Managing Big Science Projects

LIGO

Barry Barish

E103 Management Lecture

27 May 03

Thanks to Gary Sanders for much of these materials
Small vs. Big Science
“In early 1943, John Manley, the experimental physicist from the University of Illinois on assignment to the Metallurgical Laboratory of the University of Chicago, visited University of California theoretical physicist J. Robert Oppenheimer, whom he had been assisting with plans for the new laboratory at Los Alamos. He had 'bugged Oppie for I don't know how many months about an organization chart - who was going to be responsible for this and who was going to be responsible for that. But one day in January, I climbed to the top floor of LeConte Hall where Robert had his office and pushed open the door. Ed Condon (the Westinghouse physicist whom Oppenheimer had chosen as his deputy director) happened to be in there with him at the moment, but Oppie practically threw a piece of paper at me as I came in the door and said, 'Here's your damn organization chart,' " Manley recounted.”
Big science is public

- Everything about the conduct of big science must be transparent to the public
- This is an ethical imperative
  - You are consuming resources that could make a difference to:
    - The public
    - Other recipients of the private support
    - Other scientific opportunities
- Your project’s resources are not an entitlement
- You must be prepared to be on “60 Minutes”
The Scientist’s Cultural Setting
Project Science as a culture

- Theoretical scientists
- Experimental scientists
- Project scientists

Three distinct cultures and temperaments
Caltech LIGO Group
The training and filtering of scientists

- **Undergraduate study** – reading and problem sets
  - Filters out productive problem solvers

- **Graduate study** – *Apprentice* research under an advisor
  - Absorb the advisor’s techniques and values

- **Early postdoctoral career** – *Independent contributor* to research
  - Show independence, innovation, creativity, analytical and technical mastery, focus, teaming in small teams

- **Midcareer** – *Mentor* in research
  - Confidence, mastery, emergence as a leader in a research field, strong focus, tenacious, competitive, seeker of “truth”
Big science – Big cultural gap

- The filtering process that yields excellent mid-career scientists provides little preparation for this
- Mismatch of normal scientific research culture and the culture of project management
- Early project stumbles lead to trouble, reorganization, delay, poor reputation of scientific projects
- Experience and expertise in managing large ongoing scientific labs/teams does not bridge this gap
<table>
<thead>
<tr>
<th>Attribute</th>
<th>Small Science</th>
<th>Big Science</th>
</tr>
</thead>
<tbody>
<tr>
<td>Success defined by</td>
<td>scientists, creators, inventors, peers</td>
<td>managers, reviewers, sponsors, peers</td>
</tr>
<tr>
<td>Decisions made by</td>
<td>scientists, creators, inventors</td>
<td>managers, directors, delegated</td>
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<tr>
<td>Design flexibility</td>
<td>flexible, creative</td>
<td>fixed, baselined</td>
</tr>
<tr>
<td>Fabricated by</td>
<td>in-house craftwork, &quot;make&quot;</td>
<td>industrial approach, &quot;buy&quot;</td>
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<tr>
<td>Team composition</td>
<td>predominantly scientists</td>
<td>scientists, engineers, accountants, PMs</td>
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<tr>
<td>Visibility of project</td>
<td>private</td>
<td>public</td>
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<tr>
<td>Project process</td>
<td>opaque</td>
<td>transparent</td>
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</table>

From discussions with Harry Collins
Gravitational Waves

"Colliding Black Holes"

Credit:
National Center for Supercomputing Applications (NCSA)
Caltech 40 m LIGO Prototype
Big science approach

- Create planned project
  - Convince yourself that you can do the project this way
    - Own the plan
    - Use the plan
    - Perfect/adapt/repair the plan in a highly disciplined manner
  - Develop confidence of sponsor
    - Planned project approach is not just a defensive shield against sponsor intrusion
    - Sponsor is an ongoing partner
The project manager’s challenge in bridging/combining cultures

- Appropriately emphasize the small science culture and big science culture in different amounts in
  - Design – small science leads
  - Planning – big science leads
  - Execution – big science leads
    - Repair of the project – small science crucial
  - Transition to science usage – transition towards small science
The project manager’s motto

"le mieux est l'ennemi du bien."
“the better is the enemy of the good enough”

Voltaire, 1764

John Mather, GSFC
LIGO Organization & Support

LIGO Laboratory
MIT + Caltech
~140 people
Director: Barry Barish

LIGO Science Collaboration
44 member institutions
> 400 scientists
Spokesperson: Rai Weiss

National Science Foundation

UK
Germany
Japan
Russia
India
Spain
Australia
The “Linear” Project
The “Linear” Project: An Ideal

Before we can create and manage a real world project we must be able to isolate the “ideal” project inside the real project

What are the identifying features of the ideal project?

– The project that can be managed in a straightforward “linear” manner
The “Linear” Project

Executing the project consists solely of carrying out a well defined plan

- Project goals and requirements are stable
- Sponsor support and funding are stable
- Managing institutions do not confuse the goal of project success with their other goals
- Resources are matched to project
- Resources are really controlled in one project office
- Project team owns the plan

The result is that the major risks are technical
  - Remaining risks are inexperience and human behavior
Stages In A Project

From an experiment to a project…
A Conceptual Problem is solved!

