Planning and Deterministic Scheduling

Nathaniel Osgood

3-8-2004

Topics

- Problem set background
- Planning
  - CBS
  - OBS
  - WBS
- Scheduling
  - Motivations and context
  - Gantt charts
  - CPM
    - Float
    - Critical path
    - Float ownership

A Word on the Problem Set

- Construction methods
  - Assume tie-backs required to support structure during construction (need invert slab formwork)
  - Slab on grade
    - Not responsible for slab on grade
  - Casting using invert forms
    - Can cast beams and slabs at same time
  - Wall casting (illustration only)
- Don't worry about formwork reuse
- Several types of anchor bolts in structure

Casting a concrete slab on grade

Sequence: **(You are not responsible for this formwork in the assignment)**

1. Form and edges
2. Reinforcement and embedment
3. Striking off or straightedge
4. Floating (if smoother surface is needed)
5. Control joints
6. Troweling (if very smooth surface is needed)
7. Curing (under damp conditions)

Casting a concrete wall

Sequence:

1. Coated form (one side only)
2. Reinforcing
3. Placement of Ties
4. Placement of construction joints (if needed)
5. Inspection
6. Coated form (2nd side)
7. Placing concrete
8. Curing
9. Stripping of formwork and snapping off ties
10. Point and Patch
11. Rub

Planning Components

- What: Scope (Plans and specifications)
- How much $: Budget (via CBS – and estimate)
- Who: OBS
- How: WBS
- When: Schedule

Topics

- ✓ Problem set background
- Planning
  - CBS
  - OBS
  - WBS
- Scheduling
  - Motivations and context
  - Gantt charts
  - CPM
    - Float
    - Critical path
    - Float ownership

Cost Breakdown Structure (CBS)

- Canonical way of accounting for costs in the project
- Assigns accounts for different types of expenditures
- Should permits tracking expenditure by activity (work item)
- Often includes WBS-based characterization (e.g. CSI Masterformat)

CSI Masterformat (Building Const)

Bidding Requirements, Contract Forms, and Conditions of the Contract

00010 Pre-bid Information
00100 Instructions to Bidders
00200 Information available to Bidders
00300 Bid Forms
00400 Supplements to Bid Forms
00500 Agreement Forms
00600 Bonds and Certificates
00700 General Conditions
00800 Supplementary Conditions
00900 Addenda

Note: The items listed above are not specification sections and are referred to as "Documents" rather than "Sections" in the Master List of Section Titles, Numbers, and Broadscope Section Explanations.

Specifications

Division 1 - General Requirements

01010 Summary of Work
01020 Allowances
01025 Measurement and Payment
01030 Alternates/Alternatives
01035 Modification Procedures
01040 Coordination
01050 Field engineering
01060 Regulatory Requirements
01070 Identification systems
01090 References
01100 Special Project Procedures
01200 Project Meetings
01300 Submittals
01400 Quality Control
01500 Construction Facilities and Temporary Controls
01600 Material and Equipment
01650 Facility Startup/Commissioning
01700 Contract Closeout
01800 Maintenance

Division 2 - Site Work

02010 Subsurface Investigation
02050 Demolition
02100 Site Preparation
02140 Dewatering
02150 Shoring and Underpinning
02160 Excavation Support Systems
02170 Cofferdams
02200 Earthwork
02300 Tunneling
02350 Piles and Caissons
02450 Railroad Work
02480 Marine Work
02500 Paving and Surfacing
02600 Utility Piping Materials
02660 Water Distribution
02680 Fuel and Steam Distribution
02700 Sewerage and Drainage
02760 Restoration of Underground Pipe
02770 Ponds and Reservoirs
02780 Power and Communications
02800 Site Improvements
02900 Landscaping

Division 3 - Concrete

03100 Concrete Framework
03200 Concrete Reinforcement
03250 Concrete Accessories
03300 Cast-In-Place Concrete
03370 Concrete Curing
03400 Precast Concrete
03500 Cementitious Decks and Toppings
03600 Grout
03700 Concrete Restoration and Cleaning
03800 Mass Concrete

Division 4 - Masonry

04100 Mortar and Masonry Grout
04150 Masonry Accessories
04200 Unit Masonry
04400 Stone
04500 Masonry Restoration and Cleaning
04550 Refractories
04600 Corrosion Resistant Masonry
04700 Simulated Masonry

Division 5 - Metals

05010 Metal Materials
05030 Metal Coatings
05050 Metal Fastening
05100 Structural Metal Framing
05200 Metal Joists
05300 Metal Decking
05400 Cold Formed Metal Framing
05500 Metal Fabrications
05580 Sheet Metal Fabrications
05700 Ornamental Metal
05800 Expansion Control
05900 Hydraulic Structures

Division 6 - Wood and Plastics

06050 Fasteners and Adhesives
06100 Rough Carpentry
06130 Heavy Timber Construction
06150 Wood and Metal Systems
06170 Prefabricated Structural wood
06200 Finish Carpentry
06300 Wood Treatment
06400 Architectural Woodwork
06500 Structural Plastics
06600 Plastic Fabrications
06650 Solid Polymer Fabrications

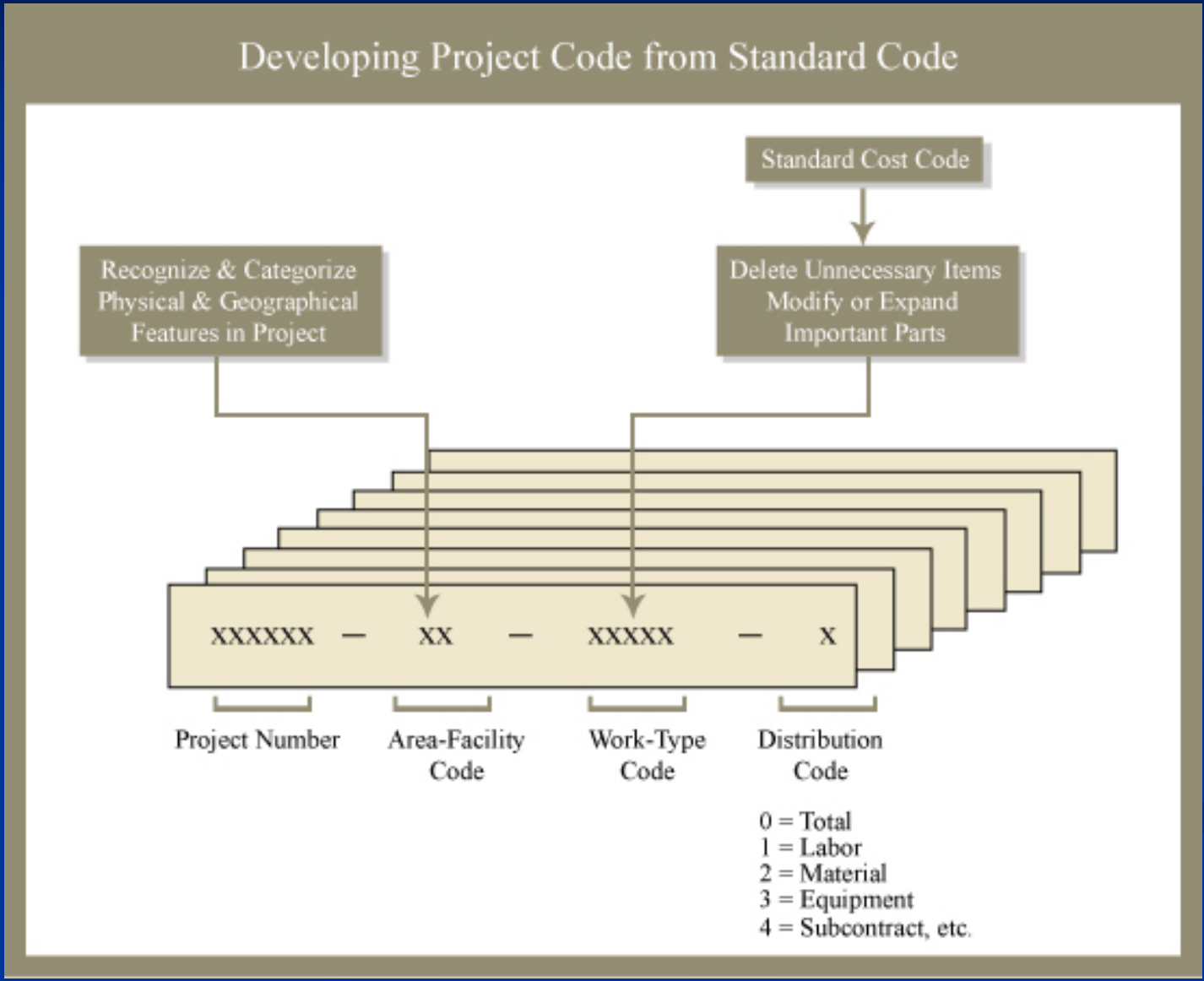
Division 7 - Thermal and Moisture Protection

07100 Waterproofing
07150 Damproofing
07180 Water Repellents
07190 Vapor Retarders
07195 Air Barriers
07200 Insulation
07240 Exterior Insulation and Finish Systems
07250 Fireproofing
07270 Firestopping
07300 Shingles and Roofing Tiles
07400 Manufactured Roofing and Siding
07480 Exterior Wall Assemblies
07500 Membrane Roofing
07570 Traffic Coatings
07600 Flashing and Sheet Metal
07700 Roof Special Ties and Accessories
07780 Skylights
07790 Joint Sealers

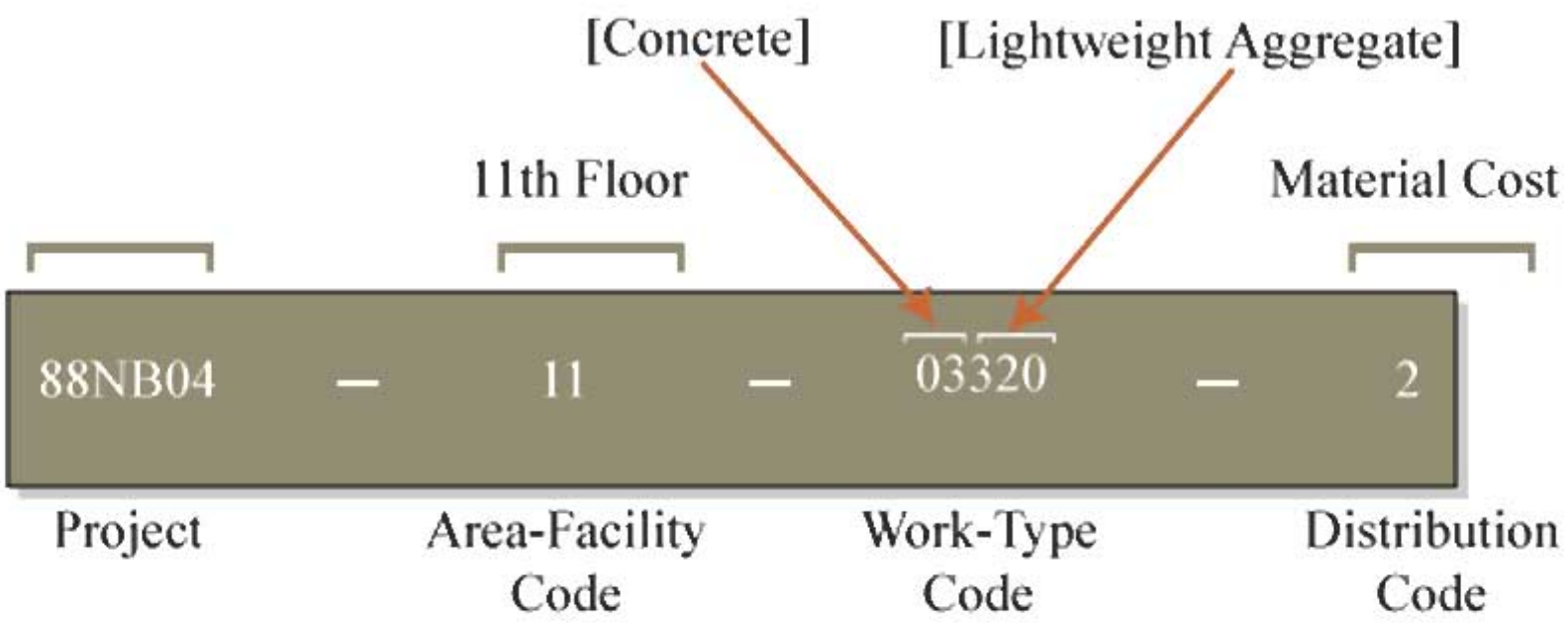
Cost Code

- Mirrored by cost hierarchy
- Commonly include standardized and project components
  - Project id (often has useful info to avoid lookup)
    - Often omitted from internal project references
  - Area-facility code (geographically distributed projects, or areas of a facility *unique to project*)
  - Work-type code: WBS May be standard code (e.g. CSI Masterformat) if uniform across projects
  - Distribution code: Cost type associated with work
    - (e.g. Materials, Equipment, Labor, Subcontract, etc.)

