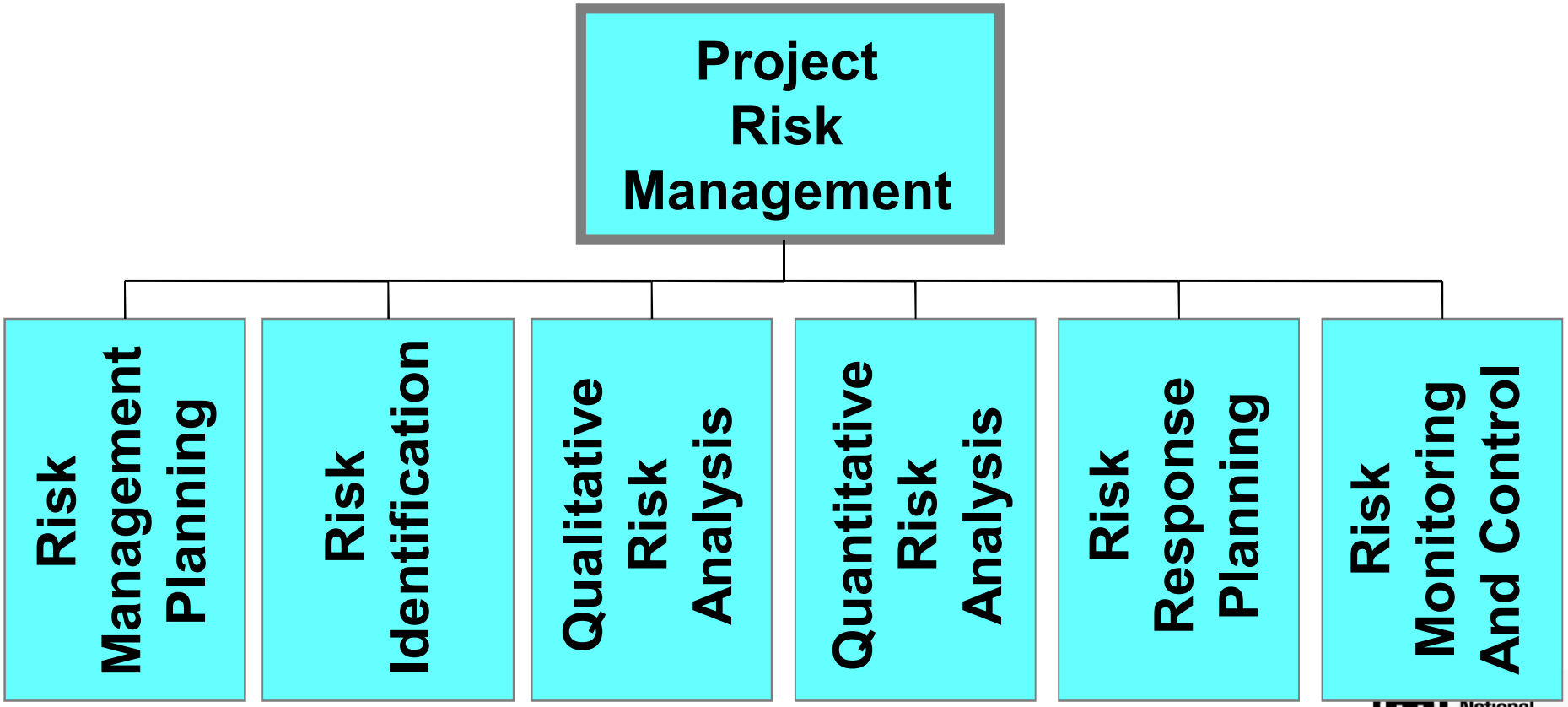
Project Risk Management

- *"Systematic process of identifying, analyzing, and responding to project risk" - PMI PMBOK Guide*



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Risk Management Process

The risk management process involves the five steps listed below:

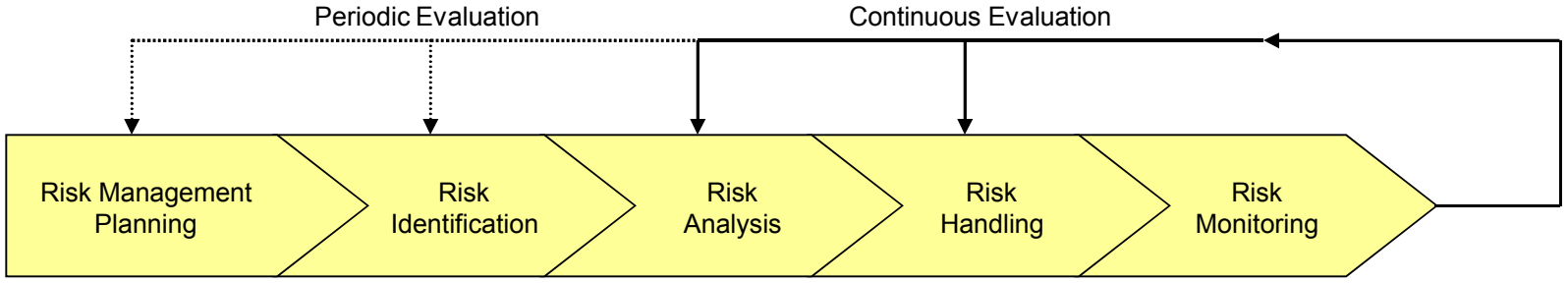
Risk Management Planning – Identifying how risk management will be performed

Risk Identification – Developing a comprehensive list of risks for qualitative analysis, quantitative analysis, and response planning.

