Product Assurance

Space System Design, MAE 342, Princeton University
Robert Stengel

- **Assembly, Integration, and Verification**
- **Dependability**
- **Reliability**
- **Task Planning**
- **Quality Assurance**

Failure Analysis of Cygnus CRS Orb-3

Orbital Sciences Antares 130

- **Possible causes**
  - **Manufacturing defect in turbopump Aerojet Rocketdyne AJ-130 motor**
    - **Refurbished Energomash NK-33 motor from stockpile**
    - **Built in 1970s**
  - **Design flaw in hydraulic balance assembly and thrust bearings**

Assemble, Integrate, and Verify

- **Assemble**
  - Build spacecraft
- **Integrate**
  - Make it function
- **Verify**
  - Demonstrate compliance with goals
    - Qualification of design
    - Acceptance of hardware
  - Methods
    - Test
    - Analysis
    - Inspection
    - Design Review
  - System Level
    - Spacecraft
    - Module or sub-system
    - Unit
    - Equipment or component

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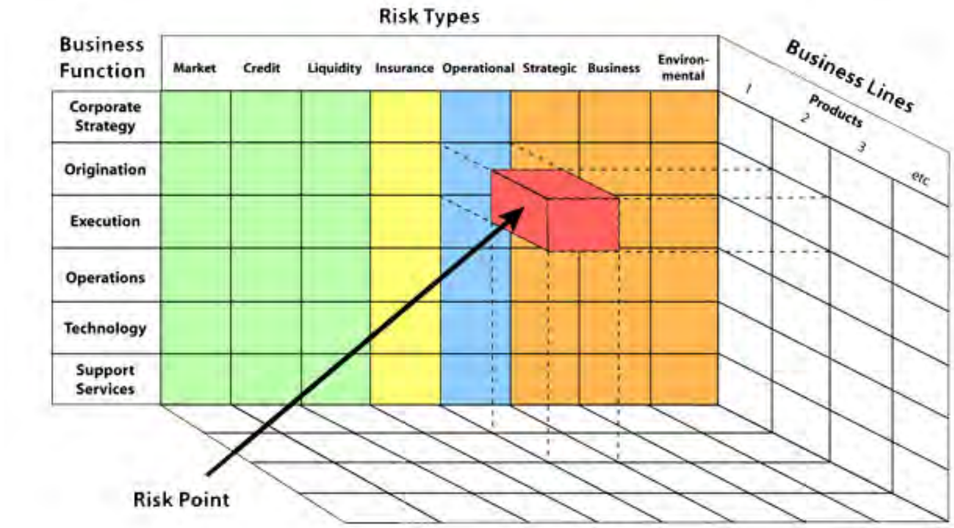
Manage Risk

Classify Risk



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Assess Risk

		Process Risks				Conduct Risks							External Risks			
		Execution, Delivery and Process Management			Business Disruption	Clients, Products and Business Practices		Internal Fraud and Theft		Employment Practice and Workplace Safety			Damage to Assets		External Fraud	
		Transaction Management	Data Management	Reporting and Disclosure	Infrastructure and Systems	Fiduciary	Improper Practices	Unauthorised Market Activity	Internal Fraud and Theft	Diversity and Discrimination	Employee Relations	Safe Environment	Natural Disaster and Accident	Wilful Damage	Hacking and Disruption	External Fraud and Theft
Origination	Product or Service Development and Suitability	16	27	13	27	31	[illegible]	12	25	8	8	8	8	8	10	12
	Relationship Management	17	31	28	24	[illegible]	[illegible]	9	23	11	10	8	10	14	14	[illegible]
	Credit Review and Approval	17	[illegible]	13	21	18	27	12	24	8	8	8	9	8	12	41
	Models and Methodologies	13	[illegible]	19	27	8	26	13	27	8	8	8	8	12	10	15
	Research	10	24	16	17	25	31	9	16	8	8	8	8	9	11	19
Execution	Advisory Services	14	20	15	13	[illegible]	[illegible]	12	13	8	8	8	8	9	11	11
	Custom or Structured Transaction Requirements	17	[illegible]	19	24	26	29	13	18	8	8	8	8	8	12	15
	Pricing and Quotations	14	[illegible]	18	[illegible]	22	[illegible]	19	29	8	8	8	9	9	14	14
	Limits and Facility Checking	12	28	15	28	15	28	15	21	8	8	8	9	8	11	10
	Instruction or Order Management	[illegible]	[illegible]	33	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	8	8	8	11	10	21	[illegible]
Processing and Operations	Reference Data Creation and Maintenance	15	[illegible]	11	27	17	12	10	20	8	8	8	12	10	11	20
	Transaction/Fees Capture and Record Update	[illegible]	[illegible]	22	[illegible]	19	26	32	[illegible]	8	8	8	11	11	14	14
	Confirm/Affirm/Matching and Documentation	[illegible]	30	27	31	22	25	26	29	8	8	8	24	13	13	31
	Transaction Maintenance and Administration	[illegible]	[illegible]	16	[illegible]	17	28	23	24	8	8	8	13	12	11	10
	Interest Calculation and Application	27	[illegible]	15	25	13	23	10	20	8	8	8	10	8	8	10
	Client/Customer Valuation and Reporting	20	32	21	30	32	31	10	16	8	8	8	10	9	12	14
	Internal Valuation	20	33	14	28	8	21	12	25	8	8	8	10	8	10	8
	Trust and Fiduciary Administration	21	23	24	20	[illegible]	33	10	31	8	8	8	10	8	10	18
	Collateral/Margins/Netting	[illegible]	32	24	[illegible]	22	30	10	27	8	8	8	16	9	13	29
	Payment/Settlement/Collection (cash/securities)	[illegible]	[illegible]	[illegible]	[illegible]	26	26	10	[illegible]	8	9	12	30	23	22	[illegible]
	Custody and Actions (including assets)	[illegible]	[illegible]	31	32	[illegible]	32	14	[illegible]	8	8	13	25	17	13	[illegible]
	Asset Maturity and Disposals	20	17	9	10	13	22	9	20	8	8	9	16	15	9	18
	Reconciliation and Resolution	17	25	11	24	12	25	9	22	8	8	8	9	8	11	14
	Workouts and Credit Recoveries	28	28	15	16	15	33	13	24	8	8	8	8	17	10	[illegible]
	Cash Management	32	28	13	[illegible]	12	21	12	20	8	8	8	12	8	10	11
	Transaction Accounting	[illegible]	[illegible]	20	27	11	18	9	19	8	8	8	9	12	10	8
Business Continuity	Planning, Training, Testing, Execution	16	21	12	30	18	20	10	10	14	14	22	18	17	17	12
Technology	Development, Implementation & Project Mgmt	24	20	8	24	12	25	8	17	8	8	12	14	25	15	14
	Infrastructure, Networks & Maintenance	16	17	10	33	9	20	9	26	10	11	19	[illegible]	32	24	26
	IT Security	13	18	11	[illegible]	19	23	8	15	10	10	9	21	32	[illegible]	15
	Disaster Recovery	17	23	10	[illegible]	13	20	8	14	11	9	11	20	18	21	13
Finance	Financial Reporting	8	26	[illegible]	23	12	[illegible]	8	16	8	8	8	9	8	9	8
	Taxation	15	29	[illegible]	20	22	[illegible]	8	21	8	8	8	8	8	8	13
	Regulatory Reporting	12	33	[illegible]	28	11	32	8	10	8	8	8	9	12	11	8
Oversight	Policy, Surveillance and Monitoring	12	13	18	17	17	24	8	12	16	17	8	8	8	8	10
	Legal Advisory	11	13	9	9	14	16	10	9	9	10	8	8	8	8	8
	Litigation Management	11	19	17	9	12	17	8	8	11	12	8	8	10	8	12
	Audit and Investigation	9	18	16	15	8	18	8	10	16	17	8	8	8	9	10
Human Resources	Recruitment and Training	9	14	17	9	14	22	8	11	29	19	9	9	12	8	21
	Appraisal and Termination	9	16	9	9	10	24	8	11	[illegible]	30	9	8	8	10	8
	Remuneration, Expenses and Payroll	9	25	15	19	10	22	8	27	29	32	8	12	8	14	12
Corporate Services	Physical Security	8	10	8	21	14	14	8	13	18	15	22	19	24	9	20
	Property and Facilities Management	8	13	8	16	17	17	8	33	17	16	30	[illegible]	32	8	31
	Insurance and Recoveries	8	18	12	11	9	15	9	16	8	8	9	9	12	8	12
	3rd Party/Vendor Management	12	17	11	16	15	26	10	17	8	11	12	10	8	9	15