**Newton’s Theory**

“instantaneous action at a distance”

\[ F = G \frac{m_1 \times m_2}{d^2} \]

**Einstein’s Theory**

Information carried by gravitational radiation at the speed of light

\[ G_{\mu\nu} = 8\pi T_{\mu\nu} \]
- A necessary consequence of Special Relativity with its finite speed for information transfer

- Gravitational waves come from the acceleration of masses and propagate away from their sources as a space-time warpage at the speed of light

Gravitational radiation
Binary inspiral
Of compact objects
Detectors in space LISA

Gravitational Wave Astrophysical Source

Terrestrial detectors LIGO, TAMA, Virgo, AIGO

Experimental Idea
The Concept - Interferometry

- Laser used to measure relative lengths of two orthogonal arms
- Arms in LIGO are 4km
- Measure difference in length to one part in $10^{21}$ or $10^{-18}$ meters

As a wave passes, the arm lengths change in different ways....

...causing the interference pattern to change at the photodiode
Distinct stages in a project...

- Definition to Reference Design
- Reference Design to Baseline Definition
- ...to Final Design and Commitment
- ... to Industrialization
- Execution and Performance Measurement
- Integration and Plan to Completion
- Endgame

“broke and done on the same day”

Manage obligations
Manage costs
Project phases

- Conceptual - proposal, R&D
- Planning - defining baseline
- Design - requirements, prelim., final
- Industrialization - obligate
- Performance - earn value, quality
- Integration
- End Game - done & broke together
Definition to Reference Design
Definition to Reference Design

- Define scientific question(s)
- Define science requirements
- Develop informal conceptual design
- Define and initiate needed R&D
- Define technology options*
- Produce traditional small science experiment proposal
- Define “reference design”*
Reference Design to Baseline Definition
Reference Design to Baseline Definition

- Turn a defined experiment into a defined project
- The Baseline Definition is the basis for comprehensive organization of the
  - work to be performed
  - technical scope of product
  - cost and resource estimates
  - workplan and schedule
  - risk management plan
The baseline...

- Scientific requirements are defined and fixed
- Technical requirements meet the scientific requirements and are fixed
- Project deliverable is defined in a conceptual design
- Subsystems are defined
  - interfaces are defined
- Work Breakdown Structure (WBS) defines all work to be performed in the project including delivery of each subsystem and their integration
...The baseline

- Costs are estimated at the lowest level in the WBS
- Schedule is developed following the WBS
- Costs and other resources are integrated with the schedule to define the value of each scheduled activity, and a profile of obligations and costs
- Risks are assessed at the cost estimate level in the WBS and a contingency pool of funds are defined for project-wide management of risks
- Basis for performance measurement is established
When to “baseline”?

- On day 1 with pencil sketch?
- ...
- After conceptual reference design defined?
- ...
- When sponsor makes full commitment?
- ...
- At Final Design Review?
- ...
- When “as-built” drawings are completed?
When to “baseline”?

- This question is very much misunderstood
- At some point the sponsor accepts a baseline definition as a solemn promise
  - Project definition frozen too early can be source of great tension when normal project development process leads to prudent evolution
  - Recent tendency is to delay freezing formal baseline as much as possible so that adopted formal baseline can be stable
- This leads to irresponsible softness in project team commitment to the reference design
  - “After all, we aren’t baselined yet, so...”
Put reference design under early configuration control as interim baseline

- You are trying to grow a culture of disciplined work that fosters commitment to timely decisions
  - Team commits to “strawman”
  - Team learns process of orderly change
  - Team learns that work can now move forward
  - Team learns hierarchy of technology options and design choices
    - Baseline choice with fallback option and decision date
    - Equal options with decision date
    - Firm baseline choice with no option
  - Sponsor must recognize what this is
The design process

- Design Requirements
  - Including Conceptual Design
- Preliminary Design
- Final Design
- These phases structure the design process
- Deliverables of each phase structure the workplan and schedule
Design Requirements phase

- Define science requirements
- Define technical design requirements that meet the science requirements
- Develop an illustrative conceptual design that meets the design requirements
- Carry out needed R&D
- Prepare a Design Requirements Document including a companion Conceptual Design Document
  - Conceptual design is an illustrative design that meets the design requirements
- Satisfy a thorough review (DRR) of these deliverables that enables progression to next phase
Preliminary Design phase

- Based upon the products of the previous phase, carry out sufficient R&D and design to fully define the design to be built in sufficient detail to demonstrate that the Design Requirements are met and that all significant design choices are made
  - Include specification of processes in fabrication
  - Include all needed analytical calculations
  - May include production of prototypes
  - This design will not be sufficient to define the fabrication

- Prepare a Preliminary Design Document and an updated Design Requirements Document

- Satisfy a thorough review (PDR) of these deliverables that enables progression to next phase
Final Design phase