Risk Analysis – Qualitatively assigning likelihood and consequence ratings to each risk and possibly quantitatively determining the likelihood of cost or schedule overrun and performance nonconformance.

Risk Handling – Developing and implementing strategies with the purpose of eliminating, or minimizing, the likelihood and/or consequences of an identified risk.

Risk Monitoring – Tracking the identified risks and ensuring the execution of risk-handling plans



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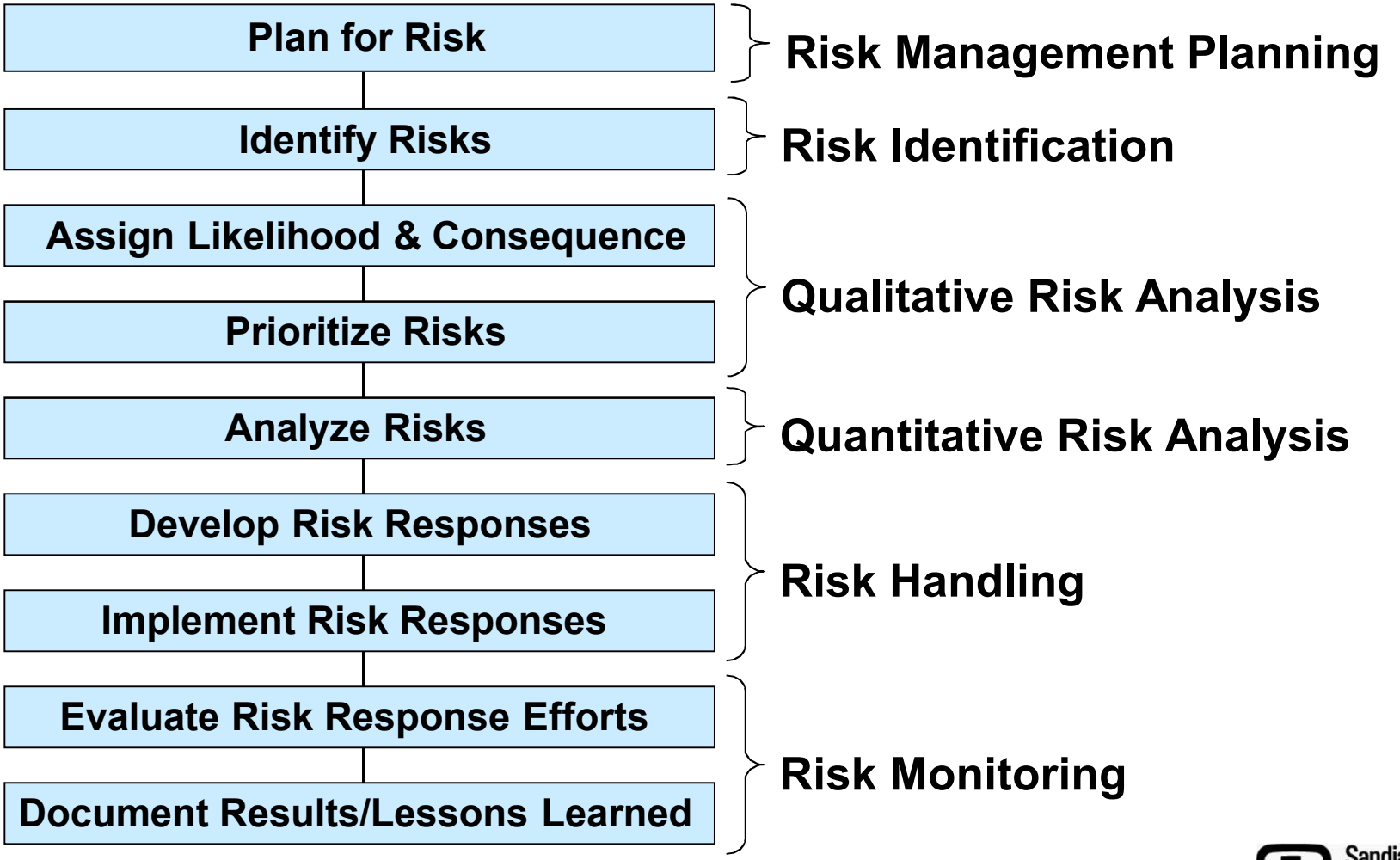
Risk Management Definition

- ***Risk Management* is the systematic approach to identifying, analyzing, and handling risk**
  - The purpose of risk management is to maximize the *likelihood and consequence* of positive events and minimize the *likelihood and consequence* of adverse events to project objectives
  - It is through risk management that risk events are assessed and systematically managed to reduce project risk to an acceptable level
  - Formal Risk Management is expected by customers and management
  - Risk Management is a good business practice

Risk Management Plan



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Risk Quantification

- **Analyze the Highest Risks**
  - **Focus on High risks (from preliminary assessments)**
  - **Establish the Likelihood of Occurrence (each risk)**
    - **Qualitative Criteria:**

Low = 1

- Routine for similar items. No difficulty is expected.