Cost Code Illustration



Example Project Code

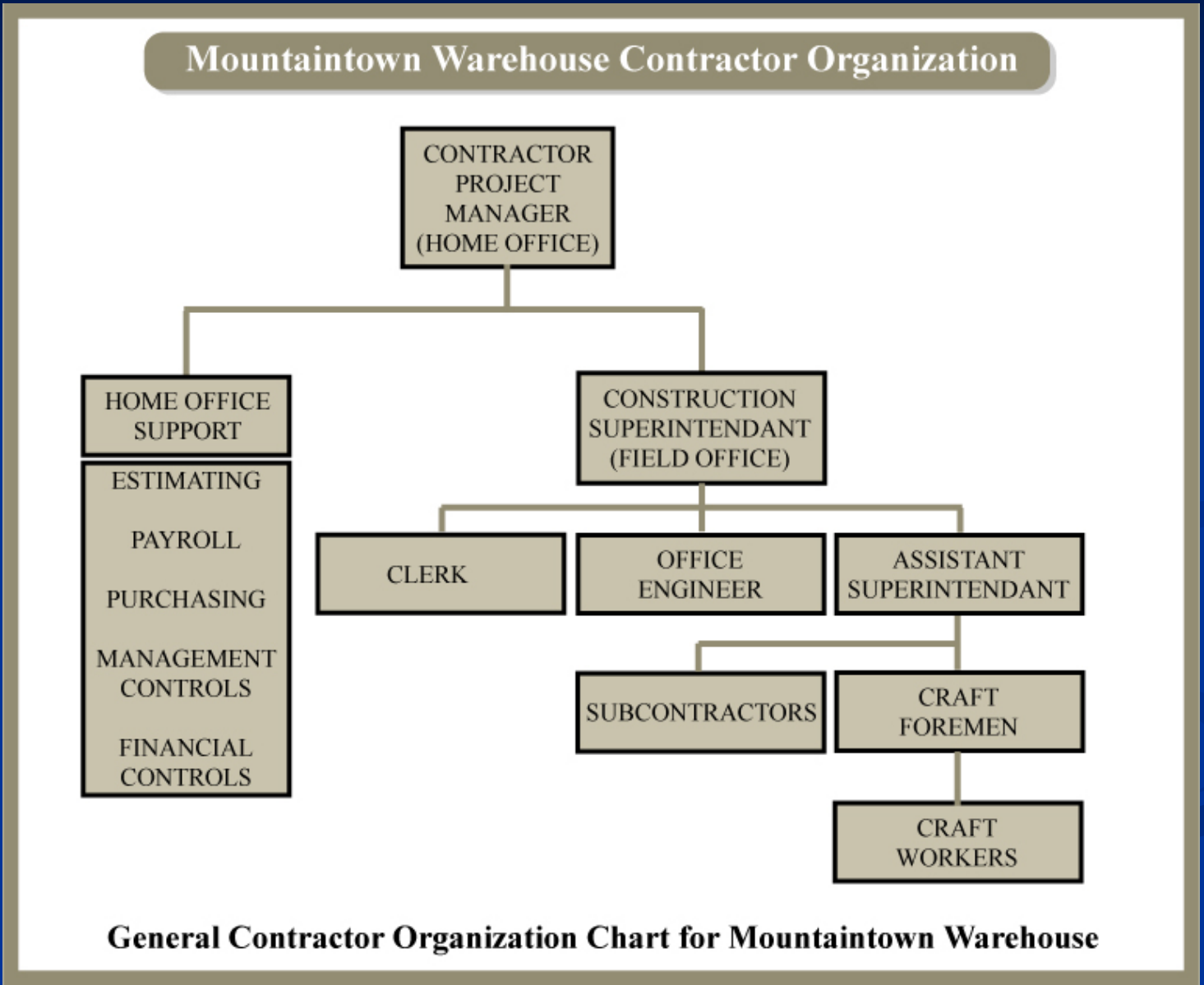


88 = Job Start 1988
N = Negotiated Contract
B = Building
04 = 4th Building this year

Topics

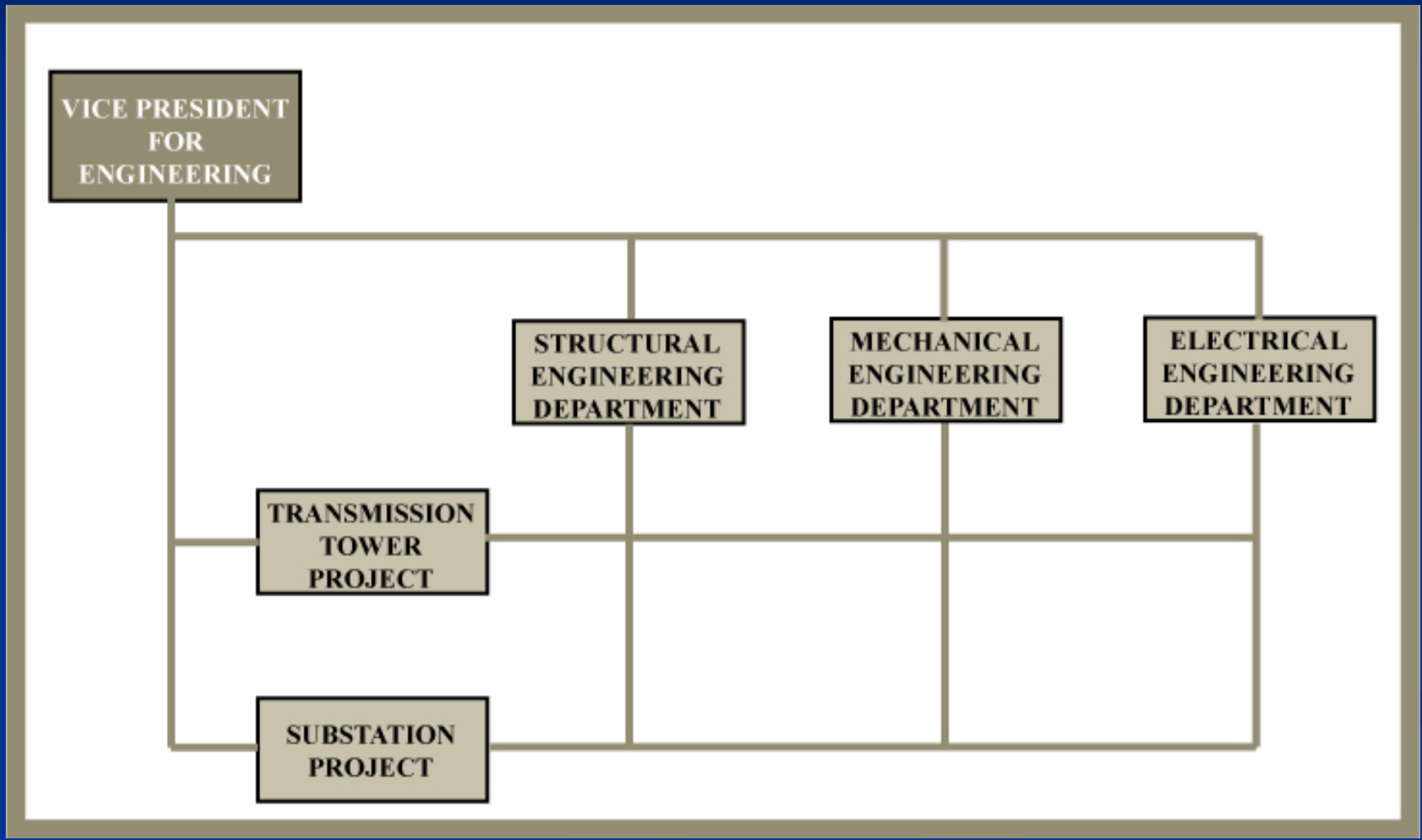
- ✓ Problem set background
- ✓ Planning
  - ✓ CBS
  - OBS
  - WBS
- Scheduling
  - Motivations and context
  - Gantt charts
  - CPM
    - Float
    - Critical path
    - Float ownership

Organizational Breakdown Structure



General Contractor Organization Chart for Mountaintown Warehouse

In Broader Context (Matrix Org)



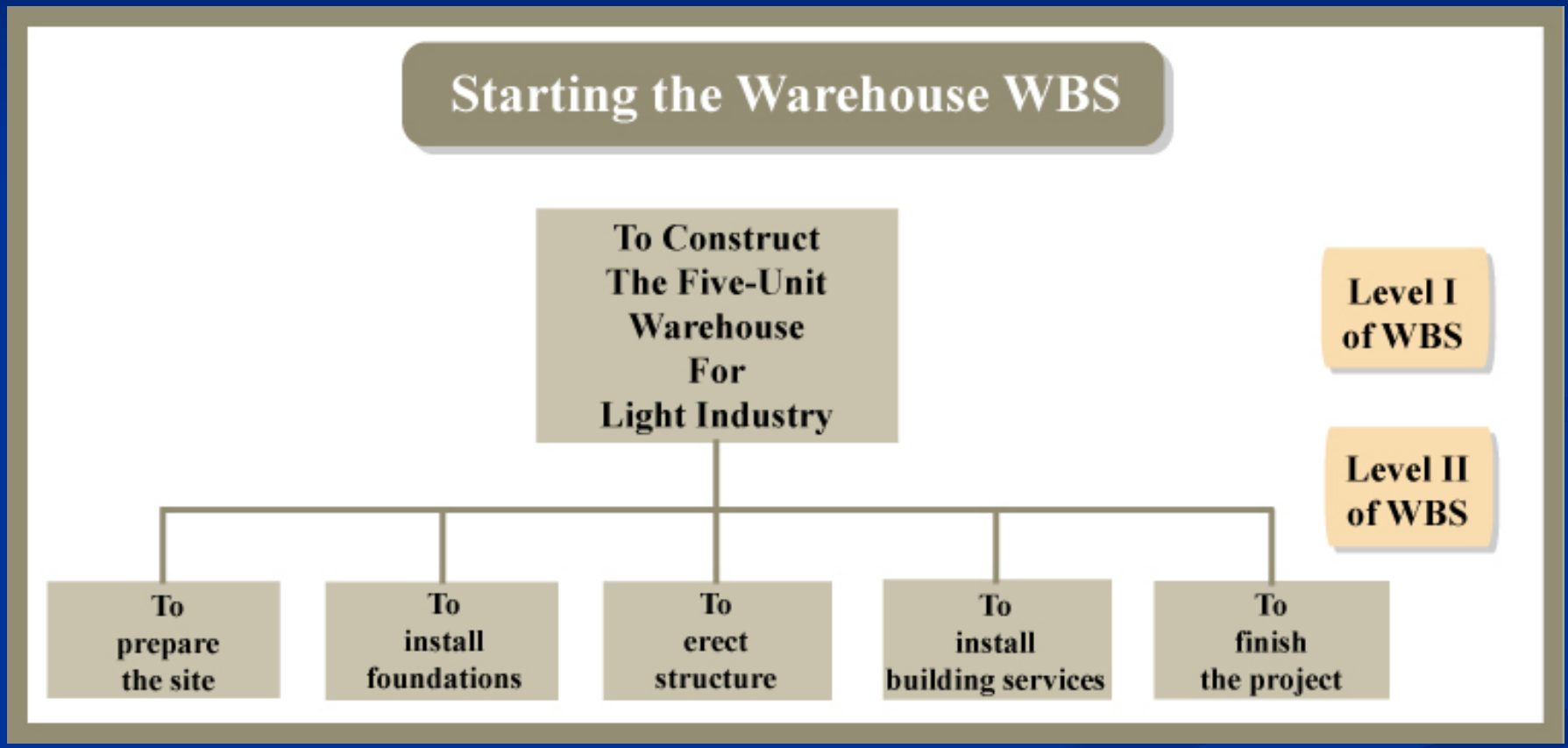
Topics

- ✓ Problem set background
- ✓ Planning
  - ✓ CBS
  - ✓ OBS
  - WBS
- Scheduling
  - Motivations and context
  - Gantt charts
  - CPM
    - Float
    - Critical path
    - Float ownership