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Spacecraft Product Assurance

- Origins
  - Industrial Revolution
  - Formal quality assurance during WWII
- Evolution
  - Standards and certification methods borrowed from USAF, ABMA
  - *See Lecture 24 Course Materials on Blackboard*
- Special problems
  - Extremes of operating conditions
  - Length of unattended operation
  - Inaccessibility for maintenance

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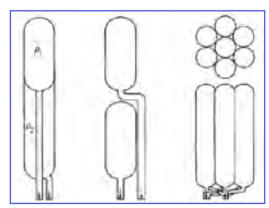
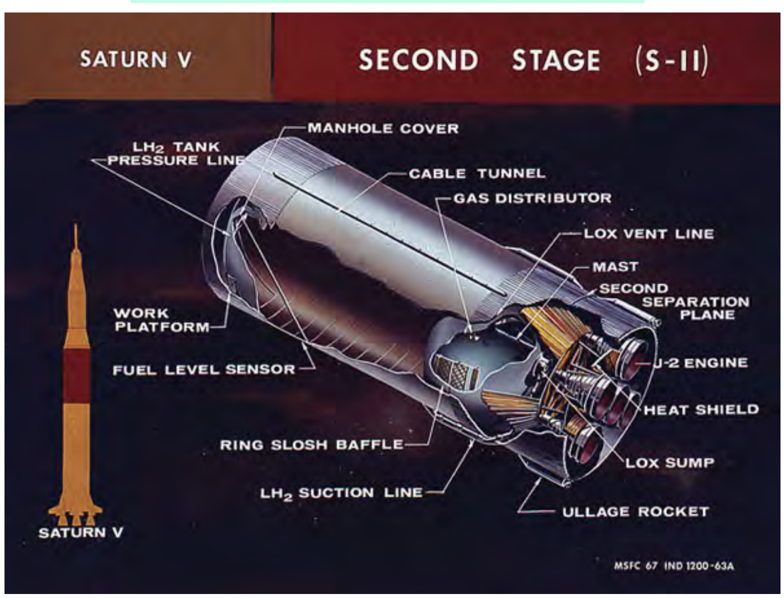
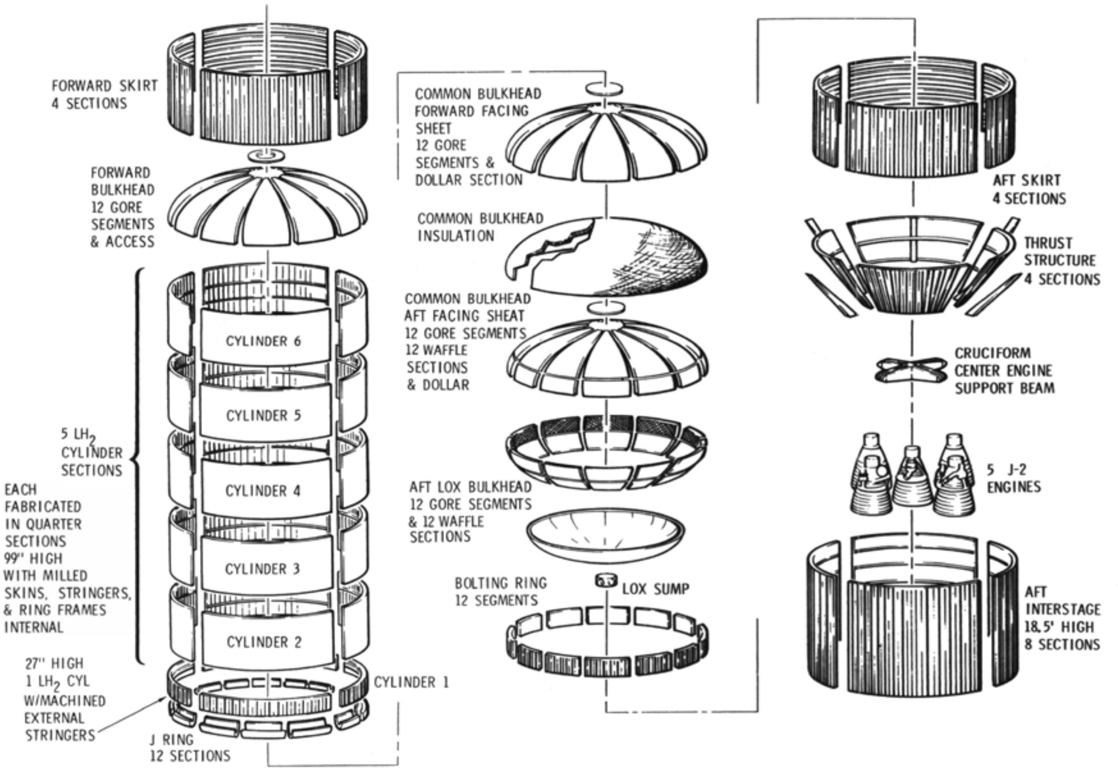
Saturn V Second Stage