Moderate = 3

- Not routine. Pushing the limits of previous experience and current existing capabilities. Dependent on deliverables and successes from others who are not directly a part of and funded by the project.

High = 5

- Outside current experience and is in an unknown domain. Impossible to difficult. Extremely complex.

  - **Document the Likelihood analysis**

Risk Quantification

- **Analyze the Highest Risks (continued)**
  - **Establish the Impact/Consequence (each risk)**
    - **Qualitative Criteria:**

Low = 1

- Requires changes to requirements or the project plan that are believed to be negotiable and that and that can be worked around without loss of capability or project impact.

Moderate = 3

- Requires changes to requirements or the project plan that may be negotiable, but for which there is some loss in capability or project impact.

High = 5

- Requires unacceptable changes to requirements or project plan resulting is a significant loss in capability or impact to the project.

  - **Document the Impact/Consequence analysis**

Criteria for Probability / Likelihood Values

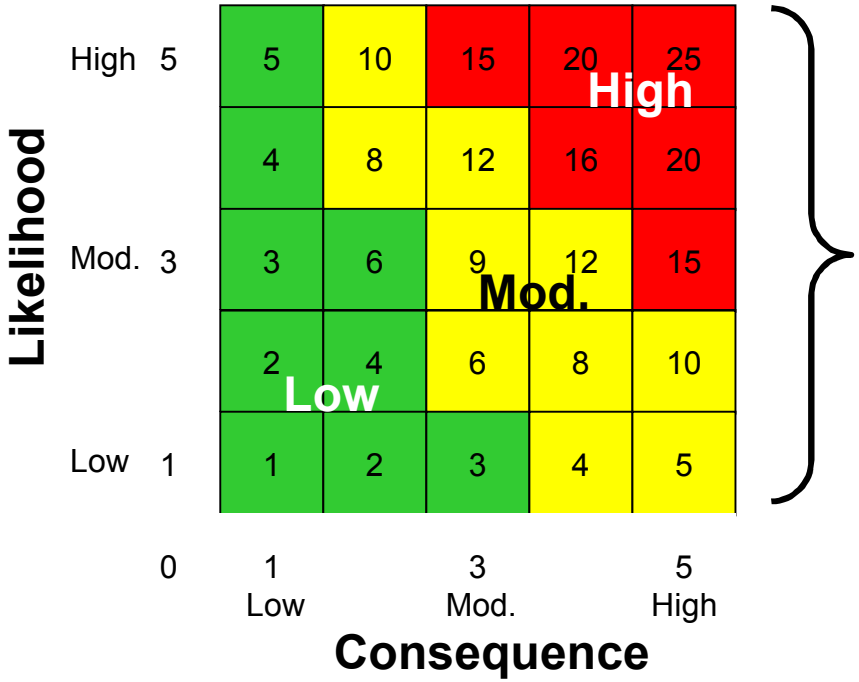
Probability or Likelihood	Area	Criteria
A Very Low	Design	All design and development activities are routine and involve standard application of existing technology.
	Safety	Activity does not involve safety or environmental issues.
	Processes	Existing process meets manufacturing requirements for item being fabricated.
	Facilities	Suitable facilities and equipment exist and are in use.
B Low	Design	Design and development activity is nearly routine in nature or involves no more than a new application of an existing technology.
	Safety	Activity involves no more than standard safety or environmental issues.
	Processes	Required process is a combination of demonstrated manufacturing processes that all exceed manufacturing requirements.
	Facilities	Suitable facilities exist. Minor equipment modifications or investment are needed.
C Moderate	Design	Design and development activities are complex, involve a new technology or process at a site, or require modification of an existing technology or process.
	Safety	Activity involves new safety or environmental issues for which general solutions are defined.
	Processes	Required process is a combination of demonstrated manufacturing processes, some of which exceed manufacturing requirements.
	Facilities	Moderate facilities and/or equipment modifications are required.

Criteria for Probability / Likelihood Values (cont.)

D High	Design	Design and development activities are very complex or involve a technology or process new to any of the involved sites.
	Safety	Activity involves new safety or environmental issues for which general solutions are not defined but tractable.
	Processes	Required process is a combination of demonstrated manufacturing processes, some of which fall below industry state of the art.
	Facilities	Major facilities and/or equipment development are required.
E Very High	Design	Design and development are extremely complex or involve a technology that is new to the industry.
	Safety	Activity involves new safety or environmental issues for which general solutions are not defined and cannot be developed in a tractable manner.
	Processes	Comparable process is not available and some of the manufacturing requirements are expected to be above the state of the art.
	Facilities	The necessary facilities and/or equipment exceed the state of the art.