- Based upon the products of the previous phase, carry out sufficient R&D and design to fully define the design to be built in sufficient detail to support production fabrication
  - Include specification of processes in final fabrication
  - Include all needed analytical calculations
  - All relevant R&D results available and incorporated
  - May include production of “first articles” with testing
  - This design will be fully sufficient to define the fabrication
- Prepare a Final Design Document and an updated Design Requirements Document
- Satisfy a thorough review (FDR) of these deliverables that enables progression to production fabrication
The design process and system engineering

- The design reviews at the DRR, PDR and FDR stages are to be separately carried out for the overall system and for each of the subsystems
  - Definition of interfaces between subsystems to be included in each review

- This structures the system engineering
  - Apportionment of noise budgets, tolerances, contributions to performance requirements are thus included in this process
  - Interface definition
LIGO Optics

Substrates: SiO₂
25 cm Diameter, 10 cm thick
Homogeneity < 5 x 10⁻⁷
Internal mode Q’s > 2 x 10⁶

Polishing
Surface uniformity < 1 nm rms
Radii curvature matched < 3%

Coating
Scatter < 50 ppm
Absorption < 2 ppm
Uniformity < 10⁻³
Core Optics Integration

Installation and Alignment
What we have covered

- The scientist’s cultural setting
- Small vs. Big science
- The “Linear” Project
  - Stages in a Project
  - The Baseline
  - The Design Process
  - Work Breakdown Structure
  - Project Organization
  - Management Plan
  - Cost Estimate and Risk Analysis
  - Schedule Development
  - Performance Measurement

From small science to big science

To a baselined project ready to build
Planning for Performance Measurement
From a reference design to a defined and baselined project

- Work Breakdown Structure
- Project Organization
- Management Plan
- Cost Estimate and Risk Analysis
- Schedule Development
- Performance Measurement
Work Breakdown Structure (WBS)
Work Breakdown Structure (WBS)

- Break down **all** of the work required to complete the project
  - Include all physical deliverables, subsystems
  - Include R&D, design, prototyping, fabrication, assembly, installation, acceptance testing leading to a deliverable product
  - Include administration, system engineering, purchasing, reporting not directly related to deliverable products
  - Break work down to 5-8 levels from top **when mature**

- Organize work in a way to support delivery of “products”

- If work will be accomplished through major contracts, represent them in the WBS
Work Breakdown Structure (WBS)

- WBS will structure cost estimating, schedule planning, tracking of actual costs and progress
- It should reflect how you will manage the project toward its goals
- Do not make the common mistake of organizing it to keep accountants happy, or to reflect geography or existing organizations
- Structure your organization to parallel the WBS
- Write a Work Breakdown Structure Dictionary and maintain it
  - For each entry in the WBS Dictionary state:
    - What the element is
    - And what it is not
Figure 5-3. Work breakdown structure for yard project.

YARD PROJECT

- CLEANUP
  - Pick up trash—15
  - Bag grass—30
  - Hedge clippings—15
  - Haul to dump—45

- CUT GRASS
  - Mow front—45
  - Mow back—30

- TRIMWORK
  - Weeds @ trees—30
  - Edge sidewalk—15

- PREPARE EQUIPMENT
  - Put gas in equipment—5
  - Get out hedge clipper—5

- TRIM HEDGE—30
LIGO Work Breakdown Structure
LIGO: Laser Interferometer Gravitational-wave Observatory

Hanford Observatory

Caltech

Livingston Observatory

MIT

3002 km
\( \text{LIGO} = 10 \text{ ms} \)
LIGO Livingston Observatory
Project Organization
Work Breakdown Structure (WBS)
LIGO Organization
Beam Tube under High Vacuum

- LIGO beam tube under construction in January 1998
- 65 ft spiral welded sections
- Girth welded in portable clean room in the field

1.2 m diameter - 3mm stainless
50 km of weld

NO LEAKS!!
Vacuum Chambers
LIGO organization philosophy

- Organization has only three levels
  - Tasks - execute specific tasks
  - Groups - coordinate related work (subsystem)
  - Project Office - integrate and insure progress and control

- “Product Oriented”
  - Middle managers under pressure to deliver a “product”

- Integration
  - Project Management at top level provides integration and system engineering
Project Management’s roles

- Responsible to deliver the Project
- Manage system engineering and Project cost/schedule/technical progress
- Assure scientific success
- Chair Technical Board/Change Control Board
- Chair _weekly_ Project Control Meeting
- Chair _monthly_ Performance Meeting
- Responsible for interactions with sponsor
- PM should have no individual tasks
Change Control/Configuration Management

- Baseline must be documented
- Baseline is fixed and respected
- Changed only by a disciplined process
- Changes proposed formally and reviewed
- Adopted changes must be documented and communicated
- Change history must be traceable

Remember Voltaire...
Technical/Change Control Board

- Members are leaders of subsystems and PM, subcontracts, project controls, QA
- Review of all requests for:
  - cost changes > $50K
  - major milestone changes > 1 month
  - technical interface or performance changes
- **Recommendation** to Project Management
- Reviews all major technical choices
Project Controls Group