Integral serial tanks, with common bulkhead





S-II EXPLODED VIEW

Principles and Definitions for Product Assurance

- Quality
- Basis for quality assessment
- Proof of quality

Objectives and Project Phases

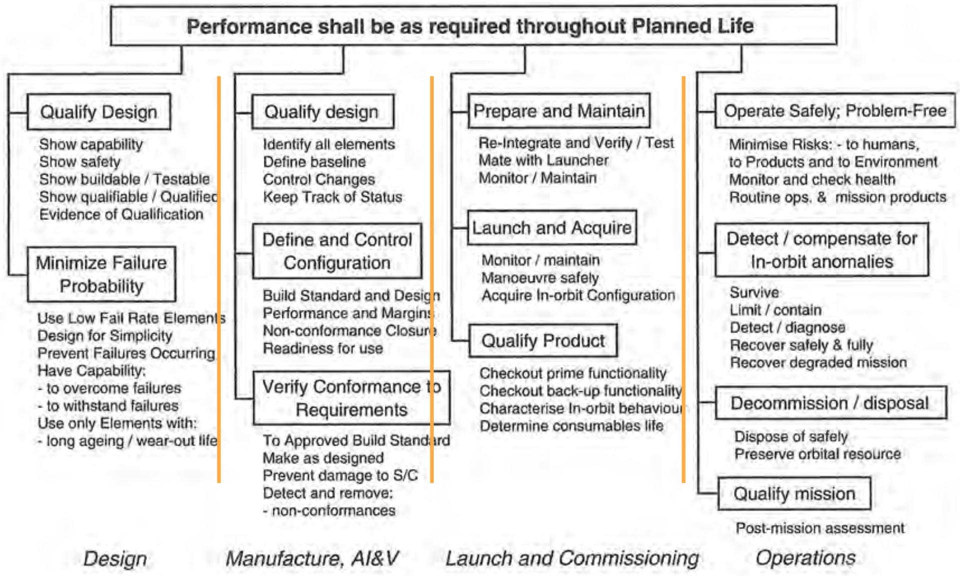


Figure 19.1 PA objectives vs. project phases

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Overlapping Issues

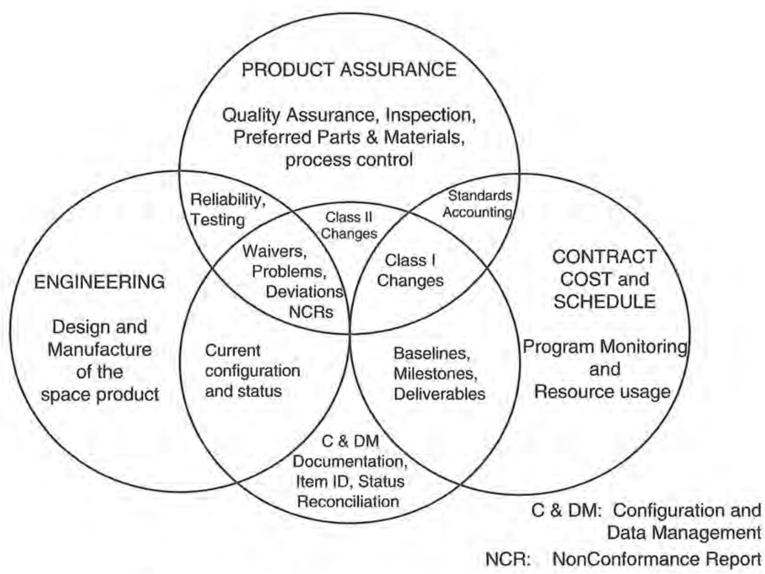

Figure 19.2 Product Assurance in a project context

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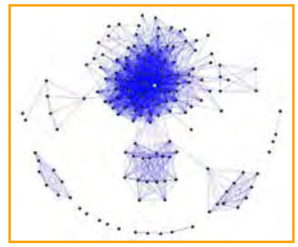
Task Planning

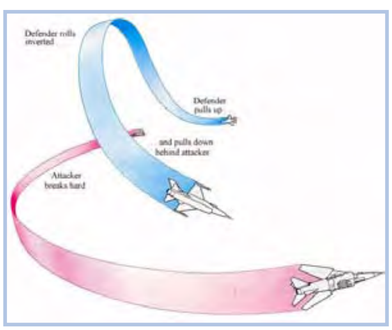


Situation awareness

Decomposition and identification of communities

Development of strategy and tactics

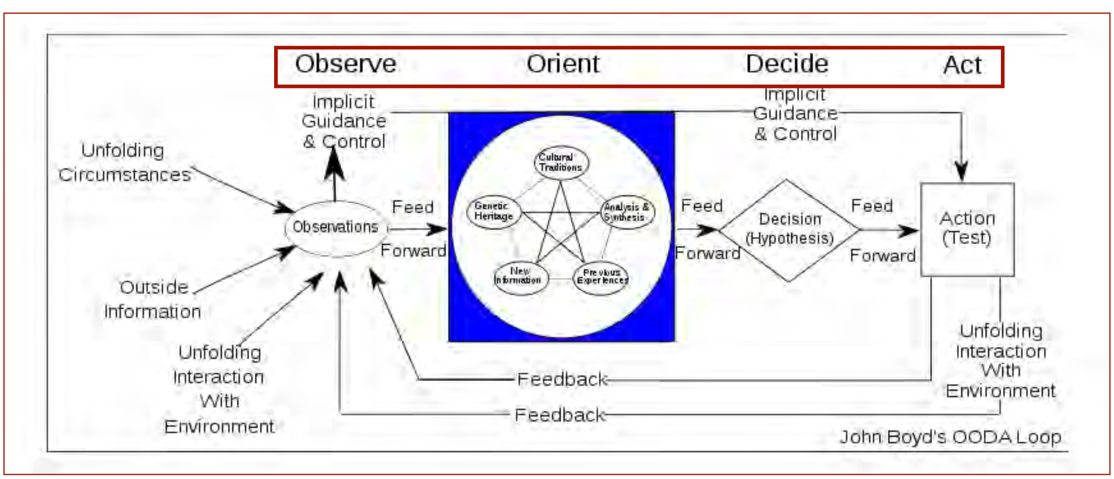
		Phase	
		Process	Outcome
Objective	Tactical (short-term)	Situation Assessment	Situation Awareness
	Strategic (long-term)	Comprehension	Understanding



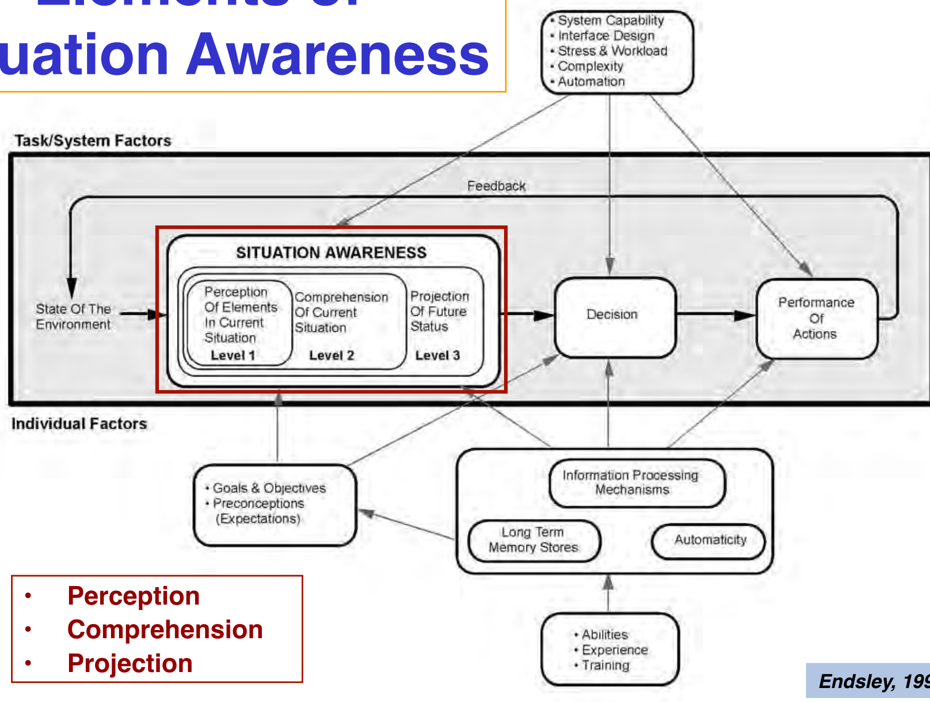
Boyd's "OODA Loop" for Combat Operations