Risk Quantification

- **Analyze the Highest Risks (continued)**
  - **Assess Each Risk**
    - **Establish an overall risk rating using a qualitative risk matrix**
    - **Document the overall Risk assessment**
    - **Identify "Triggers" or "Trip Points" to evaluate mitigation strategy effectiveness**



Risk Rating =
Likelihood X Consequence

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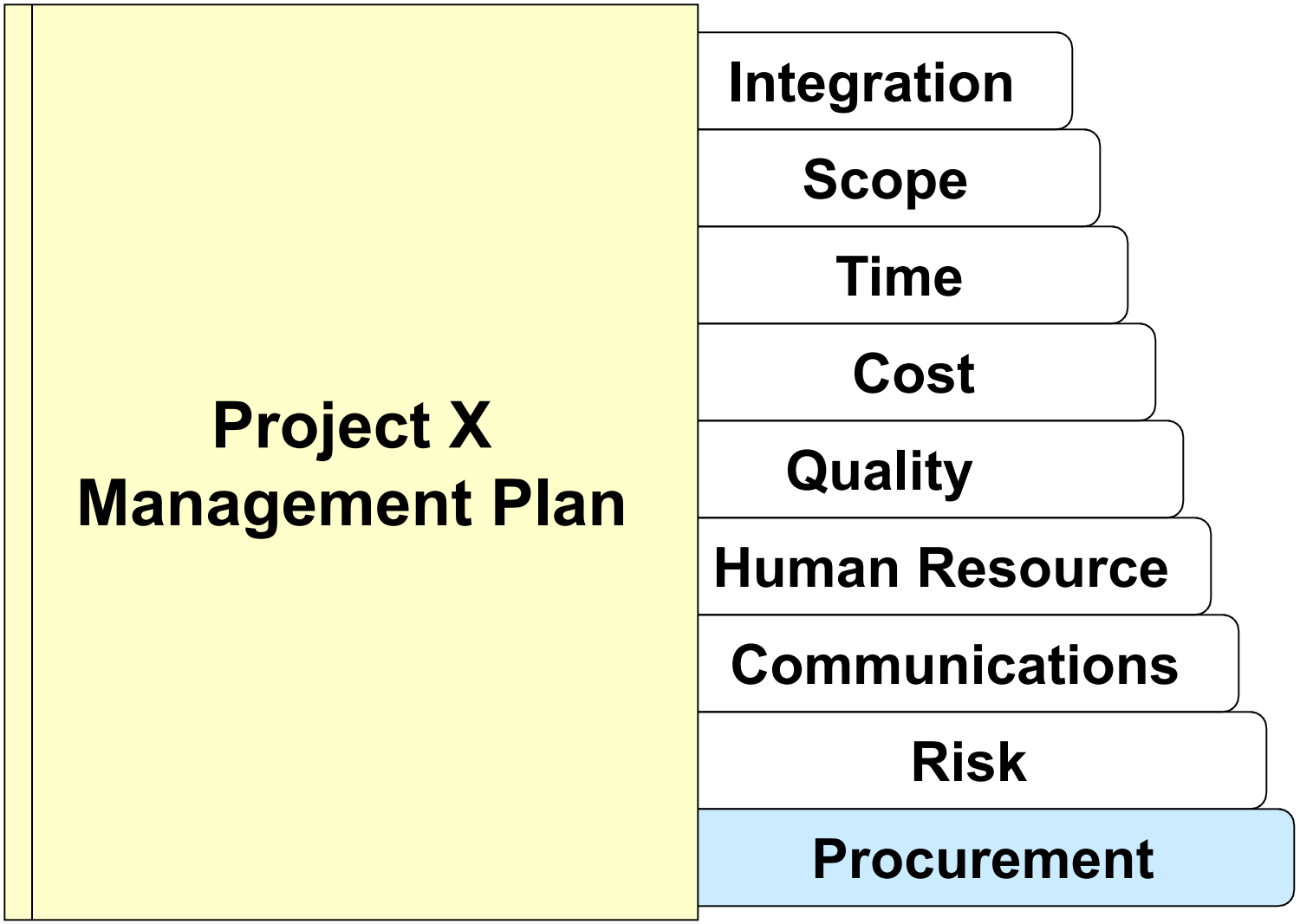
Risk Response Development

- **Risk Response Strategies:**
  - **Avoidance: eliminate the Risk by eliminating the cause**
  - **Mitigation: reduce the likelihood of occurrence or the impact, or both**
    - **Transfer (e.g., insurance)**
    - **Deflect (e.g., life-of-program buy)**
    - **Reduce (e.g., use of proven technology)**
  - **Acceptance: accept the Risk event and its consequences**

Lessons Learned

- Risk management is critical to project success
- Minimize impact of unknown-unknown risks by managing known risks
- Engineers have difficulty with their technical risk being managed at the project level - perceived loss of design control
- Risk Management requires a dedicated risk manager with some independence