- Responsible to provide detailed visibility of Project performance in cost and schedule
- Manage review of technical configuration changes
- Manage cost estimating and revisions
- Manage schedule development and routine and urgent revisions
- Manage performance measurement
- Manage formal reporting to sponsor
- Manage procurements, industrial contracting and payment actions
- Manage all documentation
Cost Estimate
Cost Estimate - Basis

- Establish detailed Work Breakdown Structure
- All estimating to be done “bottom up” by the engineers and scientists directly responsible for each item
  - scientist + engineer
- Establish a written Cost Estimating Plan that defines uniform formats and procedures for all estimators
- Each estimated item should have all information supporting the estimate for that item recorded in a standard Basis of Estimate worksheet for that item. The Basis sheet should be signed and dated by the estimator.
<table>
<thead>
<tr>
<th>WBS Code</th>
<th>Description</th>
<th>WBS Level</th>
<th>Material, k$</th>
<th>ManHours</th>
<th>Labor, k$</th>
<th>M + L, k$</th>
<th>Markup, k$</th>
<th>% Contingency, k$</th>
<th>% TOTAL, k$</th>
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Magnet
Basis of Estimate

WBS: 40.03.12.3
Date: 6/13/92
Item: Vessel Support Structures
Rev: 0C
By: G. Deep/J. Bowers

Element Scope: This element includes all of the hardware required to physically support the coil, vessel, and muon sector assemblies in the underground hall. This will include the saddles to support the outer vessel as well as any jacking hardware provided to align the magnet, to compensate for ground motion, or to move the magnet assemblies. This does not include any concrete structures, such as piers or support beams, which are assumed to be parts of the hall facility.

Technical design description:
The saddle support structures are low carbon steel weldments consisting of large flat plate sections. Four saddle weldments are provided to support each vessel assembly, including the magnet and all internal detectors. Total weight supported by four saddle supports is conservatively 3000 tons.

It is assumed that all four saddles see equal dead loads and horizontal loads.

All saddles can be hydraulically jacked to transport the vessel system and for alignment. The jacking system is part of the transporter, and will be capable of lifting the weight of the vessel system plus the saddles, and have sufficient control to enable pitch, roll, and elevation positioning.

Interface to the building foundation is through shim blocks mounted to the floor.

Total weight of four saddle support weldments is 121 tons

Two sets of four are required, one set for each vessel.

Inspection/Admin
Basis:

Coordinator support during construction: 3 mm
Off-site/on-site inspections: 2 mm

EDIA/OA Material & Services
Basis: Quality Assurance weld inspection time: .5 my

Procurement/Fabrication
Basis: Each vessel
Raw materials
Saddles: 121 tons 304L stainless steel in finished structures
Add 9% waste giving 131 tons of raw material
Mill rate = $2.00/ lb yielding $524k

Support blocks: 40 tons 304L stainless steel in finished structures
Mill rate = $2.00/ lb yielding $160k

Weld material cost is included in welding cost.

Transportation: $2500/load x 10 loads = $25k
Plate section burning: 0.5 days/section, $600/section x 60 sections = $36k
Machine base plate: 2 days/ weldment x 4 weldments = 8 days = $7k
Weld fixtures and alignment: $20k
Welding: $10k/per weldment x 4 weldments = $40k
Blasting: $2.5k/per weldment x 8 weldments = $20k
Rigging: $50k
Total cost per vessel: $882k
Total cost for two vessels: $1764k
Cost of hydraulic jacking system: $200k
Cost of 24 transporter grease pads: $200k

Installation/Asst V
Material (SK): 2
Basis: This is covered in WBS 40.02.9.2.1, 40.04.1.1 - Magnet Installation

Unit type: ea
Number of units: 2
Estimate Type: BU

Risk Factors:
Technical: 2

Cost: 4
Basis: Vendor quotes on hydraulics and bottom up construction factors for structural assemblies. Mill costs for steel will vary based on the state of the national economy at the time of construction.

Schedule: 8
Basis: If built in sections off site, will have minimal impact on vessel installation schedule.

Misc Comments:
Current assumptions of floor movement vary up to 15 cm up and down.
## GEM Cost Estimate Details

**40.03.1.2.3 Vessel Support Structures Fab/Assy**

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<th>MI/Unit</th>
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<td>10</td>
<td>P/F</td>
<td>Blasting</td>
<td>16.00</td>
<td>WLD MTS</td>
<td>BU</td>
<td>2,596</td>
<td>41,538</td>
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<tr>
<td>11</td>
<td>P/F</td>
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<td>1.00</td>
<td>LS</td>
<td>BU</td>
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<td>12</td>
<td>P/F</td>
<td>Hydraulic Jacking System</td>
<td>1.00</td>
<td>LS</td>
<td>BU</td>
<td>207,690</td>
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<tr>
<td>13</td>
<td>P/F</td>
<td>Transporter Grease Pads</td>
<td>24.00</td>
<td>EA</td>
<td>BU</td>
<td>207,697</td>
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<td>14</td>
<td>I&amp;A</td>
<td>On/off Site Inspections</td>
<td>2.00</td>
<td>MM</td>
<td>BU</td>
<td>8,859</td>
<td>207,697</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Subtotal** - **40.03.1.2.3 Vessel Support Structures Fab/Assy**