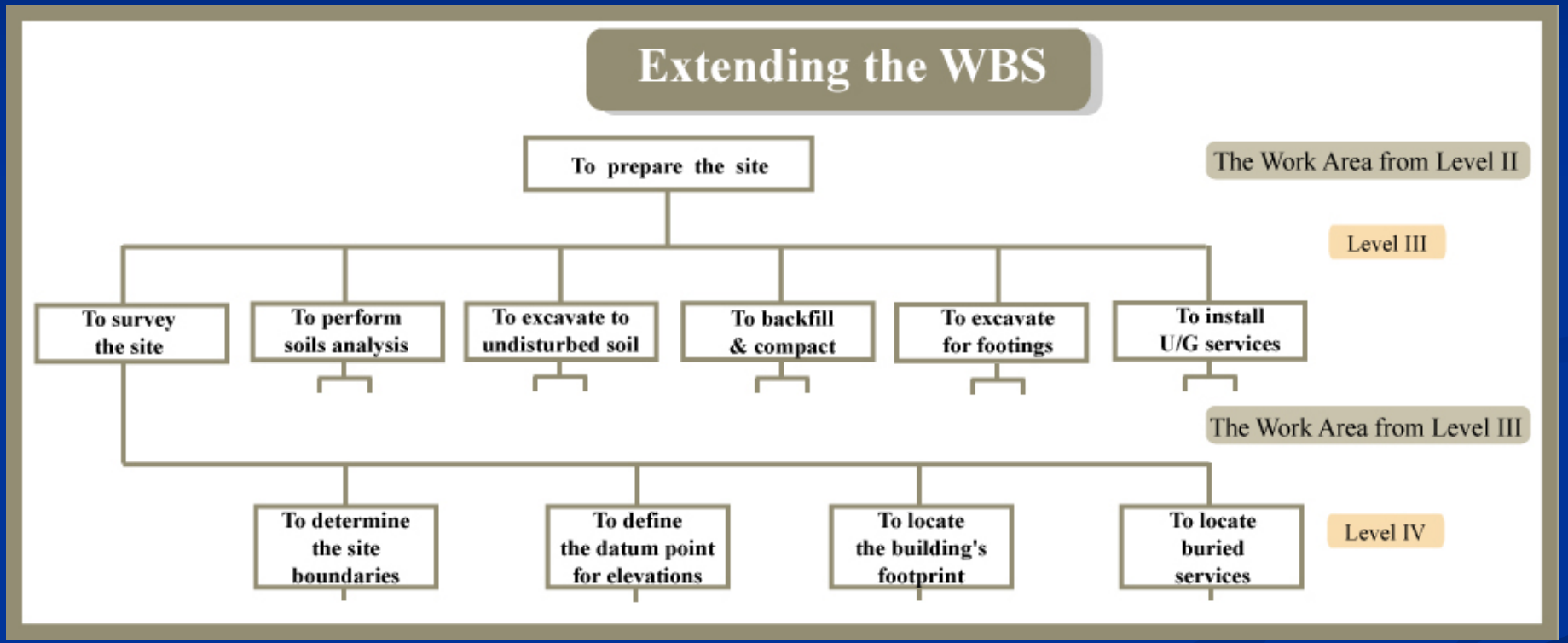
Work Breakdown Structure

- Central role in project monitoring, control
- Create through collaboration of
  - Estimation team
  - Project control team
  - Field operations maintenance group
- Often do not include procurement
  - But do need to reflect in schedule!

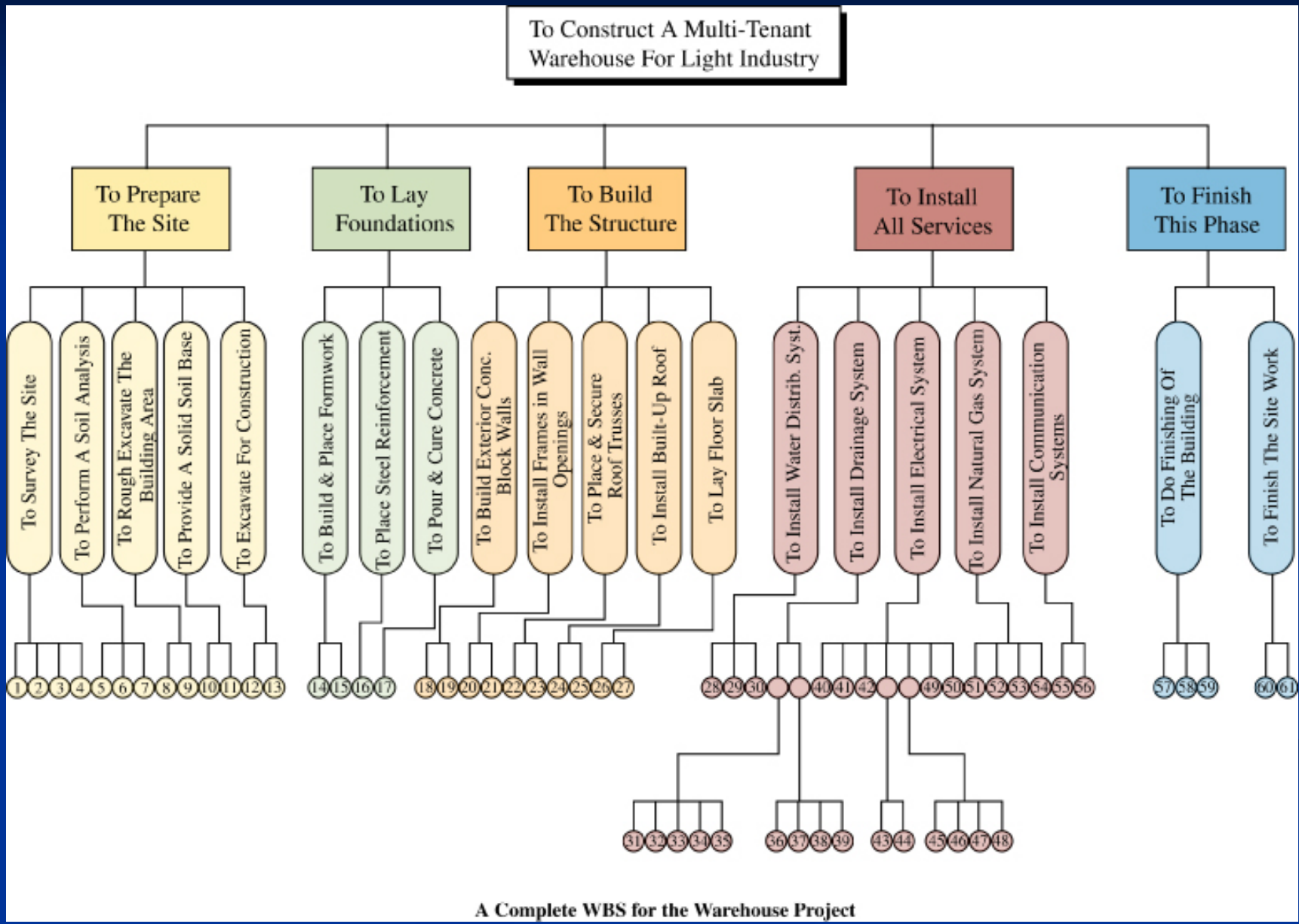
WBS Phase 1


Starting the Warehouse WBS
To Construct The Five-Unit Warehouse For Light Industry
Level I of WBS
Level II of WBS
To prepare the site
To install foundations
To erect structure
To install building services
To finish the project

WBS Refinement



Refined WBS



A Complete WBS for the Warehouse Project

Combinations

- CBS + OBS: Budget monitoring of crews, etc.
- WBS + OBS: Task assignments
- Schedule + OBS: Crew assignments
- Schedule + CBS: Cost monitoring

Topics

- ✓ Problem set background
- ✓ Planning
  - ✓ CBS
  - ✓ OBS
  - ✓ WBS
- Scheduling
  - Motivations and context
  - Gantt charts
  - CPM
    - Float
    - Critical path
    - Float ownership

Motivations for Scheduling

- Key: Both lowers chance of delay and assists in recovering from delay, resolving responsibility
- Assistance in reasoning about huge number of details (e.g. 1000s of activities)
- Delays often result simply from poor planning
- Resources are most
  - Valuable components
  - Hard to manage
- Can identify resource conflicts far ahead of time
- *Formalization necessary but not sufficient for managing*

Ubiquitous Role of Schedule

- Importance of schedule
  - Design (preliminary schedule)
  - Establish finish, milestone times for choreographing activities
    - Procurement time, subcontractor presence, tenant occupancy
  - Importance for thinking through issues
  - Identify critical path
  - Communication tool between parties
  - Framework for monitoring
  - Role in control
    - Assessing impacts of changes
      - Allows demonstration of indirect costs
    - Legal importance
  - Link to resources
    - Payments
    - Resource usage
  - Identify exposure to crowding, weather conditions

Legal Ramifications

- In some cases, must produce schedule by law
- Precedence-encoding schedules pay key role in addressing
  - Impact of change
  - Responsibility for delay
- Schedule considered by court need not be used in field
- Schedule proposed by contractor can be taken as approach – even if only passively accepted by owner
- Mega Construction Co. Inc. v. United States 29 Fed. Cl. 396 (1993)
  - "Plaintiff's bar chart depicted its version of the numerous work items. However, it failed to prove that the claimed delays occurred along the critical path, because it does not indicate the interdependence of any one or more of the work items that were on the critical path while the project was ongoing, but offered no credible evidence of the interdependence of the project's activities"

Linkage to Estimation

- Scheduling allows understanding of cash flow over time
- Given time value of money, scheduling critical to understanding present value of estimate
- Quantity takeoff reasoning can be used to inform both
  - Estimation
  - Scheduling

Scheduling Considerations

- Risk of
  - Imbalanced use
    - Use early on
    - Discarding later
  - Central office use only
    - Danger scheduling information not propagated from CM/owner/Designer to contractors
    - Need buy-in by superintendents
- Want *shared* schedule
- Small projects may not need–but collection does

Contractor Scheduling

- Contractor scheduling very simple, short-term
  - E.g. meet once a week to plan next two weeks
- Focus is on keeping crews busy
  - If master schedule doesn't accomplish this, may perform work out of synch

Important Scheduling Factors

- Delay time for reviews, approvals
  - Submittals
  - Permitting
- Procurement
- Planning for changes
- Coordination of labor & equipment
- GC coordination of subcontractors
  - Critical – and difficult due to interfaces
- Design scheduling difficult
  - Highly iterative
  - Hard to know when design, cost will converge

Procurement Scheduling

- Especially key in urban areas
- Custom production items difficult
  - Latencies uncertain
  - Different parties
  - Complex workflow (CM, structural engineer)
  - Quality checks
- Different classifications
  - Bulk materials : Fast delivery (1-5 days)
  - Commodity fabrication (3-12 weeks)
  - Customized fabrication (10-16 weeks)

Long-Lead Items

- Conveyance
  - Elevators
- Mechanical/plumbing
  - Fire protection
  - Pumps
  - Boilers
  - Cooling towers
  - Control systems
  - Air handling units
  - Chillers/refrigeration unit
- Structural steel
- Reinforcing rods
- Precast panels/decks
- Special cladding
- Electrical
  - Transformer
  - Motors
  - Switch boxes
  - Special conduits

Critical Role of Resources

- Key: Mutual dependence bt. schedule, resources
  - Schedule depends on activity durations, which assume some resource availability
  - Resource availability depends on scheduling
- Highly complex problem
- Key for effective work
- Informal means of handling: Iteration
- *A later lecture will focus on this topic*