Key Elements of System Engineering



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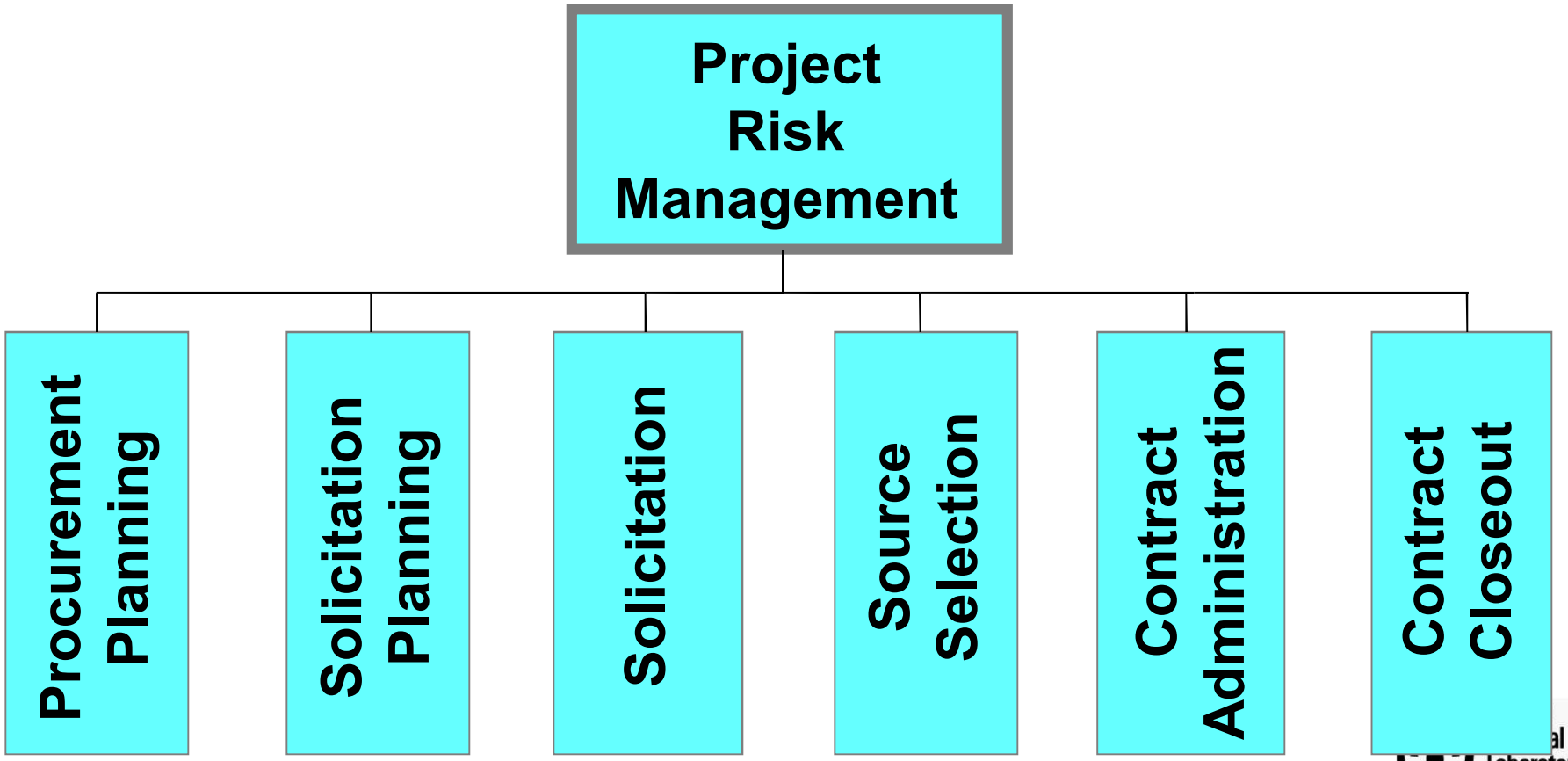
Project Procurement Management

- *"Processes required to acquire goods and services, to attain project scope, from outside the performing organization" – PMI PMBOK Guide*



Common Project Pitfalls

- Unclear Scope Definition allows for “Scope Creep” or “Scope Gallup”
  - Understand cost, schedule and performance requirements
  - Document assumptions and constraints
- Unclear of conflicting roles and responsibilities will degrade team performance
  - Low morale and Infighting
- Lack of buy-in during planning from key stakeholders can cause problems downstream
  - Bottoms-up input required
- Poor and late communication will impact project cost, schedule and performance
- Weak project leadership and management support
- No formal risk management

Outline

- Some definitions
- Elements of System Engineering at Sandia
- Sandia Initiatives in System Engineering

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Product Delivery

- We delivers and maintain products that meets their performance requirements and are affordable throughout their lifecycle by:
  - Understanding customer needs and negotiating/validating requirements with the customers
  - Owning the customer interface, project integration role, and product lifecycle
  - Establishing the system architecture, managing the interfaces, and developing the design by transforming requirements into specifications
  - Conducting design and technology tradeoffs with a broad set of competing requirements
  - Using modeling and simulation and engineering analysis for product prototyping in support of exploring options and down-selecting
  - Drawing upon technical experience from working with products that have a high consequence of failure for not meeting nuclear safety and security requirements
  - Generating and managing lower-tier product requirements

Product Delivery Continued

- Controlling and managing product configuration and information.
- Leading teams in a concurrent engineering environment to support the development, production, evaluation and use of the product.
- Validating that the product meets all of its performance requirements (functional, environmental, interface, etc.).
- Managing the delivery, deployment, continuing evaluation, maintenance and ultimate disposition of delivered products.
- Providing continuous product and customer support, as required.
- Managing and meeting cost, schedule, quality, risk, and communication requirements.
- Capturing lessons learned and improving the engineering and management processes.
- Conducting all operations in a safe and secure manner.
- Performing critical technical and programmatic reviews.

Product Qualification

We demonstrate the product meets performance requirements and characterizes margin through a combination of test, modeling and simulation, engineering analysis, and critical design reviews.