$2,295,019

**735**

$44,297

$2,346,117

**Prime Contractor Markup** 7.71%

$180,373

$2,520,490

**Contingency** 20.00%

$554,098

**Cost Plus Contingency** $3,974,998

### Cost Matrix

<table>
<thead>
<tr>
<th>Eng/Des</th>
<th>M&amp;S</th>
<th>INSP/ADM</th>
<th>Proc/Fab</th>
<th>Assbly</th>
<th>Install</th>
</tr>
</thead>
<tbody>
<tr>
<td>LABOR</td>
<td>0</td>
<td>48,805</td>
<td>0</td>
<td>2,247,015</td>
<td>0</td>
</tr>
</tbody>
</table>

**Total, $**

48,805

44,297

2,247,015

0

0

**Manhours**

0

735

0

0

### Labor

**Touch Labor = $0**

**EDA Labor = $44,297**

### Risk

- **Technical Risk** 6%
- **Cost Risk** 8%
- **Schedule Risk** 8%

**Estimator:** G. DeSuj. Bowers

**Date of Estimate:** 06/15/92

Page 74
Cost Estimate - Base currency year

- All estimates to be performed in the currency for the year in which the estimate is made, as if the work is performed or contract placed in the current year
- Define a standard table of currency inflation for all years in which the project is to be executed
- Old industrial price quotations should be corrected for inflation up to the current year if a new estimate is not obtained from industry
Cost Estimate - Source of estimate

- Clearly identify the type of the source of the estimate
  - Engineering Estimate (EE) - least reliable
  - Vendor Quotation (VQ) - better, but likely to increase
  - Placed Order (PO) - even better
  - Actual Costs (AC) - best
  - Other methods include Parametric, Trends, Specific Analogy

- For every material subsystem, work to increase the fraction of the estimate based upon industrial vendor quotations
Cost Estimate - Roll up

- Structure estimate so that all costs for a component can be “rolled up” and costs for the subsystem including the component can be “rolled up” and costs for the entire system can be...
  - This creates a framework for tracking actual costs during the project execution
Cost Estimate - Labor rates

- Define all generic labor categories for labor charged to the Project (manager, engineer, scientist, technician, secretary, construction worker,...)
  - Use appropriate level of detail for maturity of Project
- Establish a standard labor rate for each category based upon market survey in base currency year
- Use labor “crew” mixes if appropriate for an operation
- Replace standardized rates with specific rates only when actual labor source is certain
- Consider vacation/sick time factors
Cost Estimate - Labor rates

- Do estimate in man-hours and apply rates later!
- In mass production operations, include the “learning curve” factor
- In mass production operations, consider “crew” quality and trade off cost for productivity
Cost Estimate - Audit

- Audit all detailed estimates for uniform application of Cost Estimating Plan
- Compare labor estimates for comparable operations
- Compare material costs
- Compare fraction of estimate based upon vendor quotes
- Compare risk analysis
- Use an outside and disinterested firm to independently develop or audit estimate
Cost Estimate - Risk Analysis
Cost Estimate - Risk analysis

- “Contingency”
  - The most misunderstood word in Washington DC re scientific projects
  - Alien concept outside the USA in funding agencies
  - “Is it a slush fund for the PM?”

- It is not possible to complete a project on plan without appropriate contingency resources
Cost Estimate - Risk analysis

- Estimate for each item should be the expected cost of the item excluding unusual or adverse risks.
- For each item, separately estimate the technical, cost and schedule risks for that item.
- Use a standardized and disciplined method for all items and all estimators.
- Develop an estimate of an amount of money to be held in reserve to deal with the average of all risks.
- Not all risks will actually take place during the Project. This amount of money is “contingency.”
Cost Estimate - Risk analysis

- Primitive method - bulk percentage rule of thumb
  - “15% for civil works, 10% at contract signing”
  - “30% for technical systems”...
  - Rates pronounced by grizzled veterans

- Better method - Standard Risk Factor/Percentage
  - One method of this type described here

- Best method – cost of point design response to each risk estimated one by one
  - not usually practical
## Cost Estimate - Risk factors