Derived from air-combat maneuvering strategy

General application to learning processes other than military



Elements of Situation Awareness



- **Perception**
- **Comprehension**
- **Projection**

Endsley, 1995

Important Dichotomies in Planning

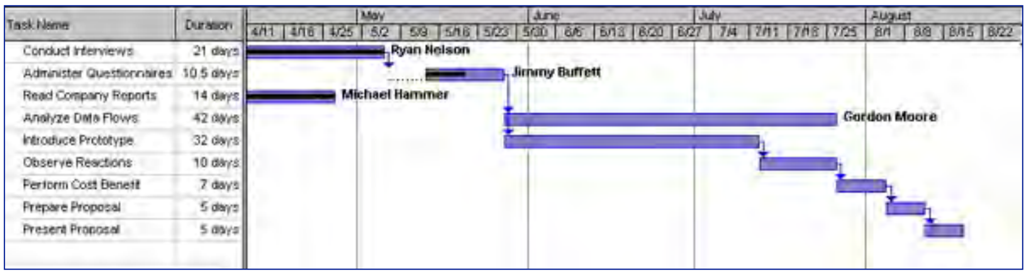
Strength, Weakness, Opportunity, and Threat (SWOT) Analysis

"Knok-Knoks" and "Unk-Unks"

Known Knowns	*Known Unknowns*
Unknown Knowns	*Unknown Unknowns*

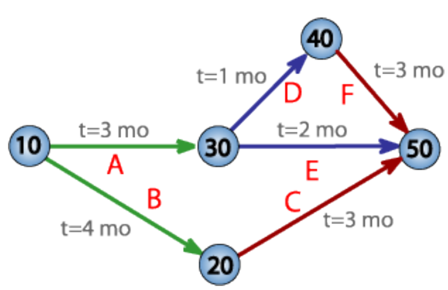
Program Management: Gantt Chart

Project schedule
Task breakdown and dependency
Start, interim, and finish elements
Time elapsed, time to go



Program Evaluation and Review Technique (PERT) Chart

Milestones
Path descriptors
Activities, precursors, and successors
Timing and coordination
Identification of critical path
Optimization and constraint



-ilities

- Dependability
  - Availability
  - Maintainability
  - Security
- Reliability
  - Qualitative
  - Quantitative
  - Design or predicted
  - Operational

Parts Procurement

- Vendors' track record
- Standardization
- Procurement systems
  - Organization
  - Documentation
- Substitution of less reliable equivalents
- Out-of-date/specification parts

Materials and Processes

Table 19.7 Material functional properties and constraints

Functional properties	Constraints
	Common constraints
Strength	Outgassing
Adhesion	Radiation resistance
Elastic moduli	Inertness
Thermal stability	Reproducibility
Ductile properties	Tolerance to processing
Malleability	Matching coefficients of expansion
Cuttable without shatter	Man-rated constraints
Reflectivity	Low toxicity
Absorptivity/transmittance	Low odour
Energy content:	Non-flammable
-propellant, electrolyte, springs	Low outgassing/offgassing

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Materials to Avoid

Table 19.8 Prohibited materials and materials to be avoided

Material	Type of problem
Flexible adhesives	Loses elasticity; fractures when solidified
Polyvinyl chloride backing tapes	Unstable properties
Cellulose, paper, fabrics, etc	Unstable properties
Varnishes and coatings which rely on solvent evaporation for hardening	Properties change in vacuum and with temperature cycling
Canada balsam; organic glasses in high precision equipment	Unstable
Most oils and greases	Material migration
Graphite	Abrasive in vacuum
Cadmium, zinc and tin	Dendrite growth; risk of shorting
Most paints	Outgassing unstable properties
Polyvinyl chloride, cellulose and acetates, Plastic film	Unstable properties
Potting	Fracture at temperature extremes
Polyester laminates	Unstable properties
Rubbers using poly-sulfides; plasticizers; chlorinated	Unstable properties
Polyvinyl chloride (PVC) thermoplastic; polyvinyl acetate; butyrate; several polyamides	Unstable properties

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Material Problems in Orbit

Table 19.9 Examples of material problems that occurred in orbit

Space Shuttle thermal tiles	The Space Shuttle has over 24 000 tiles, each with a different shape—an extreme configuration management problem. Early launches lost tiles during ascent and re-entry. An extra layer of bouding was required. This added to weight and thus reduced payload capability.
Atomic gas	Cleaning fluid can leave traces of contaminant on surfaces. The space environment encourages the release of atomic hydrogen, which disrupts the molecular lattice. The effect shows as embrittlement in metals. This can lead to fracture, and can result in a catastrophic failure in springs.
Growth of dendrites	Cadmium, zinc and tin have all exhibited dendrite (whisker) growth at corner sites when in the presence of an impurity and/or an electric field. This can lead to short circuits.
GOES lamps	Specialist lamps of an exact light frequency were used on a series of GOES satellites. The first lamps were successful. Later lamps failed in orbit before end of duty life. Part way through the production cycle, the lamp manufacturer had changed the supplier of the filament material for the lamps. The newly supplied raw material was of a different composition and its life characteristics had not been checked for application in the space environment.

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Materials Problems within Parts

Table 19.10 Examples of materials problems within parts

Dendrite growth in digital integrated circuits	Temperature + electrical bias + moisture = dendrites. These needle-like growths (of molybdenum) occur at corner sites in metal/substrate interfaces. They can lead to cross-track shorts and capacity changes—important in some part types.
Galvanic corrosion	Dissimilar metals + moisture + warmth = voltage couple. The moisture passes through plating and forms an electrolyte. The sustained emf causes corrosion.
Stress corrosion	Mechanical stress opens tiny fissures in material. Fissures form sites where impurities can gather and leave material without its protective coating at these sites.
Constituents have unmatched coefficients of expansion	Large temperature excursions—in/out of eclipses—generate severe strains within the part that can lead either to fracture or unstable electrical behaviour.

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Product Assurance in Manufacturing

- Controls and Records
- Training and certification
- Traceability
- Measurement and calibration
- Non-conformance control
- Alerts, handling, … margins
- Audits

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Non-Conformance Control

Table 19.12 Non-conformance NCR processing scheme

Area	Classification (acronym)	Description	Re-test and check	Notify buyer	Buyer action needed
Severity	(NCR)	Non-conformance found and Report issued with unique ID.			
	(MRB)	Material Review Board con venes; assesses significance of NCR			Yes
	Minor	Disposition locally			
	Major	Serious. Involve customer at once		Yes	Yes
Concession	(RFW)	Request for Waiver of requirement that cannot be satisfied.		Yes	Yes
	(RFD)	Request for Deviation from specification of an in-work end-item		Yes	Yes
	None	Concession not needed			
Disposition	Use-as-is	Correction of no benefit and no value. No RFW and no RFD needed.			
	Rework[2]	Rework to full compliance with specification of the item.	Yes	Yes	
	Rework[3]	Rework beyond specification for use subject to approved deviation	Yes	Yes	Yes
	Scrap	Must not be used. Segregate and send to materials reclamation.	Yes	Yes	

[1] Only when 'major' classification is declared.
[2] Will meet specification after rework/retest/inspection
[3] Will not meet specification after rework/retest/inspection