•Product Qualification for hardware and software includes the use of:

- **Test-Based Qualification**
  - Demonstrate product performance under conditions indicative of intended use, and potentially unintended use. This testing may require exposure to a wide range of environmental conditions and/or large variations in product interface conditions. Testing may serve both to assess the product directly as well as acquire data for model validation.
- **Modeling and Simulation**
  - Perform pretest predictions in support of test development, to conduct parametric analyses to determine system response over a broad range of environments, interfaces, and/or scenarios, and to predict performance for conditions that cannot adequately be demonstrated through testing.
- **Engineering Analysis**
  - Integrate test data, modeling and simulation results, engineering experience, and historical information to develop the technical basis for qualification of performance and identification of design margins.
- **Critical Design Reviews**
  - Solicit independent, subject matter expert evaluations of the product and/or program in support of key programmatic “gates” or performance assessments.

Formation of Systems Engineering Excellence Team (SEET)

- SEET is made up of staff with expertise in particular areas of Systems Engineering
- Staff that are currently working Systems Engineering projects
- Staff with a passion for excellence in engineering

What is SEET's Purpose?

- Commonality and formality in approach to SE in NWSMU that will ultimately provide:
  - Our ***customers*** with an improved interface, confidence in a solid methodology, and an improved final product;
  - Our ***leadership*** team with consistency in defining and managing weapon systems portfolio of work; and
  - Our ***engineers*** with a simplified day-to-day SE job.

- SEET should function as an advocate and source of information for SE, an "assessor" for rigor and consistency in the application of SE, and lead SE process improvement. SEET will:
  - Elicit and respond to needs of practitioners
  - Formalize SE
  - Propagate SE Knowledge
  - Measure Capability Excellence in SE

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SEET Deliverables

- **Formalize SE**
  - Guidance on SE methodologies that currently exist in industry and other sectors
  - Mapping of SNL SE to mainstream SE
  - Definitions of SE and Systems Architecture as these pertain to our operations
  - Mapping of organization processes to corporate processes
  - Formal SE framework

Formalize

- **Propagate SE Knowledge**
  - Successes, gaps, lessons learned in weapon systems
  - Current baseline of SE
  - Breakdown of SE Framework for a measured, step-by-step application to programs and projects that will increase SE capability
    - Assessing Requirements Management capability
  - Training strategy to facilitate improved SE knowledge and capabilities
    - Developing SE Curriculum with Corporate Education
  - SEET Website

Propagate

- **Measure Capability Excellence in SE**
  - Methods to measure impact and benefit of implementation of SE

Measure

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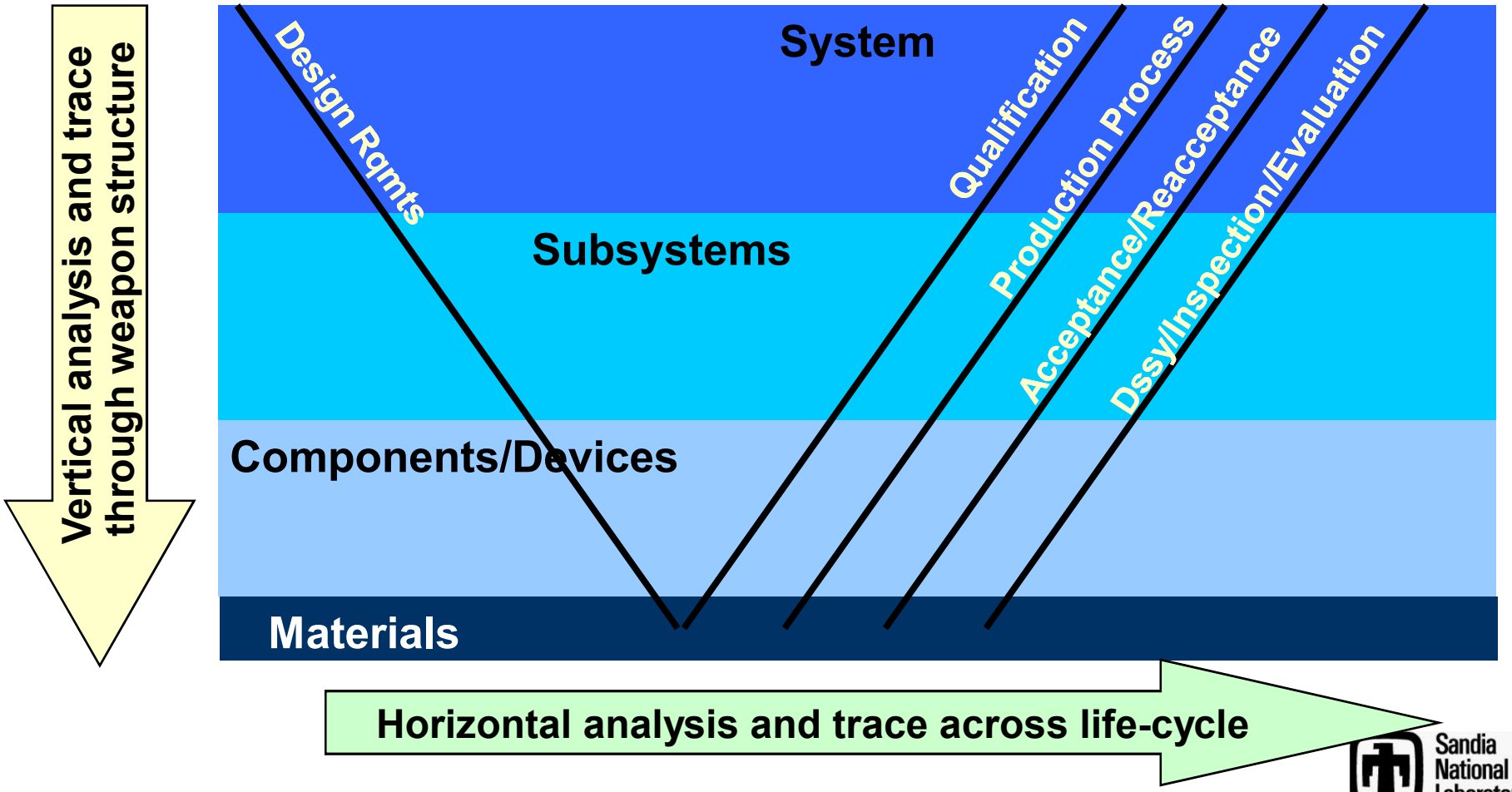
Requirements Vision