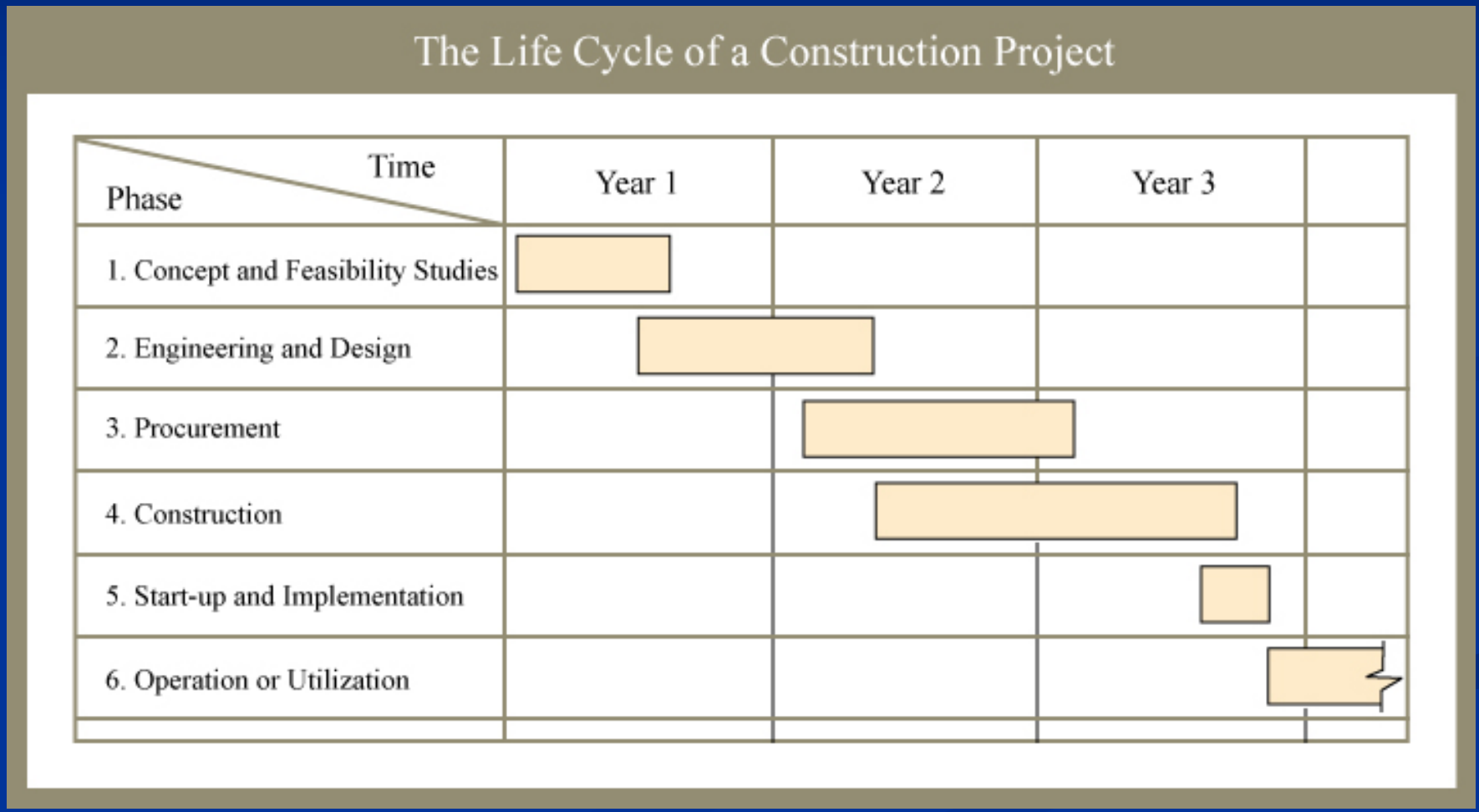
Topics

- ✓ Problem set background
- ✓ Planning
  - ✓ CBS
  - ✓ OBS
  - ✓ WBS
- ✓ Scheduling
  - ✓ Motivations and context
  - Gantt charts
  - CPM
    - Float
    - Critical path
    - Float ownership

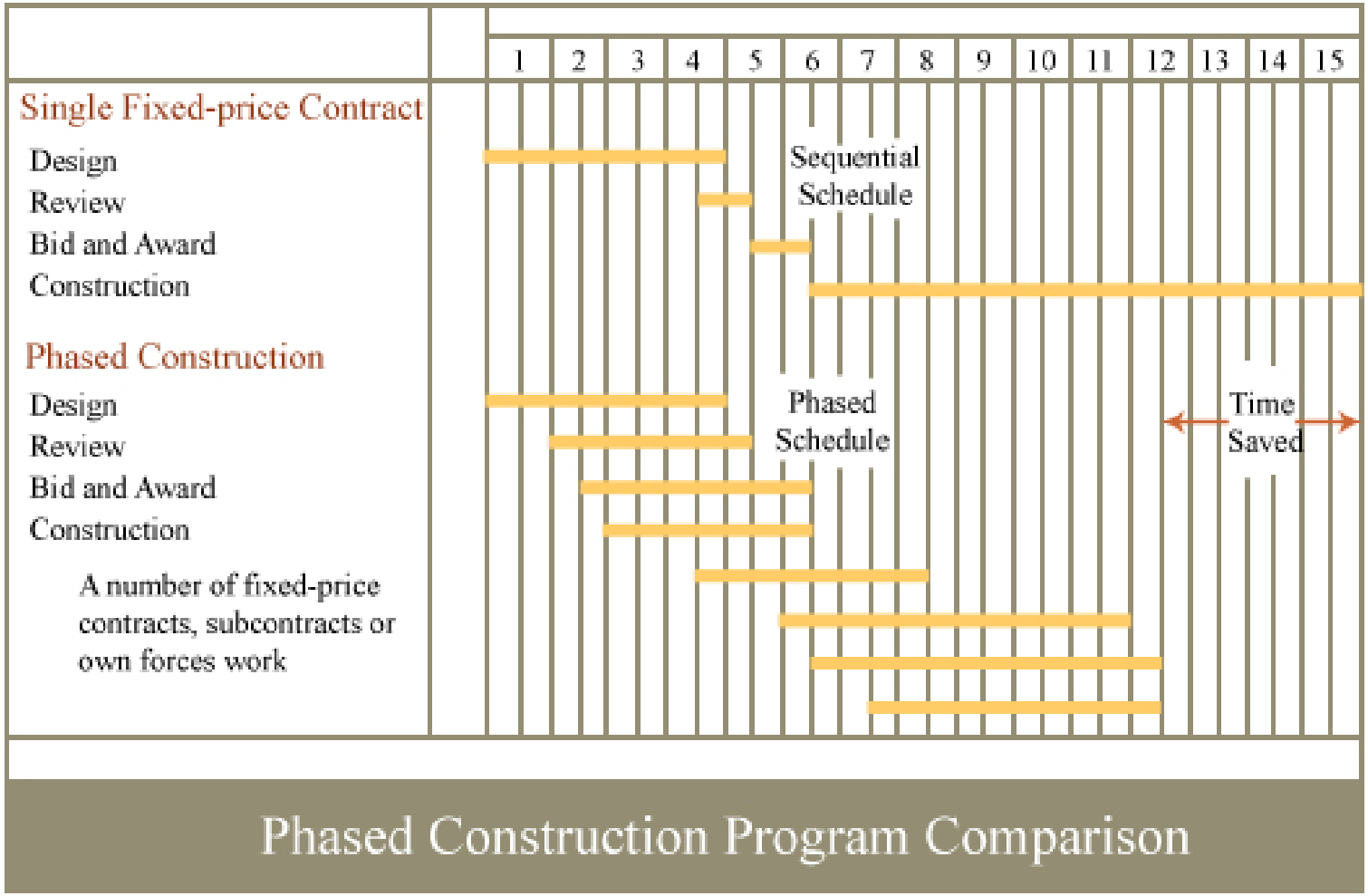
Gantt/ "Bar Charts"

- WWI Origin (systematized earlier work)
- Very effective communication tool
- Very popular for representation of simpler schedules
  - Can be cumbersome when have >50 activities
- No dependencies captured
- Most effective as *reporting* format rather than *representation*

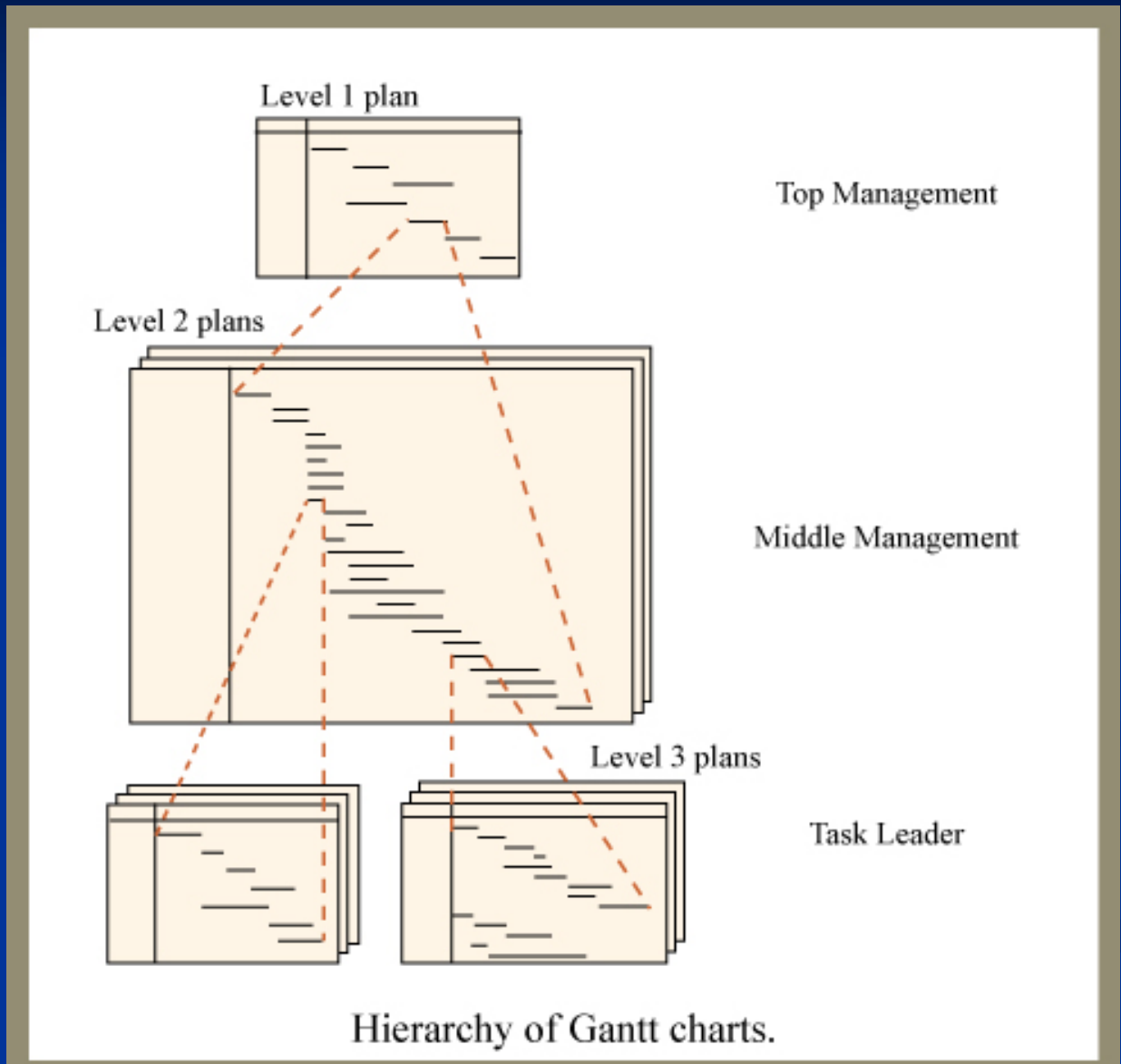
Simple Gantt Chart



Gantt: Sequential vs. Phased



Hierarchy of Gantt Charts



Hierarchy of Gantt charts.