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Technology Readiness Levels

Table 19.14 Technology readiness levels

Technology readiness level	Description
TRL 1	Basic principles observed and reported
TRL 2	Technology concept and/or application formulated
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept
TRL 4	Component and/or breadboard validation in laboratory environment
TRL 5	Component and/or breadboard validation in relevant environment
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
TRL 7	System prototype demonstration in a space environment
TRL 8	Actual system completed and 'flight qualified' through test and demonstration (ground or space)
TRL 9	Actual system 'flight proven' through successful mission operations

Table 19.15 Technology development stages

Development stage	TRL1	TRL2	TRL3	TRL4	TRL5	TRL6	TRL7	TRL8	TRL9
Basic technology research.	■	■							
Research to prove feasibility		■	■	■					
Technology development.			■	■	■				
Technology demonstration.					■	■	■		
System/subsystem dev't.							■	■	
System test, launch and ops.								■	■

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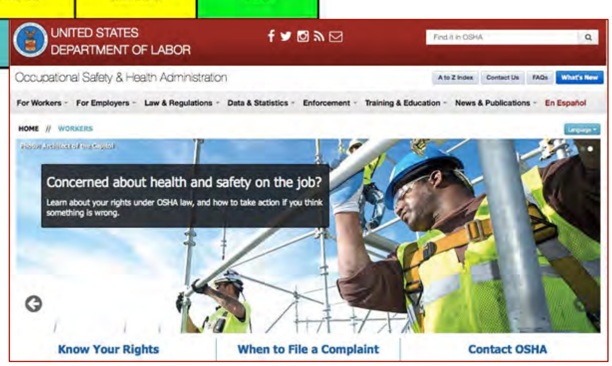
Product Assurance and Safety in Operations

RISK ASSESSMENT MATRIX				
SEVERITY / PROBABILITY	Catastrophic (1)	Critical (2)	Marginal (3)	Negligible (4)
Frequent (A)	High	High	Serious	Medium
Probable (B)	High	High	Serious	Medium
Occasional (C)	High	Serious	Medium	Low
Remote (D)	Serious	Medium	Medium	Low
Improbable (E)	Medium	Medium	Medium	Low
Eliminated (F)				



Reliability of a Component

If failure rate is constant,

$$R = e^{-\lambda t}$$

where failure rate is estimated as

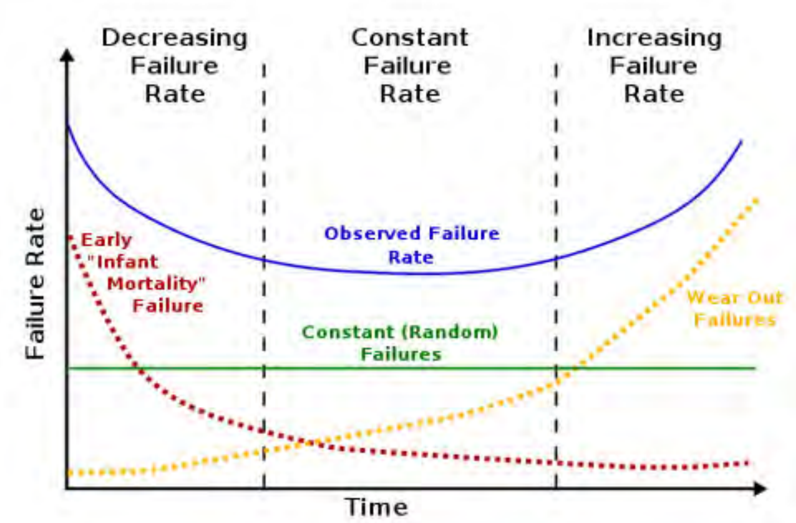
$$\lambda = \begin{cases} 1/MTBF & \text{(repairable system)} \\ 1/MTTF & \text{(non-repairable system)} \end{cases}$$

$MTBF$: Mean time between failures

$MTTF$: Mean time to failure

Also see Lecture 17 slides for reliability assessment

Failure Rate, λ



Expected number of failures per unit time

Reliability Enhancement

- Use of redundancy
- Design diversity
- Limitation of failure effects
- De-rating of parts
- Radiation screening
- Handling/assembly controls
- Inspection/testing

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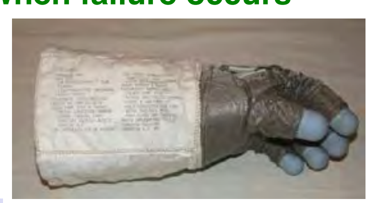
Reliability Analysis Techniques

- Failure state probabilities
- Worst-case analysis
  - *https://en.wikipedia.org/wiki/Worst-case_circuit_analysis*
- Failure modes and effects analysis
  - *https://en.wikipedia.org/wiki/Failure_mode_and_effects_analysis*
- Fault tree analysis
  - *https://en.wikipedia.org/wiki/Fault_tree_analysis*
- Contingency analysis
  - What to do when failure occurs



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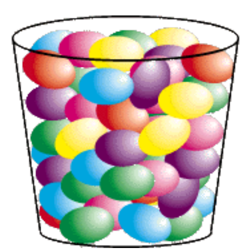
Probability Distributions

Relative Frequency of Discrete, Mutually Exclusive Events

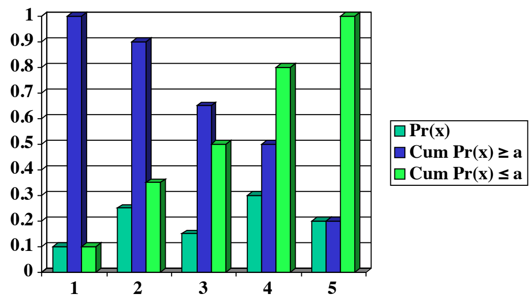
$$\Pr(x_i) = \frac{n_i}{N} \quad \text{in } [0,1]; \quad i = 1 \text{ to } I$$

- N = total number of events
- n_i = number of events with value x_i
- I = number of different values
- x_i = ordered set of hypotheses or values



$$\sum_{i=1}^{I} \Pr(x_i) = \frac{1}{N} \sum_{i=1}^{I} n_i = 1$$

Cumulative Probability, Pr(x ≥/≤ a), and Discrete Measurements of a Continuous Variable

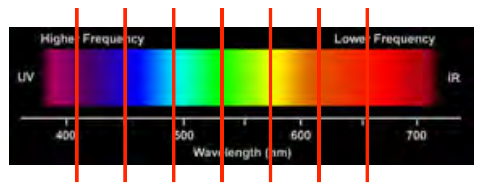


Suppose x represents a continuum of colors

x_i is the center of a band in x

$$\Pr\left(x_i \pm \Delta x / 2\right) = n_i / N$$

$$\sum_{i=1}^{I} \Pr\left(x_i \pm \Delta x / 2\right) = 1$$



Probability Density Function, pr(x) Cumulative Distribution Function, Pr(x < X)

Probability density function

$$\mathrm{pr}\left(x_i\right) = \frac{\Pr\left(x_i \pm \Delta x / 2\right)}{\Delta x}$$