- Requirements Management and Analysis Through the Weapon Structure and across the Weapon Life-cycle



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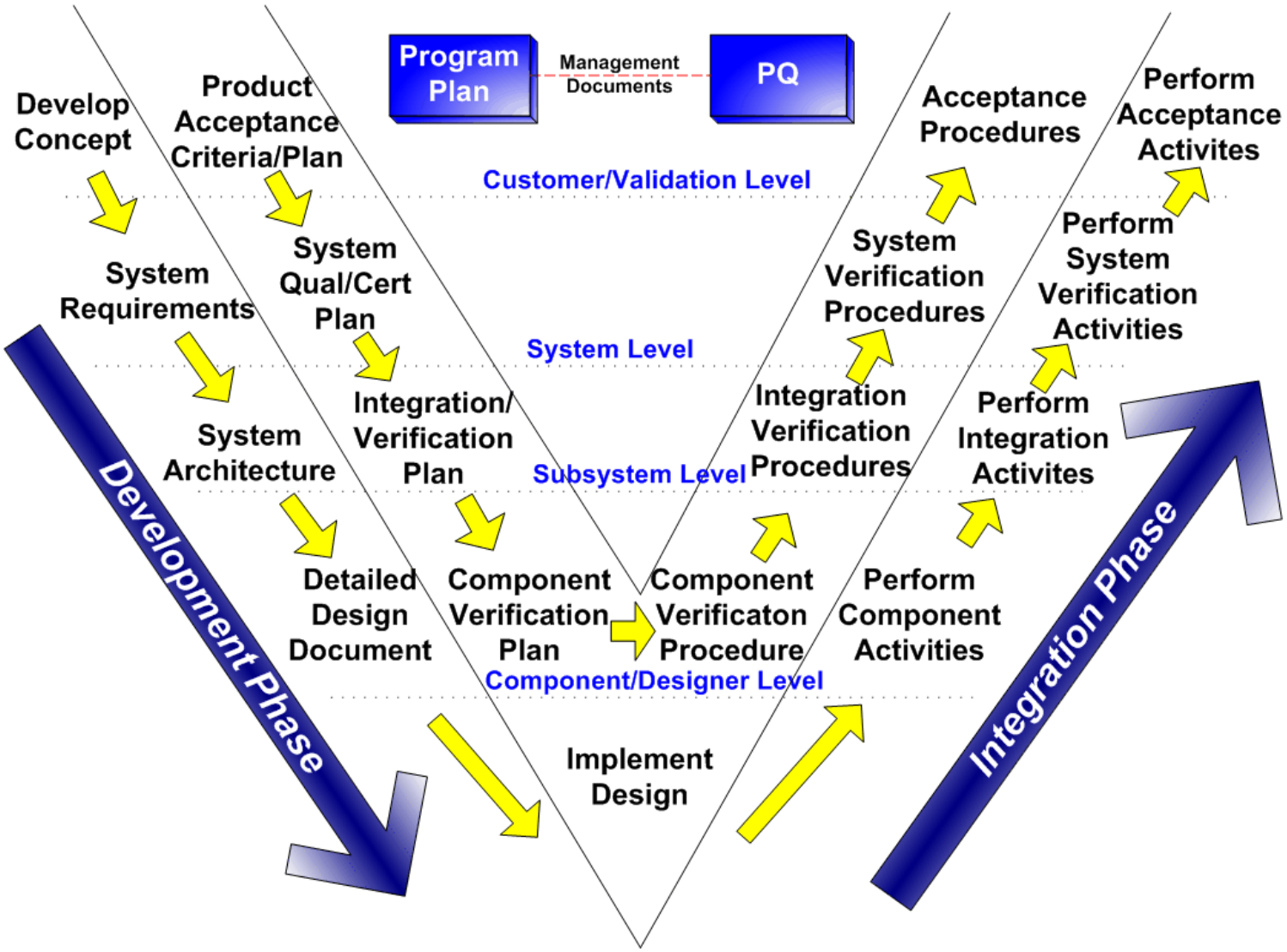
Systems Engineering 'Vee'