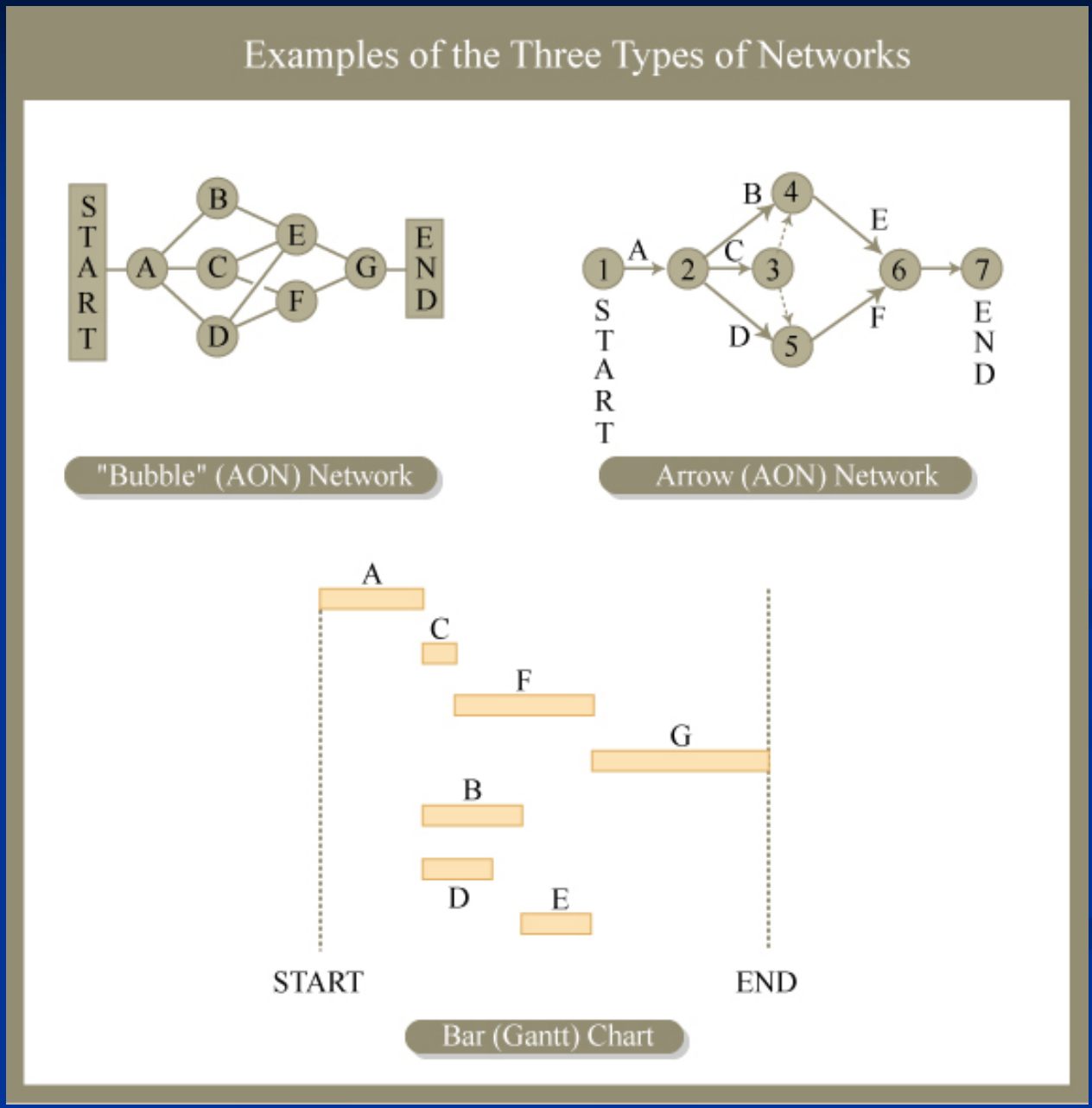
Topics

- ✓ Problem set background
- ✓ Planning
  - ✓ CBS
  - ✓ OBS
  - ✓ WBS
- ✓ Scheduling
  - ✓ Motivations and context
  - ✓ Gantt charts
  - CPM
    - Float
    - Critical path
    - Float ownership

Critical Path Method (CPM)

- Origin at Dupont (1956)
- First application to construction in early 1960s
- Sometimes narrow term, sometime more general
- Directed acyclic graph
- Drawn (topologically sorted) left to right
- Specify activities and associated information (e.g. duration) and run *scheduling algorithm* to yield scheduling recommendations/constraints

Gantt vs. CPM


Examples of the Three Types of Networks
START
A
B
C
D
E
F
G
END
"Bubble" (AON) Network
1
2
3
4
5
6
7
A
B
C
D
E
F
START
END
Arrow (AON) Network
A
C
F
G
B
D
E
START
END
Bar (Gantt) Chart

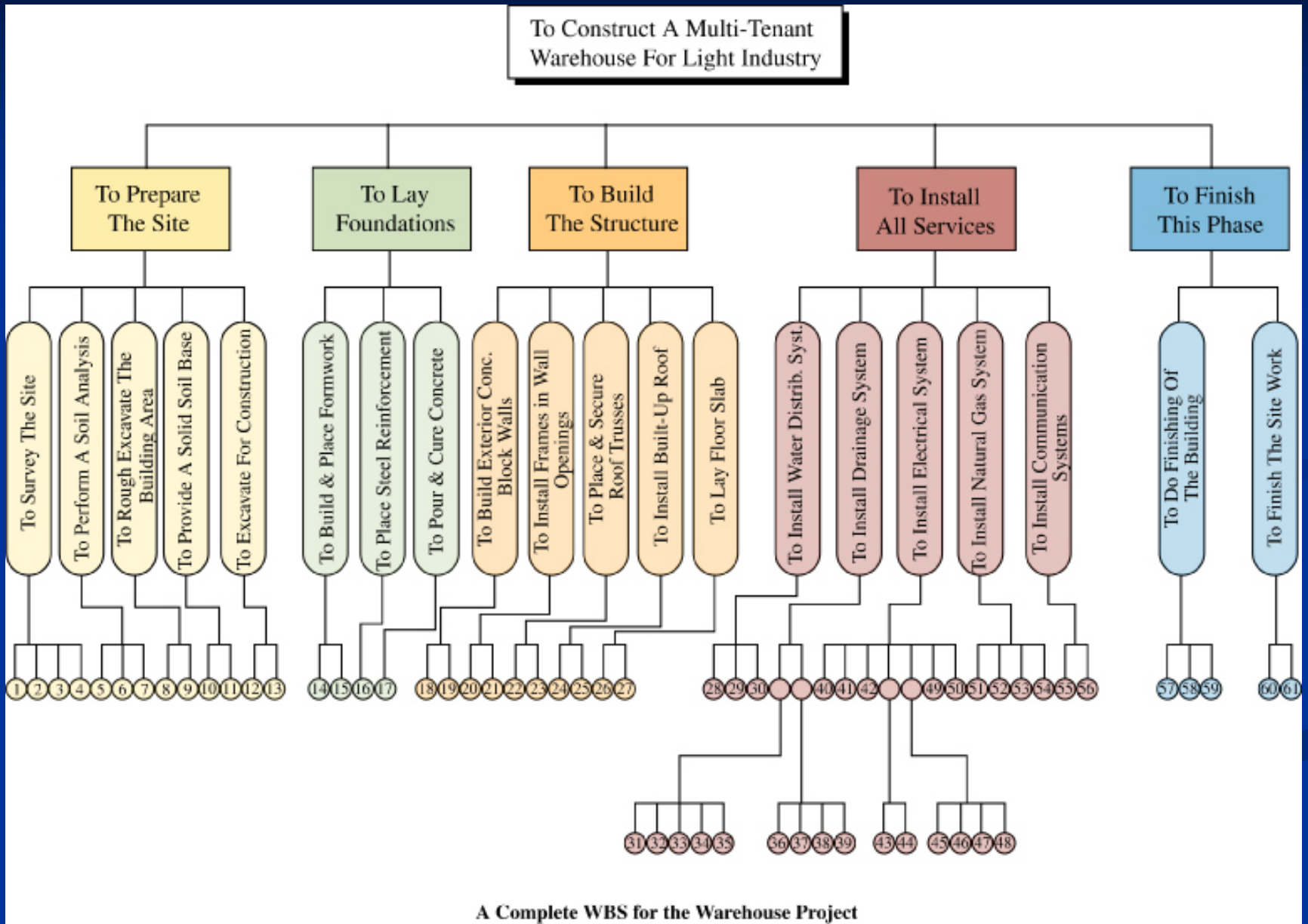
Network Methods: Basic Steps

- Define activities from WBS work packages
- Estimate $, time, resources for each activity
- Define precedence relationships between activities
- Iterate
  - Perform CPM scheduling
  - Estimate time, cost, resource usage over project
  - If acceptable, terminate
  - If not acceptable, impose dependencies or added/reduced resources

Important Considerations

- Durations depend implicitly on many things
  - Amount of work
  - Productivity (environment, skill, learning, mgmt,…
  - # of people assigned
  - Equipment assigned
- Costs from cost estimate
- Human resources from OBS/WBS and takeoff
- Materials, Equipment from takeoff
- May want to estimate durations via several ways

Recall WBS



A Complete WBS for the Warehouse Project

Listing of Tasks

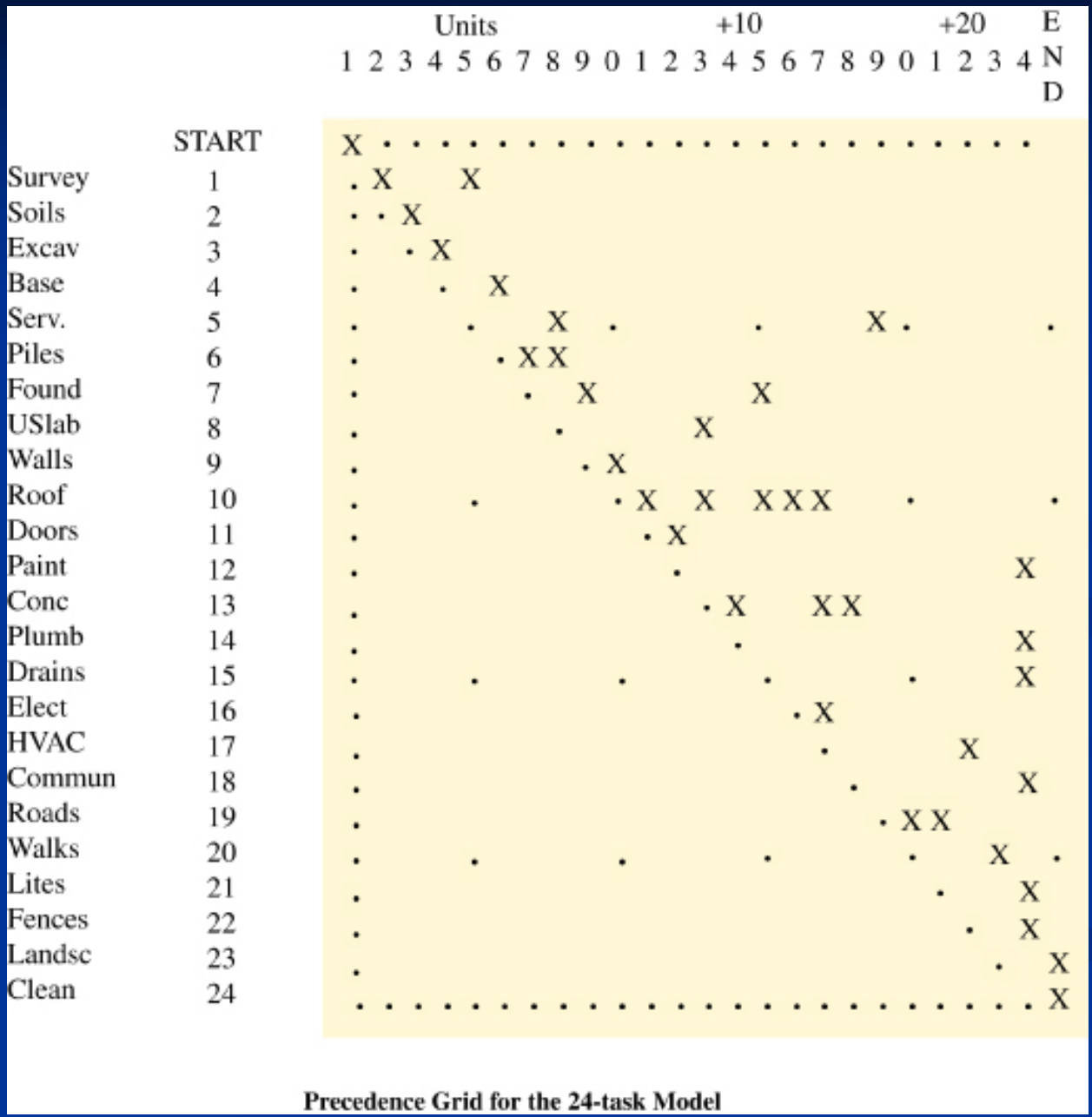
TASK LIST FOR THE 24 - TASK MODEL

IDENTITY	NAME OF TASK (OR MILESTONE)
START	(LIKELY DEFINED BY THE CLEARANCE TO SPEND MONEY)
1	LEGAL SURVEY OF THE SITE
2	PERFORM A SOILS ANALYSIS
3	ROUGH EXCAVATE THE BUILDING AREA
4	PROVIDE A SOLID SOIL BASE
5	TO INSTALL SITE SERVICES
6	DRIVE PILES
7	CONCRETE FOUNDATIONS
8	TO INSTALL UNDER-SLAB SERVICES
9	CONSTRUCT EXTERNAL BLOCK WALLS
10	ERECT ROOF STRUCTURE
11	INSTALL DOORS AND WINDOWS
12	PAINTING
13	TO LAY CONCRETE SLABS
14	SANITARY PLUMBING
15	STORM DRAINS
16	ELECTRICAL
17	HEATING AND VENTILATING
18	INSTALL COMMUNICATION SYSTEM
19	ROADWAYS AND PARKING
20	INSTALL WALKWAYS
21	AREA LIGHTING
22	FENCING - GAS METER
23	LANDSCAPING
24	CLEAN-UP
END	(OF STAGE ONE)