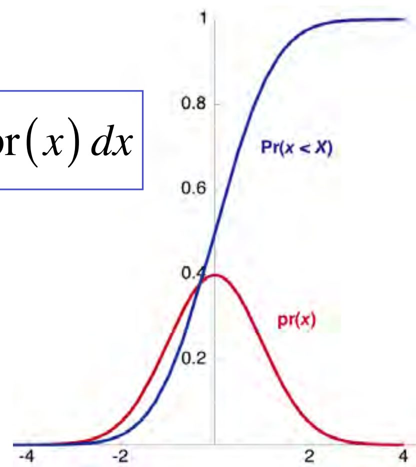
$$\sum_{i=1}^{I} \Pr\left(x_i \pm \Delta x / 2\right) = \sum_{i=1}^{I} \mathrm{pr}\left(x_i\right) \Delta x \xrightarrow[I \to \infty]{\Delta x \to 0} \int_{-\infty}^{\infty} \mathrm{pr}(x)\, dx = 1$$

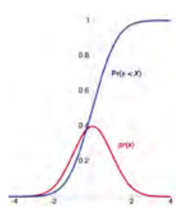
Cumulative distribution function

$$\Pr\left(x < X\right) = \int_{-\infty}^{X} \mathrm{pr}(x)\, dx$$

Probability Density Function, pr(*x*) Cumulative Distribution Function, Pr(*x* <*X*)

$$\Pr\left(x < X\right) = \int_{-\infty}^{X} \mathrm{pr}\left(x\right)\, dx$$





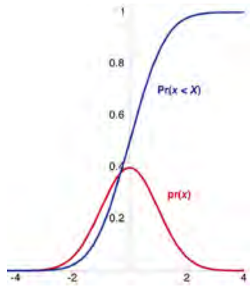
Properties of Random Variables

- **Mode**
  - Value of *x* for which pr(*x*) is maximum
- **Median**
  - Value of *x* corresponding to 50th percentile
  - Pr(*x* < median) = Pr(*x* ≥ median) = 0.5
- **Mean**
  - Value of *x* corresponding to statistical average
- **First moment of *x* = Expected value of *x***

"Force"

$$\overline{x} = E(x) = \int_{-\infty}^{\infty} x\, \mathrm{pr}\left(x\right)\, dx$$

"Moment arm"



Expected Values

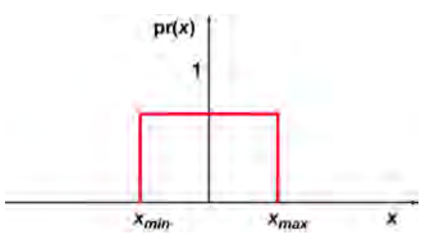
- **Mean Value is the first moment of x**

$$\bar{x} = E(x) = \int_{-\infty}^{\infty} x \,\mathrm{pr}(x)\, dx$$

- **Second central moment of *x* = Variance**
  - **Variance from the mean value rather than from zero**
  - **Smaller value indicates less uncertainty in the value of *x***

$$\sigma_x^{\ 2} = E\left[(x-\bar{x})^2\right] = \int_{-\infty}^{\infty} (x-\bar{x})^2 \,\mathrm{pr}(x)\, dx$$

Mean Value and Variance of a Uniform Distribution



$$pr(x) = \begin{cases} 0 & ; \quad x < x_{\min} \\ \dfrac{1}{x_{\max} - x_{\min}} & ; \quad x_{\min} < x < x_{\max} \\ 0 & ; \quad x > x_{\max} \end{cases}$$

Mean

$$\bar{x} = \int_{x_{\min}}^{x_{\max}} \frac{x}{(x_{\max} - x_{\min})} dx = \frac{1}{2}(x_{\max} + x_{\min})$$

Variance

$$\text{If } x_{\min} = -x_{\max} \triangleq a$$

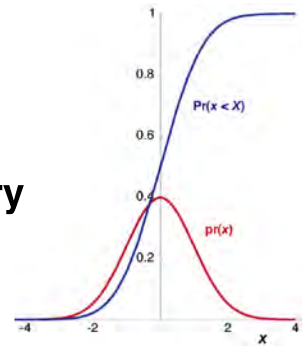
$$\sigma_x^{\ 2} = \frac{1}{2a}\int_{-a}^{a} x^2\, dx = \left.\frac{x^3}{6a}\right|_{-a}^{a} = \frac{a^2}{3}$$

Gaussian (Normal) Random Distribution

Unbounded, symmetric distribution

Defined entirely by its mean and standard deviation

$$\mathrm{pr}(x) = \frac{1}{\sqrt{2\pi}\,\sigma_x} e^{-\frac{(x-\bar{x})^2}{2\sigma_x^2}}$$



Mean value; from symmetry

$$E(x) = \int_{-\infty}^{\infty} x\,\mathrm{pr}(x)\,dx = \bar{x}$$

Variance

$$E\left[(x-\bar{x})^2\right] = \int_{-\infty}^{\infty} (x-\bar{x})^2\,\mathrm{pr}(x)\,dx = \sigma_x^2$$

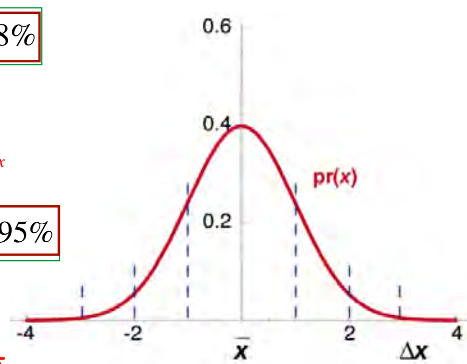
Units of *x* and σ_x are the same

Probability of Being Close to the Mean

(Gaussian Distribution)

- **Probability of being within** $\pm 1\sigma_x$

$$\mathrm{Pr}\left[x < (\bar{x} + \sigma_x)\right] - \mathrm{Pr}\left[x < (\bar{x} - \sigma_x)\right] \approx \boxed{68\%}$$



- **Probability of being within** $\pm 2\sigma_x$

$$\mathrm{Pr}\left[x < (\bar{x} + 2\sigma_x)\right] - \mathrm{Pr}\left[x < (\bar{x} - 2\sigma_x)\right] \approx \boxed{95\%}$$

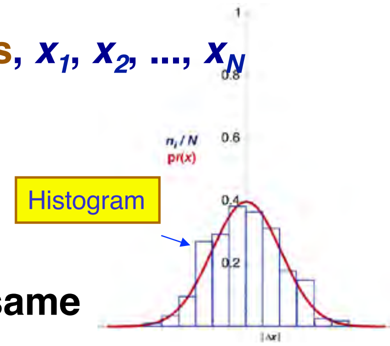
- **Probability of being within** $\pm 3\sigma_x$

$$\mathrm{Pr}\left[x < (\bar{x} + 3\sigma_x)\right] - \mathrm{Pr}\left[x < (\bar{x} - 3\sigma_x)\right] \approx \boxed{99\%}$$