<table>
<thead>
<tr>
<th>Risk factor</th>
<th>Technical</th>
<th>Cost</th>
<th>Schedule</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Existing design and off-the-shelf hardware</td>
<td>Off the shelf or catalog item</td>
<td>not used</td>
</tr>
<tr>
<td>2</td>
<td>Minor modifications to an existing design</td>
<td>Vendor quote from established drawings</td>
<td>No schedule impact on any other item</td>
</tr>
<tr>
<td>3</td>
<td>Extensive modifications to an existing design</td>
<td>Vendor quote with some design sketches</td>
<td>not used</td>
</tr>
<tr>
<td>4</td>
<td>New design within established product line</td>
<td>In-house estimate for item within current product line</td>
<td>Delays completion of non-critical path subsystem item</td>
</tr>
<tr>
<td>6</td>
<td>New design different from established product line. Existing technology</td>
<td>In-house estimate for item with minimal company experience but related to existing capabilities</td>
<td>not used</td>
</tr>
<tr>
<td>8</td>
<td>New design. Requires some R&amp;D development but does not advance the state-of-the-art</td>
<td>In-house estimate for item with minimal company experience and minimal in-house capability</td>
<td>Delays completion of critical path subsystem item</td>
</tr>
<tr>
<td>10</td>
<td>New design. Development of new technology which advances the state-of-the-art</td>
<td>Top down estimate from analogous programs</td>
<td>not used</td>
</tr>
<tr>
<td>15</td>
<td>New design way beyond the current state-of-the-art</td>
<td>Engineering judgment</td>
<td>not used</td>
</tr>
</tbody>
</table>
## Cost Estimate - Risk percentages

<table>
<thead>
<tr>
<th></th>
<th>CONDITION</th>
<th>RISK PERCENTAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>TECHNICAL</td>
<td>Design or mfg concerns only</td>
<td>2%</td>
</tr>
<tr>
<td></td>
<td>Design and mfg concerns</td>
<td>4%</td>
</tr>
<tr>
<td>COST</td>
<td>Material cost or labor rate concern</td>
<td>1%</td>
</tr>
<tr>
<td></td>
<td>Material and labor rate concern</td>
<td>2%</td>
</tr>
<tr>
<td>SCHEDULE</td>
<td></td>
<td>1%</td>
</tr>
</tbody>
</table>
Cost Estimate - Contingency %

Contingency (%) = Technical risk factor x Technical risk % + Cost risk factor x Cost risk % + Schedule risk factor x Schedule risk %

- Risk Factors - from 1 to 15
- Risk Percentages - 1% to 4%
- Range of contingency generated falls between 5% and 98%
- Best technical judgment used to override this specific graded approach to risk analysis
Cost Estimate - Contingency

- This formulaic approach may seem mindless
- It makes your estimators look carefully at each and every item at the lowest level
  - Very valuable
- It provides a common point of departure for every estimator
- It helps in auditing each estimator and comparing with the practices of other estimators
- It has been applied successfully, and extended, by numerous projects
Cost Estimate - Contingency

- Estimate of contingency made for each item at lowest practical level
- Percentage is converted to currency
- Contingency funds are held by the Project Manager and they lose their identification with each item!
- Each Task Leader controls the budget for a subsystem without the contingency funds
- Remember that the contingency pool is not designed to cover every possible risk all occurring during the Project
Cost Estimate - Request for contingency funds

- As the Project progresses, contingency funds can be requested by written application to the Project Manager.
- Requests are reviewed by Technical Board/Change Control Board consisting of all other system leaders.
- Project Manager grants requested funds, or rejects request, or requests change in schedule, technical scope or requests other corrective action.
  - **Scope contingency** - require subsystem leaders to identify 10% reductions in subsystem scope.
- Funds can be returned to contingency.
**LIGO CHANGE REQUEST**

Change Request No: CR-020016  
Date: October 1, 2002  

WBS Element and Title: WBS 1.1.4 Facilities (Hanford Irrigation, Landscaping, Erosion Control)  
Originator: O. Matherney  
Telephone: 509-372-8118  
CCB Sponsor:  

---

**Technical Change Description:** Hanford Laboratory Building Irrigation, Erosion Control, Landscaping  
Install irrigation, erosion protection and landscaping around the new laboratory building. Approximately three acres of ground will be covered by drain rock and there will be over 400 plants to be planted.

---

**Budget Impact:** $60,000  
Cost estimate based on subcontractor quote. $100,000 has been held as a Construction Planning Package for this task.

---

**Schedule Impact:**  
For best results, we need to accomplish the work before spring of 2003.

---

**Concurrence Signatures:**

<table>
<thead>
<tr>
<th>Concurrence Signatures:</th>
<th>Date:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical and Engineering Support:</td>
<td>Date:</td>
</tr>
<tr>
<td>Detector Support:</td>
<td>Date:</td>
</tr>
<tr>
<td>Data and General Computing:</td>
<td>Date:</td>
</tr>
<tr>
<td>Hanford Observatory:</td>
<td>Date:</td>
</tr>
<tr>
<td>Livingston Observatory:</td>
<td>Date:</td>
</tr>
<tr>
<td>Project Controls Manager:</td>
<td>Date:</td>
</tr>
</tbody>
</table>

---

**CCB Approval/Disposition:**

| CCB Chairman: | Date: |

---

- Identify WBS  
- State request  
- Document technical, cost, schedule impacts  
- Support documenting the approval and rationale  
- Attach additional material for complete package  
- Traceable
Cost Estimate - Actual Costs and Estimate to Complete

- If Project is estimated properly, 100% completion of Project will use 100% of direct estimate + 100% of contingency
  - Contingency is not to be hoarded till after project completion
- As Project progresses, direct cost estimate is exceeded and contingency funds are used
- Periodically (annually?) cost estimate is revised to reflect all new information including actual costs and use of contingency funds. New estimate is called Estimate To Complete
- Track (%contingency used)/(% Project complete)
(\%\text{Contingency used})/(\%\text{ Project complete})
Cost Baseline