Precedence Considerations

- Unless impose constraints, assuming that activities can be performed in parallel
- Relationships between activities reflect constraints
  - Regulatory/Contractual
  - Physical
  - Resource/Financial
  - Safety
  - Managerial
  - Environmental

Identification of Direct Precedences

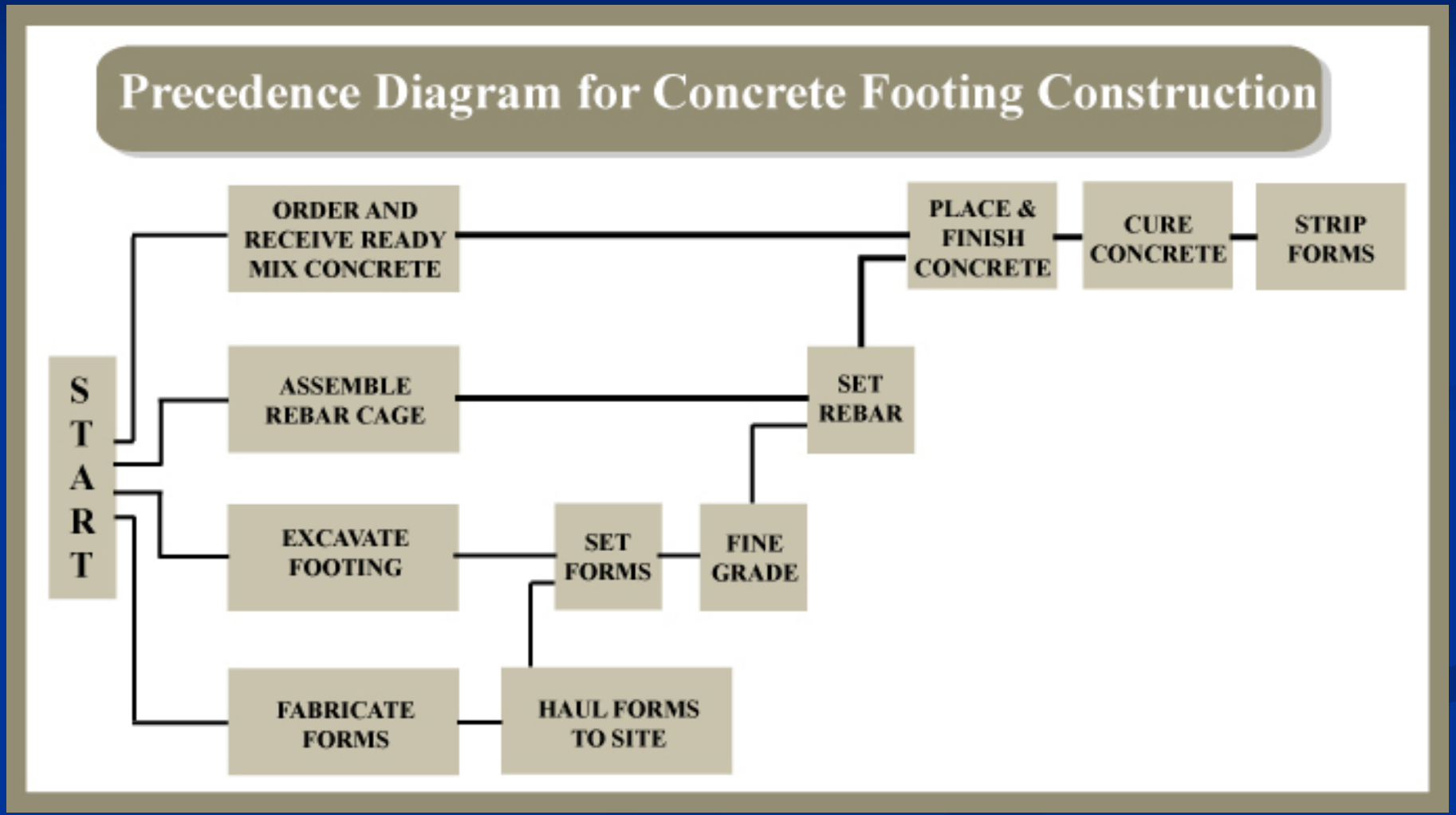


Precedence Grid for the 24-task Model

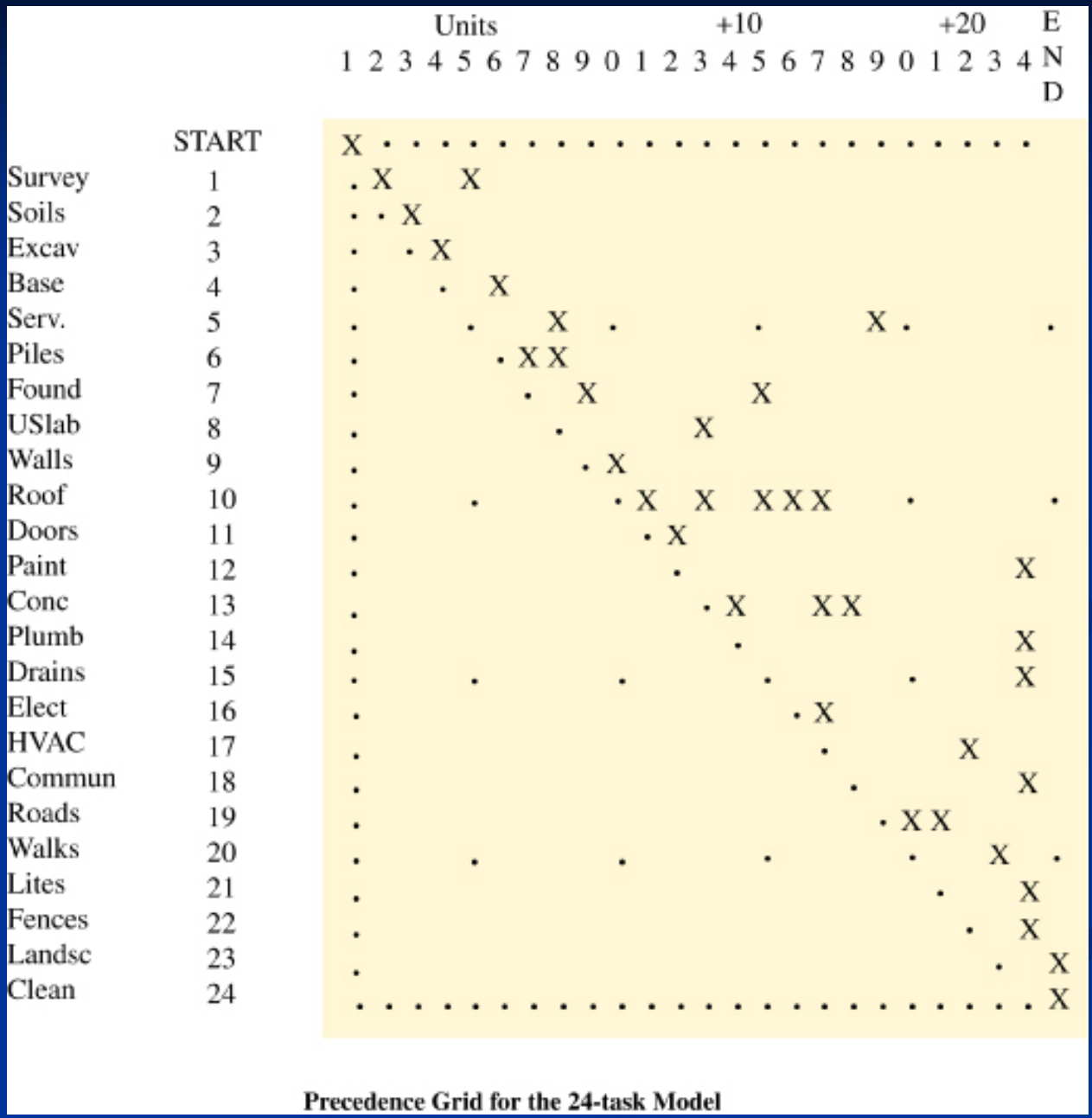
Representation Scheme:AON

- Also called “precedence diagram method” (PDM) and “bubble diagram method”
- Easier to visually recognize opportunities for concurrency
- Most popular for software
- Requires no dummy nodes
- Diagram should encode EST,LST,EFT,LFT
- Allows for representation of richer semantics
  - S2S, F2F, S2F, F2S

AON Example

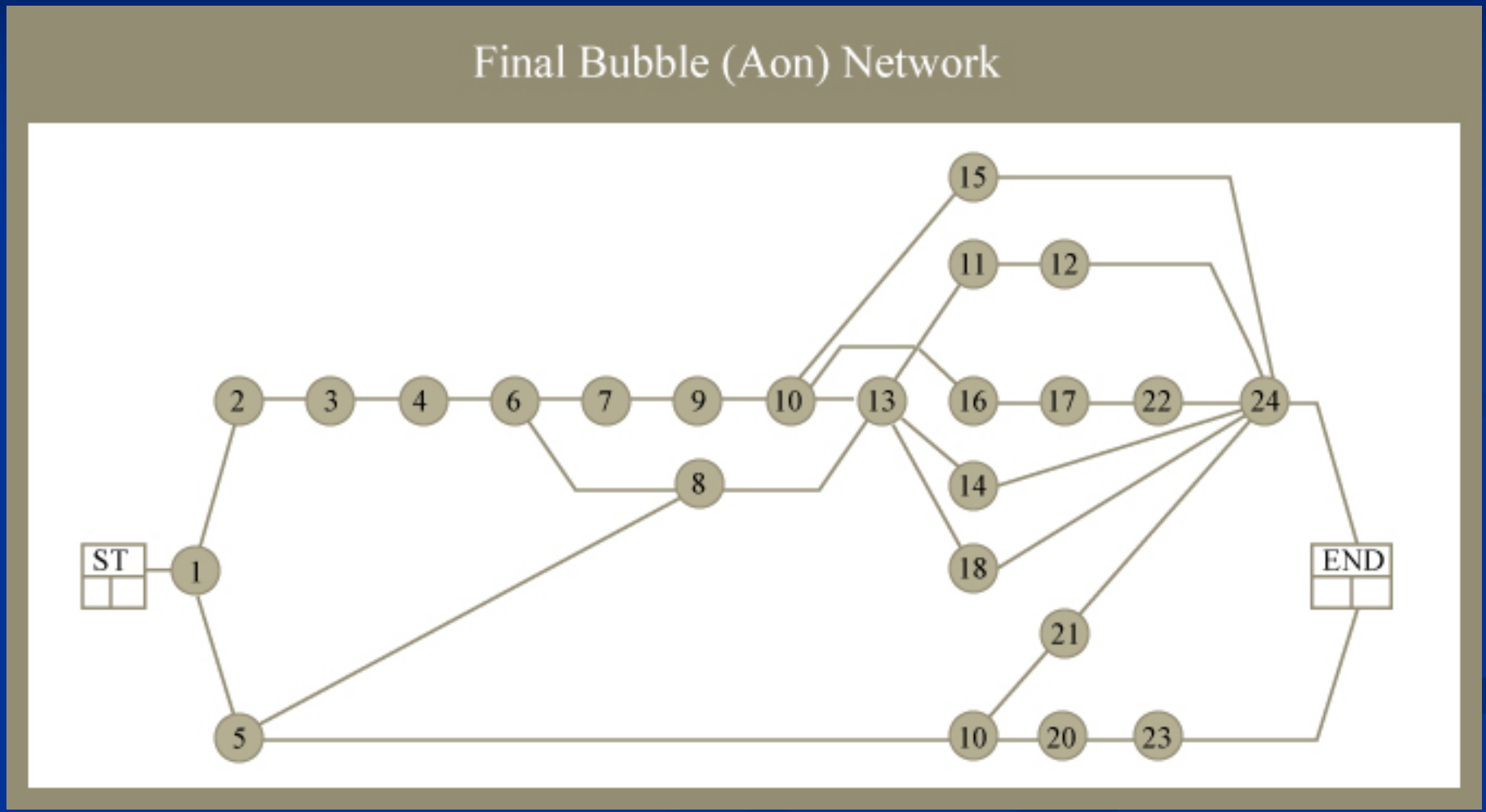

Precedence Diagram for Concrete Footing Construction
START
ORDER AND RECEIVE READY MIX CONCRETE
ASSEMBLE REBAR CAGE
EXCAVATE FOOTING
FABRICATE FORMS
SET FORMS
HAUL FORMS TO SITE
FINE GRADE
SET REBAR
PLACE & FINISH CONCRETE
CURE CONCRETE
STRIP FORMS