Experimental Determination of Mean and Variance

Sample mean for N data points, $x_1, x_2, \ldots, x_N$

$$\bar{x} = \frac{\sum_{i=1}^{N} x_i}{N}$$



Sample variance for same data set

$$\sigma_x^2 = \frac{\sum_{i=1}^{N} \left(x_i - \bar{x}\right)^2}{(N-1)}$$

Divisor is $(N-1)$ rather than N to produce an unbiased estimate

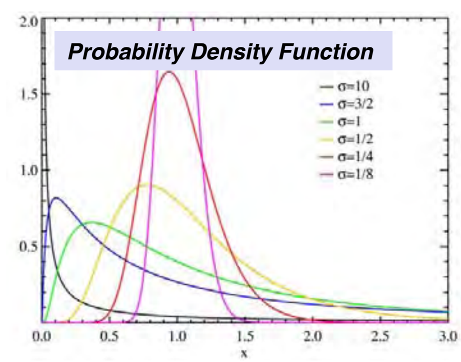
Log-Normal Distribution

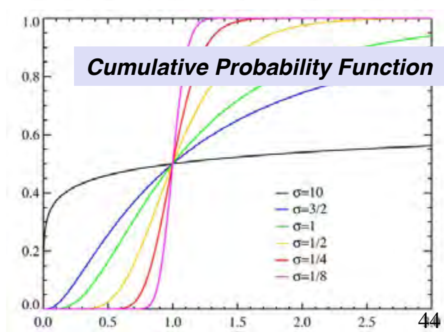
- **Variation in large ensembles for which $x > 0$**
- **The logarithm of x is Gaussian**
- **Replace x by x_l in previous equations**

$$x_l \triangleq \log x$$

$$\mathrm{pr}(x_l) = \frac{1}{\sigma_l \sqrt{2\pi}} e^{-\frac{(x_l - \bar{x}_l)}{2\sigma_l^2}}$$

$$\Pr(x_l) = \frac{1}{2}\left(1 + \mathrm{erf}\,\frac{x_l - \bar{x}_l}{\sigma_l \sqrt{2}}\right)$$





Weibull Distribution

- **Variation in life characteristics of parts or components**
- **Variation in large ensembles for which $x > 0$**

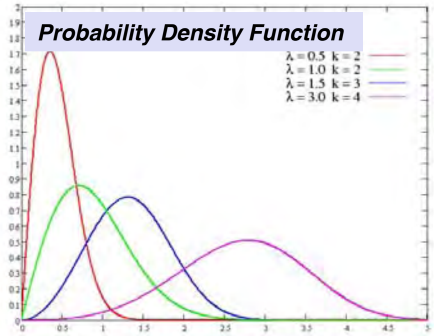
$$\mathrm{pr}(x) = \left\{ \left[\frac{b}{\theta - x_o} \right] \left[\frac{x - x_o}{\theta - x_o} \right]^{b-1} \right\} e^{-\frac{(x-x_o)^b}{(\theta - x_o)^b}}$$

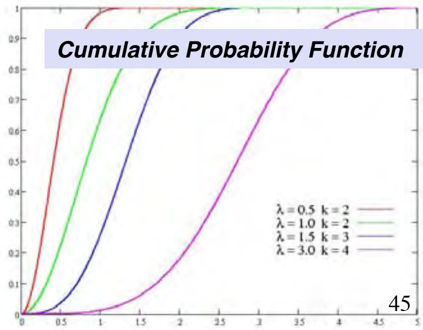
$$\mathrm{Pr}(x) = 1 - e^{-\frac{(x-x_o)^b}{(\theta - x_o)^b}}$$

x_o : expected minimum value

b : shape or slope parameter (k in figure)

θ : characteristic life or scale parameter (λ in figure)





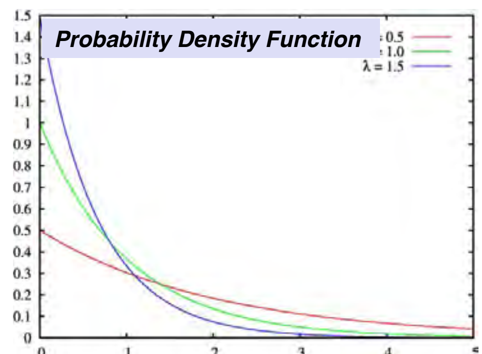
Exponential Distribution

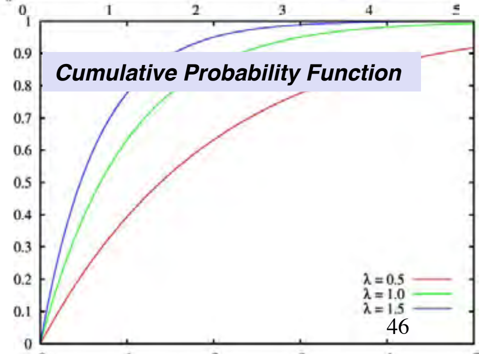
- **Special case of Weibull distribution, with $b = 1$, $x_o = 0$, and $x = t$**
- **Time to failure of systems or parts**
- **Modeling of independent events that occur at a constant average rate**

$$\mathrm{pr}(t) = \frac{1}{\theta} e^{-t/\theta}$$

$$\mathrm{Pr}(t) = 1 - e^{-t/\theta}$$

$$\lambda = 1/\theta : \text{failure rate}$$



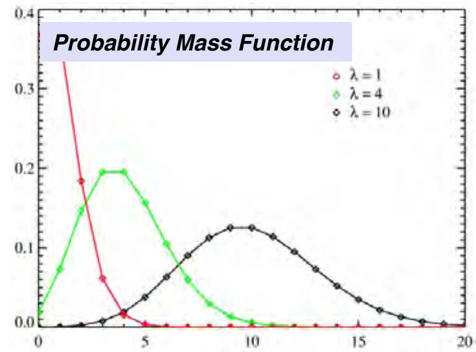


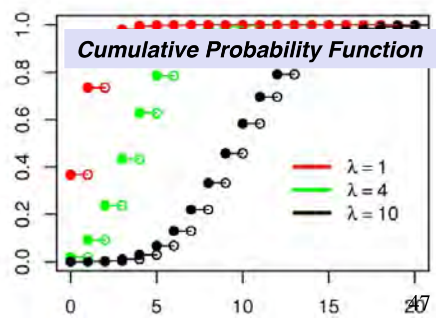
Poisson Distribution

- **Occurrence of isolated, independent events whose average rate is known**
  - **Number of events can be observed**
  - **Number of non-events cannot be observed**
- **Examples:**
  - **Number of machine breakdowns in a plant**
  - **Number of errors in a drawing**

$$\mathrm{pr}(r = r_i) = \frac{e^{-\lambda} y^{r_i}}{r_i!}$$

λ : average number of occurrences





Binomial Distribution

- **The probability of *r* successful outcomes in *n* trials**
- **Examples: inspection of parts, probability that a system will operate correctly**