- Original full cost estimate (in base year $) including the separate pool of contingency funds is entered into a database and maintained throughout the life of the Project as the Cost Baseline.
- All Project cost performance is measured monthly against the Cost Baseline in order to detect cost deviations as early as possible.
- New Estimate to Complete is used after reestimate but original Cost Baseline is preserved in database.
- Define time spread of costs using inflation factors in Cost Baseline for later use with schedule.
Schedule
Schedule - Basic

- Project Management defines a set of useful major project milestones and requests development of lower level detailed schedules to conform to top level milestones. These top level milestones define the overall project strategy and priorities and the attention of project staff.

- Subproject structure organized to agree with Work Breakdown Structure and integrated together following WBS

- Prepare Integrated Project Schedule consisting of all linked schedules for each subproject in total Project
## LIGO facilities milestones

<table>
<thead>
<tr>
<th>Milestone Description</th>
<th>PMP</th>
<th>Projection/Actual</th>
<th>PMP</th>
<th>Projection/Actual</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Hanford</td>
<td>Livingston</td>
<td>Hanford</td>
<td>Livingston</td>
</tr>
<tr>
<td>Initiate Site Development</td>
<td>Mar-94</td>
<td>Mar-94</td>
<td>Aug-95</td>
<td>Jun-95</td>
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<tr>
<td>Beam Tube Final Design Review</td>
<td>Apr-94</td>
<td>Apr-94</td>
<td>Apr-94</td>
<td>Apr-94</td>
</tr>
<tr>
<td>Complete Beam Tube Qualification Test</td>
<td>Feb-95</td>
<td>Apr-95</td>
<td>Feb-95</td>
<td>Apr-95</td>
</tr>
<tr>
<td>Select Vacuum Equipment Contractor</td>
<td>Mar-95</td>
<td>Jul-95</td>
<td>Mar-95</td>
<td>Jul-95</td>
</tr>
<tr>
<td>Complete Performance Measurement Baseline</td>
<td>Apr-95</td>
<td>Apr-95</td>
<td>Apr-95</td>
<td>Apr-95</td>
</tr>
<tr>
<td>Initiate Beam Tube Fabrication</td>
<td>Oct-95</td>
<td>Dec-95</td>
<td>Oct-95</td>
<td>Dec-95</td>
</tr>
<tr>
<td>Initiate Slab Construction</td>
<td>Oct-95</td>
<td>Feb-96</td>
<td>Jan-97</td>
<td>Jan-97</td>
</tr>
<tr>
<td>Initiate Building Construction</td>
<td>Jun-96</td>
<td>Jul-96</td>
<td>Jan-97</td>
<td>Jan-97</td>
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<tr>
<td>Joint Occupancy</td>
<td>Sep-97</td>
<td>Oct-97</td>
<td>Mar-98</td>
<td>Feb-98</td>
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<tr>
<td>Beneficial Occupancy</td>
<td>Mar-98</td>
<td>Mar-98</td>
<td>Sep-98</td>
<td>Dec-98</td>
</tr>
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<td>Accept Vacuum Equipment</td>
<td>Mar-98</td>
<td>Nov-98</td>
<td>Sep-98</td>
<td>Jan-99</td>
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<tr>
<td>Initiate Facility Shakedown</td>
<td>Mar-98</td>
<td>Nov-98</td>
<td>Mar-99</td>
<td>Jan-99</td>
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</table>
Detailed schedules developed in same manner as cost estimate
  – follow WBS
  – developed by responsible task leaders
  – basis recorded in standardized manner
  – schedule risks considered in developing details
  – technical estimate made of each task duration and dependence on other tasks

Detailed schedule development is closely related to development of cost estimate detail
**Figure 5-3.** Work breakdown structure for yard project.

- **YARD PROJECT**
  - **CLEANUP**
    - Pick up trash—15
    - Bag grass—30
    - Hedge clippings—15
    - Haul to dump—45
  - **CUT GRASS**
    - Mow front—45
    - Mow back—30
  - **TRIMWORK**
    - Weeds @ trees—30
    - Edge sidewalk—15
  - **PREPARE EQUIPMENT**
    - Put gas in equipment—5
  - **TRIM HEDGE**
    - 30
Figure 6-4. Bar chart schedule for yard project.

- Pick up trash
- Put gas in equipment
- Get out hedge clipper
- Trim weeds
- Mow front lawn
- Edge sidewalk
- Trim hedge
- Mow back yard
- Bag grass & trash
- Bundle hedge clippings
- Haul away trash

* Task with float
* Critical task

Figure 5-2. Arrow charts.

An activity-on-node network.

Activity A → Activity B → Activity D

Activity C

An activity-on-arrow network.