Recall Direct Precedences



Precedence Grid for the 24-task Model

Corresponding AON Schedule



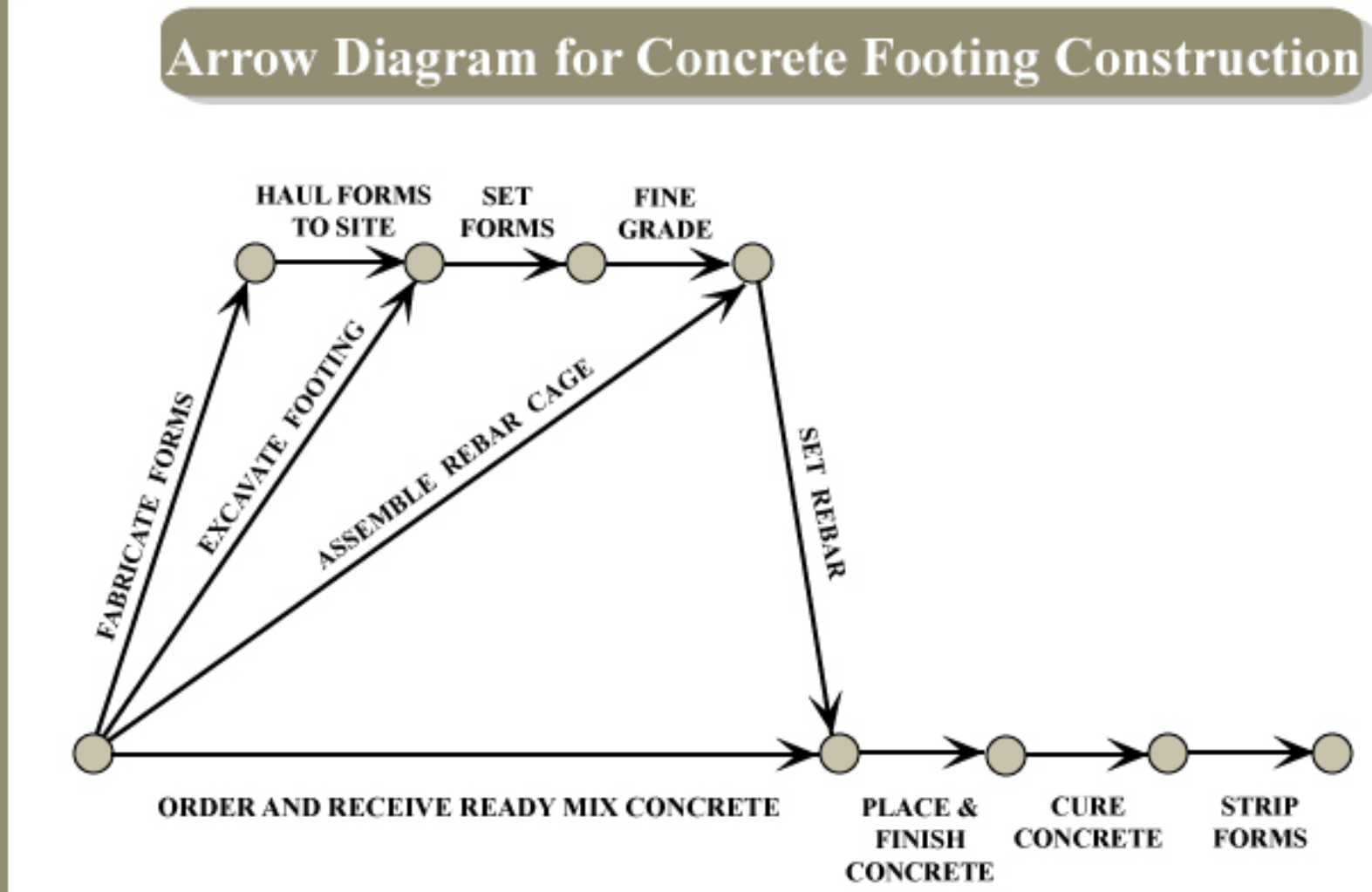
Representation Scheme: AOA

- Historically most popular
- Very similar to Gantt format when perform "manhattan" layout
- Requires dummy nodes
  - Arrows can only come from/go to single node
  - Only one arrow between two given nodes
- Workarounds for generality built into AON
  - E.g. Concurrency can be enforced via bracketing
  - Disaggregation for alternative relationships

AOA


Every Activity Has Two Events
Start the action
ACTION TO DO THE TASK
Stop the action
First break of ground
EXCAVATE FOR FOUNDATIONS
Excavate complete
EVENT
ACTIVITY/TASK
EVENT

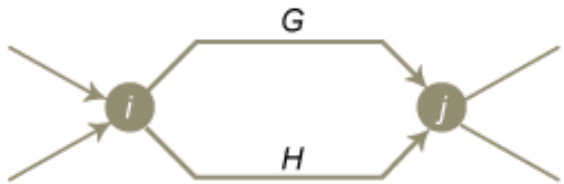
Simple Case (No Dummy Arrows)



Dummy Arrows: Case 1

Violation of Uniqueness of Node Connections

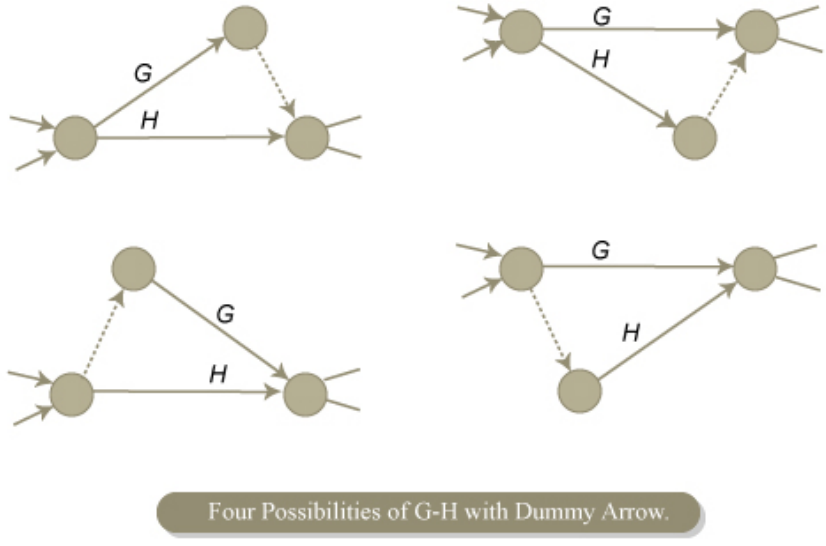
Violation of Uniqueness of Node Connections



Incorrect notation for concurrent activities.

Options for Representing

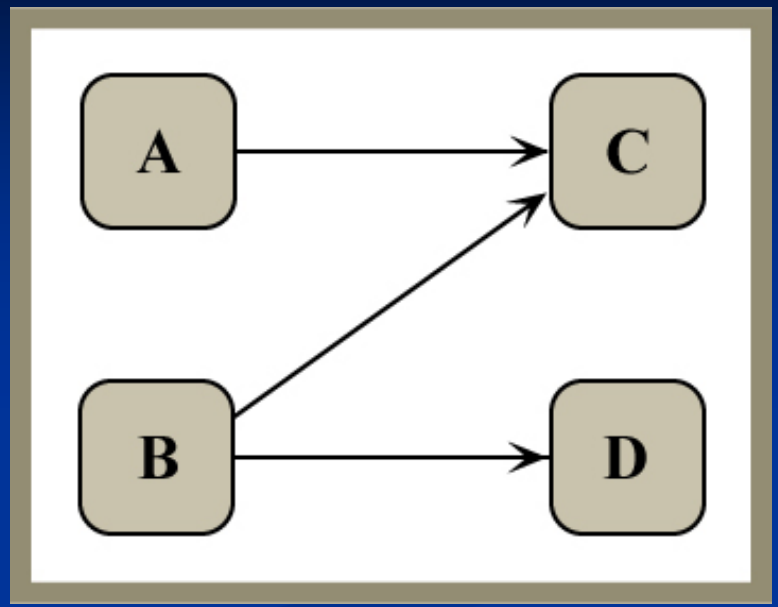
Options For Representing



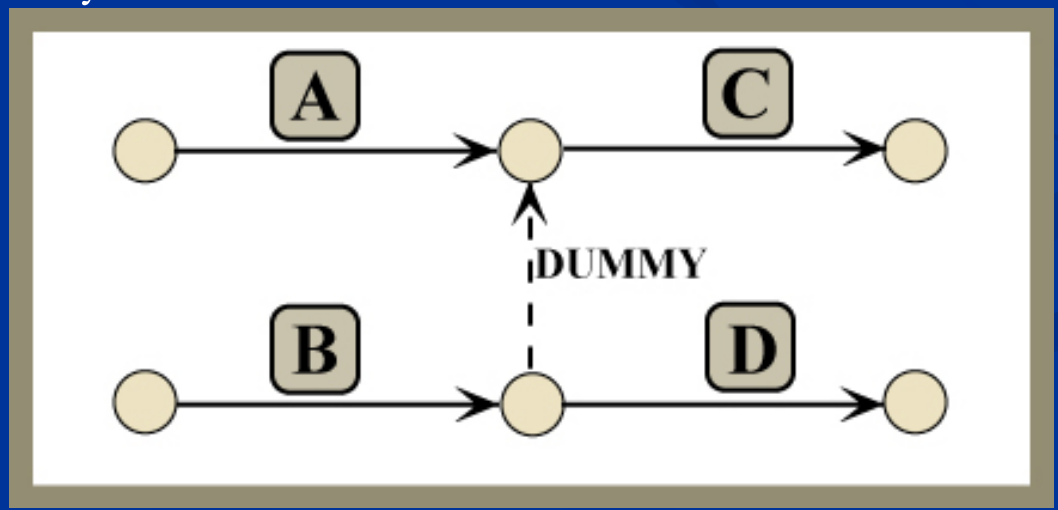
Four Possibilities of G-H with Dummy Arrow.