$$\mathrm{pr}(r) = \binom{n}{r} p^r q^{n-r} = \binom{n}{r} p^r (1-p)^{n-r}$$

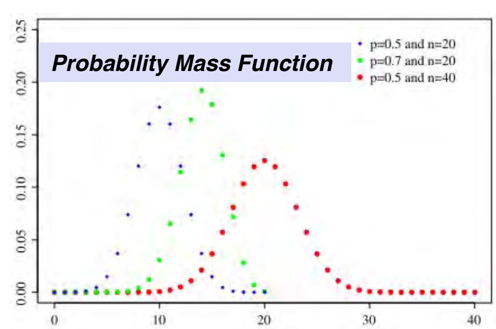
where

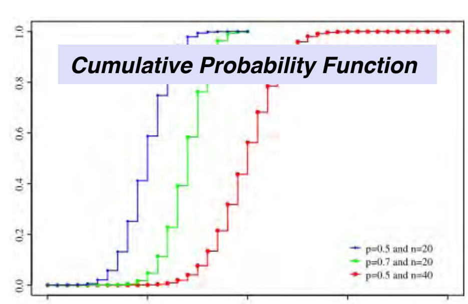
$$\binom{n}{r} = \frac{n!}{r!(n-r)!}$$

$n = number\ of\ trials$

$p = probability\ of\ success$

$q = probability\ of\ failure$

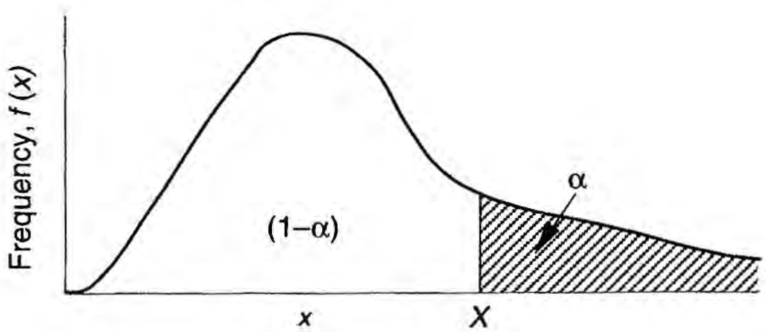




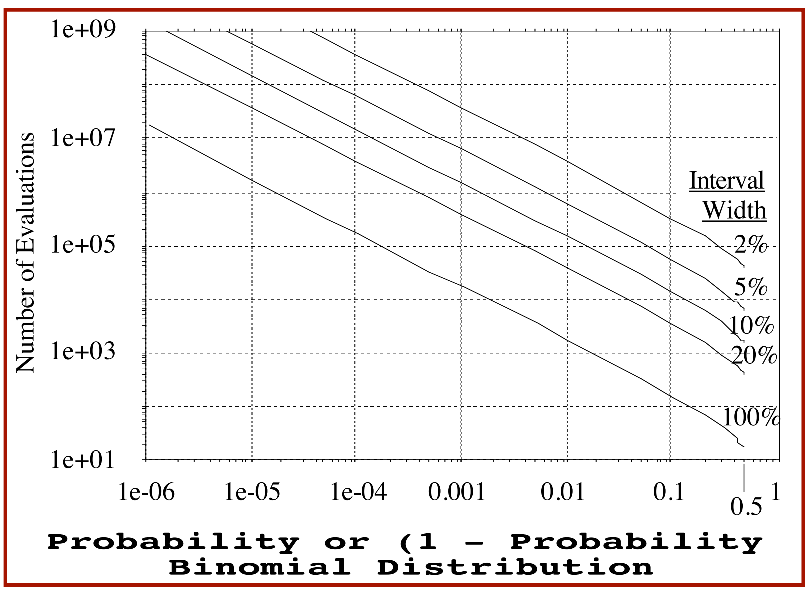
Confidence Level

- **The probability that a probability estimate is correct, e.g.,**

"The likelihood of failure is 90%, with a confidence level of 95%"

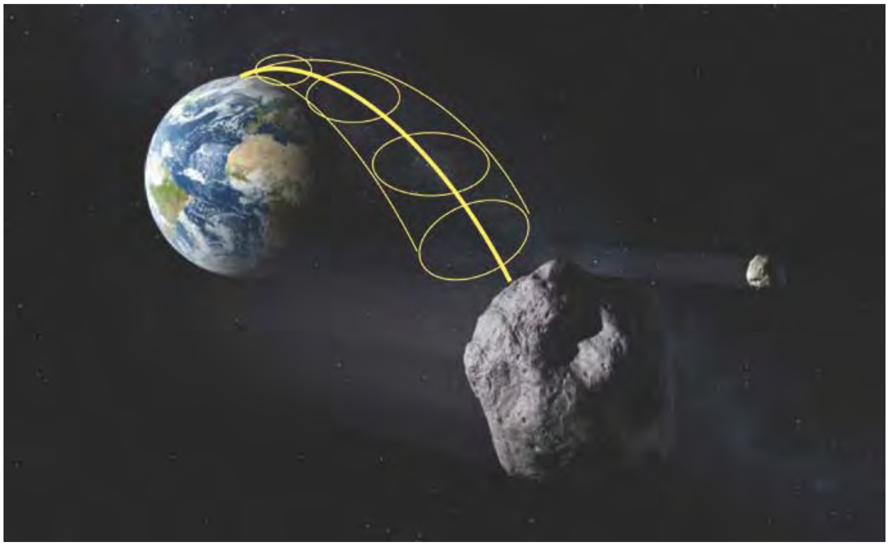


Trials Required to Estimate Probability Depend on Confidence Interval

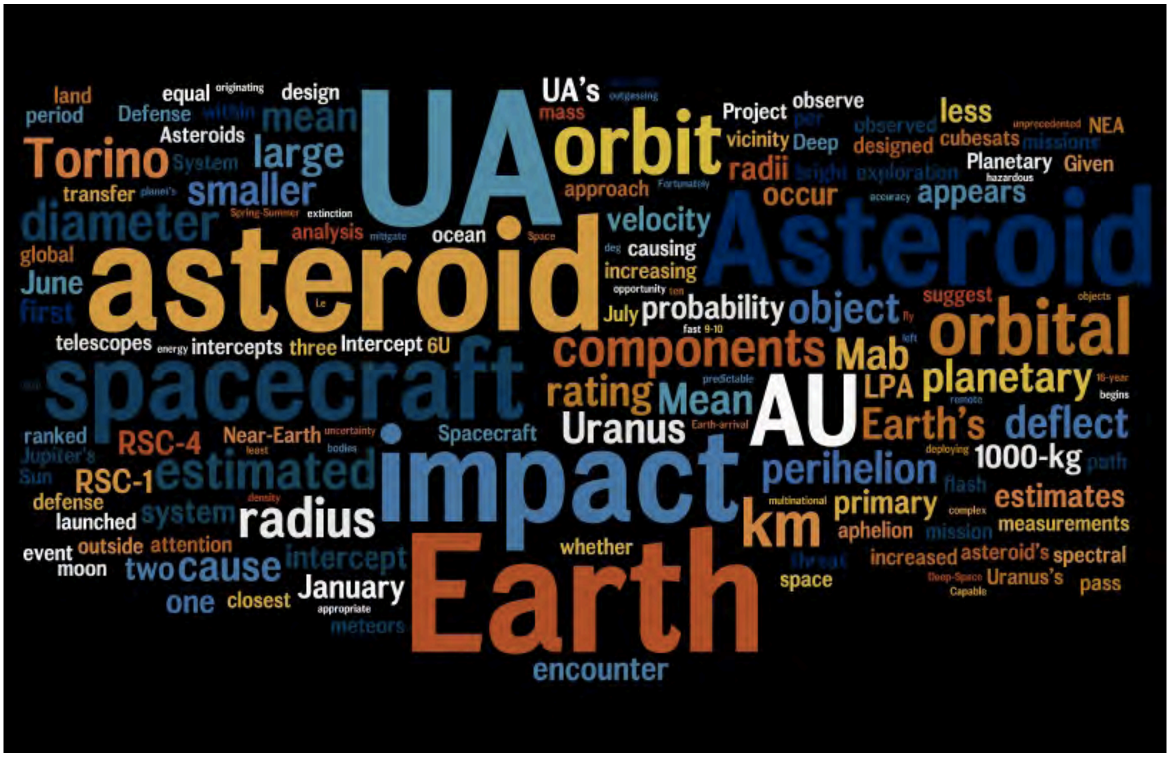


Required number of trials depends on outcome probability and desired confidence interval

How Will You Estimate the Likelihood of Success for Project 2020 UA?



MAE 342, Space System Design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object
planetary
rating
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