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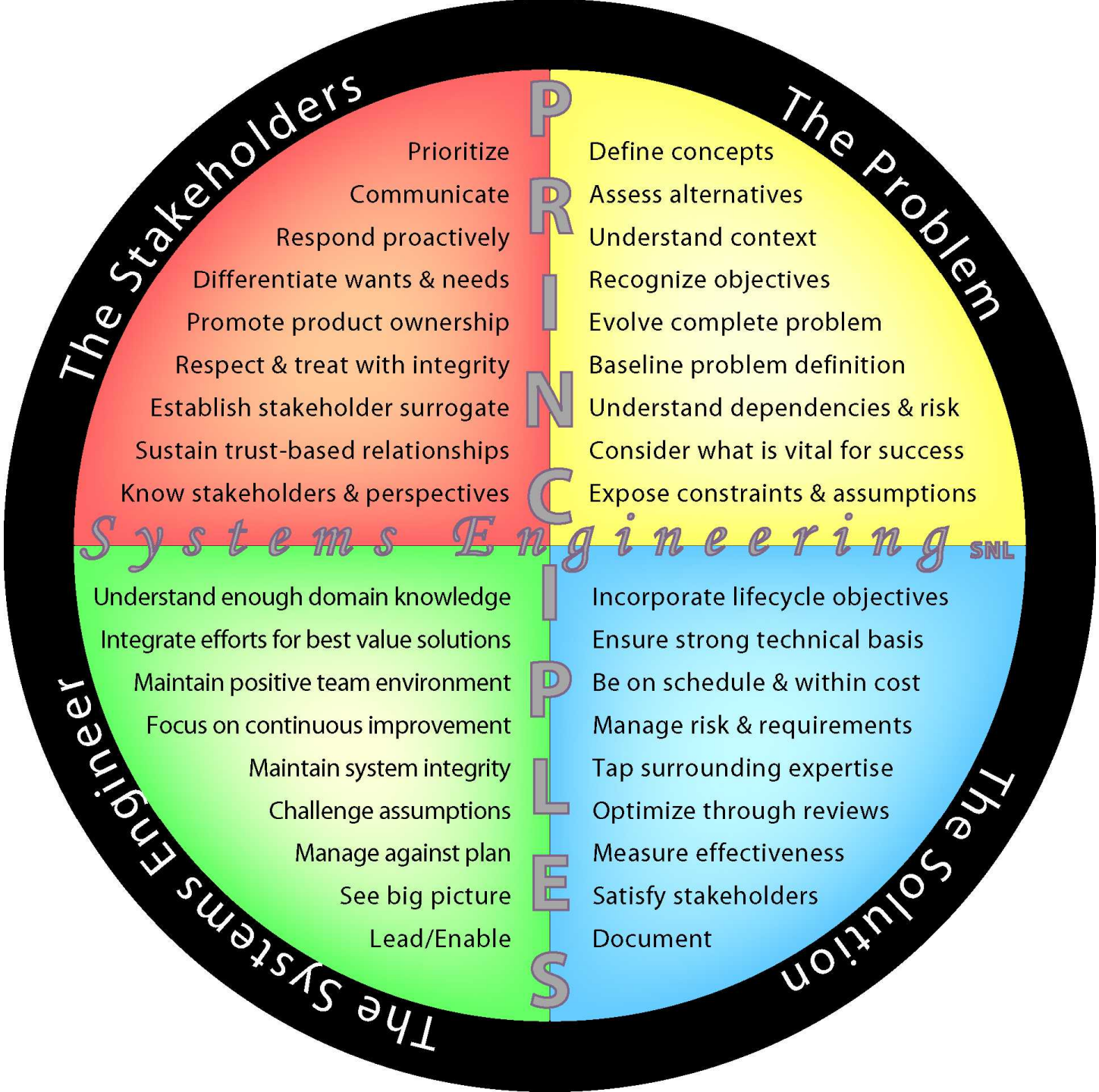
The Stakeholders
The Problem
The Systems Engineer
The Solution
PRINCIPLES
Prioritize
Communicate
Respond proactively
Differentiate wants & needs
Promote product ownership
Respect & treat with integrity
Establish stakeholder surrogate
Sustain trust-based relationships
Know stakeholders & perspectives
Define concepts
Assess alternatives
Understand context
Recognize objectives
Evolve complete problem
Baseline problem definition
Understand dependencies & risk
Consider what is vital for success
Expose constraints & assumptions
Systems Engineering SNL
Understand enough domain knowledge
Integrate efforts for best value solutions
Maintain positive team environment
Focus on continuous improvement
Maintain system integrity
Challenge assumptions
Manage against plan
See big picture
Lead/Enable
Incorporate lifecycle objectives
Ensure strong technical basis
Be on schedule & within cost
Manage risk & requirements
Tap surrounding expertise
Optimize through reviews
Measure effectiveness
Satisfy stakeholders
Document

Summary

- We have rigorous System Engineering processes in place to ensure successful product development
- We must continuously improve our processes and adapt to a changing environment
- We are developing a Systems Engineering Curriculum to improve training and qualification of our staff