Activity A → Activity B

Activity C → Activity D

Summary

Integrated schedule

<table>
<thead>
<tr>
<th>SUMMARY INTEGRATED SCHEDULE</th>
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</thead>
<tbody>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>Vacuum Equipment</td>
</tr>
<tr>
<td>Beam Tubes</td>
</tr>
<tr>
<td>Beam Tube Bakeout</td>
</tr>
<tr>
<td>Beam Tube Enclosure</td>
</tr>
<tr>
<td>Civil (Site/Buildings)</td>
</tr>
<tr>
<td>WA 2k Interferometer</td>
</tr>
<tr>
<td>WA 4k Interferometer</td>
</tr>
<tr>
<td>Control &amp; Data System</td>
</tr>
<tr>
<td>Physical Environment Monitor</td>
</tr>
<tr>
<td>LOUISIANA SITE</td>
</tr>
<tr>
<td>Vacuum Equipment</td>
</tr>
<tr>
<td>Beam Tubes</td>
</tr>
<tr>
<td>Beam Tube Bakeout</td>
</tr>
<tr>
<td>Beam Tube Enclosure</td>
</tr>
<tr>
<td>Civil (Site/Buildings)</td>
</tr>
<tr>
<td>LA 4k Interferometer</td>
</tr>
<tr>
<td>Control &amp; Data System</td>
</tr>
<tr>
<td>Physical Environment Monitor</td>
</tr>
<tr>
<td>Coincidence Tests / Operations</td>
</tr>
</tbody>
</table>

LEGEND:
- GREEN: DESIGN
- CYAN: FAB/CONST
- BLUE: INSTALL
- PURPLE: INSTALL IN VAC.
- PINK: TEST/ACCEPT
- RED: CRITICAL PATH

WA JOINT OCC.
WA DETECTOR READY
LA JOINT OCC.
LA "1st 4 km LIGHT"
LA DETECTOR READY

LIGO
Schedule - Integration

- Project Management integrates detailed schedules and reviews all schedule ties between subprojects with those developing detailed schedules.
- Identify all **Critical Paths** (paths through schedule with no extra time (slack)).
- Test alternate approaches to Critical Path.
- Test alternate project strategies.
- Attempt to build schedule slack in critical operations.
- Develop menu of “work arounds” for anticipated schedule risks.
Performance Measurement Baseline
Cost Baseline and Integrated Project Schedule are held by Project Management

Create PMB by loading costs for each task into schedule task
  - select flat, growing, falling, bell curve, or progress payment cost profile for each task
  - select an appropriate level in WBS for combining costs and schedule tasks. Goal is performance measurement by Project Manager, with lower level flexibility left to task leaders
  - match to likely funding profile from funding source
    - “Technically paced” or “funding paced”

Load into database as Budgeted Cost of Work Scheduled
Tracking and controlling performance

- Require contractors to report costs and schedule progress monthly to Task Leaders responsible for contract
- Task Leaders report cost and schedule progress to Project Management each month
  - Only this system used by Task Leaders for performance measurement
  - Must be implemented so as to be truly useful
- Progress measured by standardized methods and accumulated as Earned Value
Earned Value reporting

- Monthly measurement of progress in each task accumulated as Earned Value
  - % Complete
  - Milestones Completed
  - Progress Payments Earned
  - Level of Effort
Performance and variances

- Budgeted Cost of Work Scheduled (BCWS)
- Budgeted Cost of Work Performed (BCWP)
  - earned value
- Actual Cost of Work Performed (ACWP)
- Cost Performance Index (CPI) = BCWP/ACWP
- Schedule Performance Index (SPI) = BCWP/BCWS
- Cost Variance (CV) = BCWP - ACWP
- Schedule Variance (SV) = BCWP - BCWS

(All units are in $)
Performance Measurement display
Figure 8-4. Earned value analysis—behind schedule, overspent.

Earned Value Analysis

Cumulative Spending (Thousands)

Time, Working Weeks

- BCWS
- ACWP
- BCWP

Spending Variance
Schedule Variance
Date of progress measurement
LIGO Cost Schedule Status

- Original Plan - $250M
- Current Plan - $292M
- Cooperative Agreement (Funding) - $292M
- Performance - $285M
- Actual Costs - $284M
Staffing

labor distribution projections
LIGO Sensitivity

Livingston 4km Interferometer

First Science Run
17 days - Sept 02

Second Science Run
59 days - April 03

May 01
Jan 03
Optimal Signal Detection
Want to “lock-on” to one of a set of known signals

Requires:
• source modeling
• efficient algorithm
• many computers

Binary Neutron Star Inspiral
Loudest Surviving Candidate

- Not NS/NS inspiral event
- 1 Sep 2002, 00:38:33 UTC
- S/N = 15.9, $\chi^2$/dof = 2.2
- $(m_1,m_2) = (1.3, 1.1)$ Msun

What caused this?
- Appears to be saturation of a photodiode
Results of Inspiral Search

Upper limit binary neutron star coalescence rate

Previous observational limits
- Japanese TAMA \( R < 30,000 \text{ / yr / MWEG} \)
- Caltech 40m \( R < 4,000 \text{ / yr / MWEG} \)

Theoretical prediction \( R < 2 \times 10^{-5} \text{ / yr / MWEG} \)