Dummy Arrows: Case 2

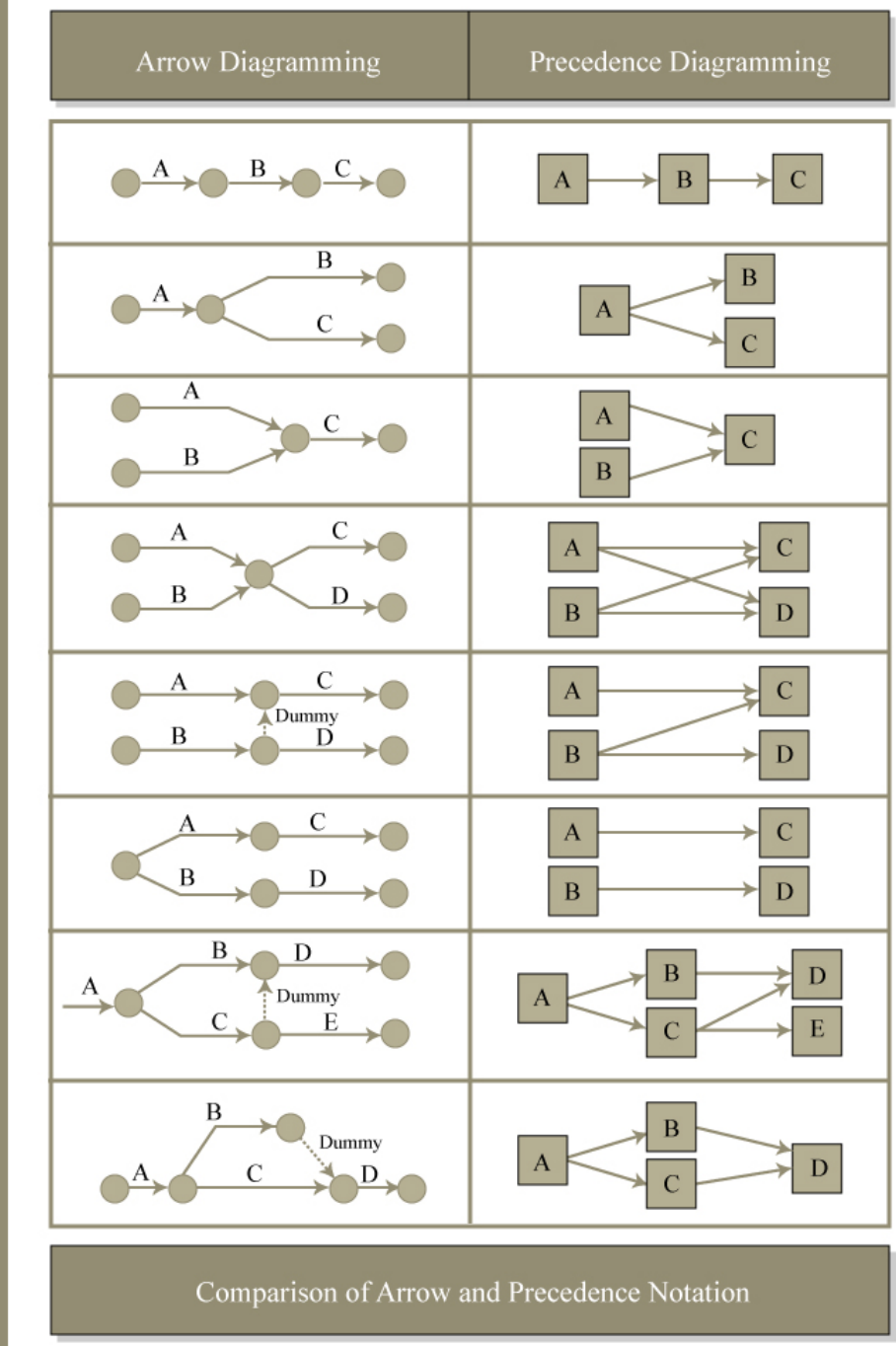
Common Successors with Distinct Sets of Predecessors



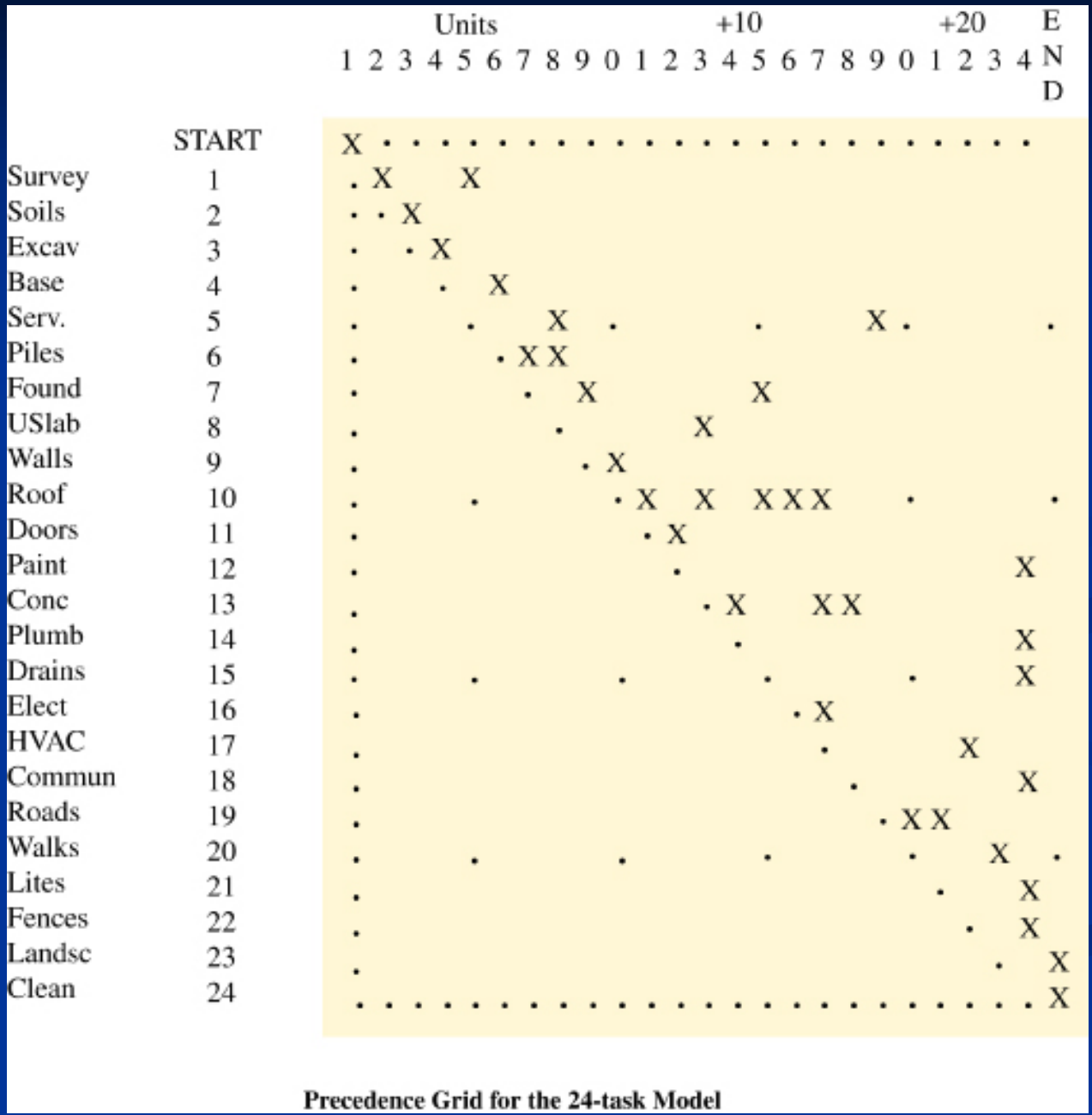
Because Arrow can only have 1 unique source and destination, must introduce dummy arrow



Dummy Nodes


Arrow Diagramming
Precedence Diagramming
A
B
C
D
E
Dummy
Comparison of Arrow and Precedence Notation

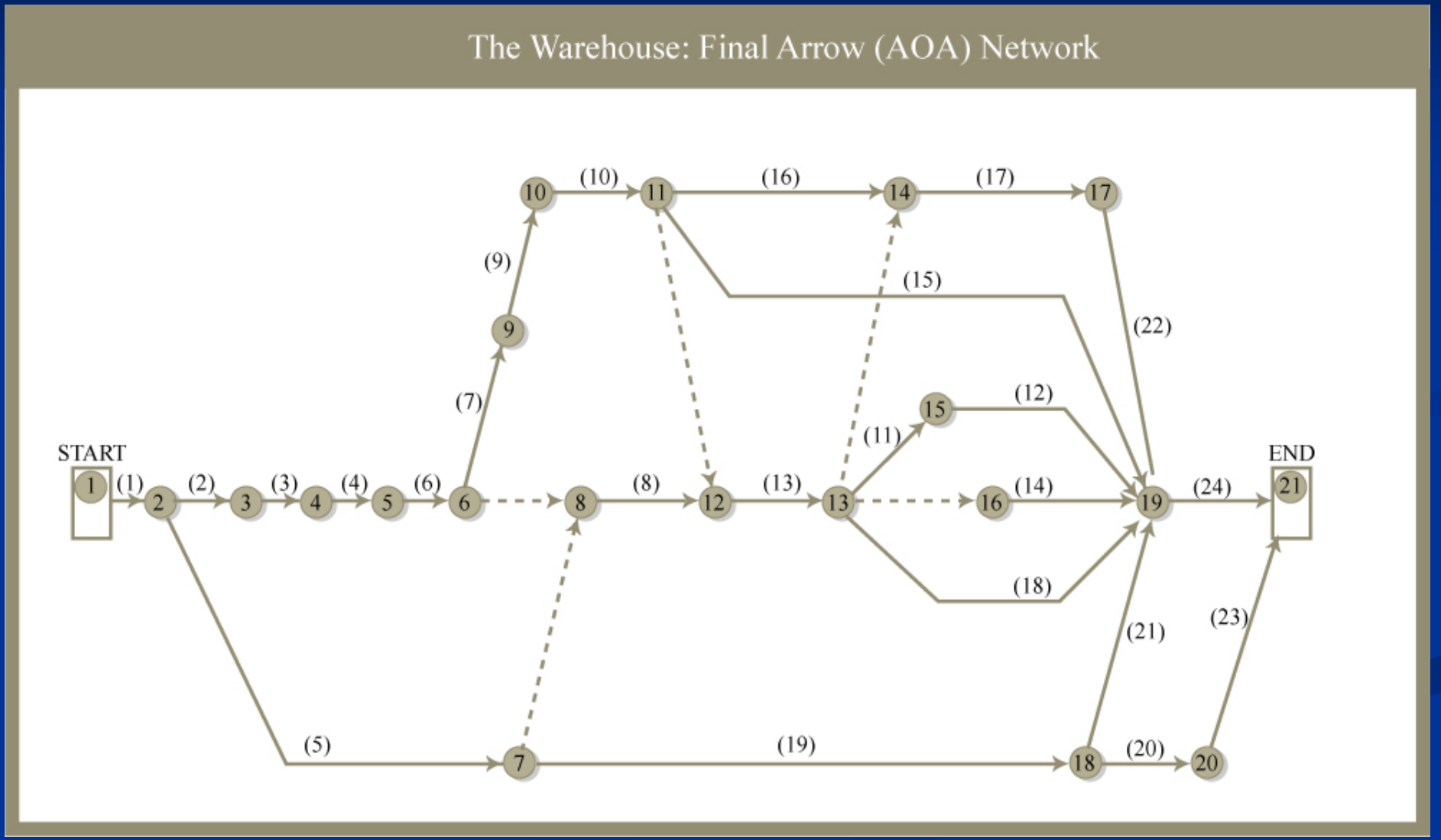
Recall Direct Precedences



		Units 1 2 3 4 5 6 7 8 9 0	+10 1 2 3 4 5 6 7 8 9 0	+20 1 2 3 4	END
	START	X			
Survey	1	. X X			
Soils	2	. . X			
Excav	3	. . X			
Base	4	. . X			
Serv.	5	. . X .	. . X .		.
Piles	6	. . X X			
Found	7	. . X	X		
USlab	8	. .	X		
Walls	9	. . X			
Roof	10	. . . X	X X X X	.	.
Doors	11	. . X			
Paint	12	. .			X
Conc	13	. . X	X X		
Plumb	14	. .			X
Drains	15	. . .	. .		X
Elect	16	. .	X		
HVAC	17	. .	.	X	
Commun	18	. .	.		X
Roads	19	. .	X X		
Walks	20	. . .	. .	X	.
Lites	21	. .	.	X	
Fences	22	. .	.	X	
Landsc	23	. .	.	X	
Clean	24	. . . . .	. . . . .	.	X

Precedence Grid for the 24-task Model

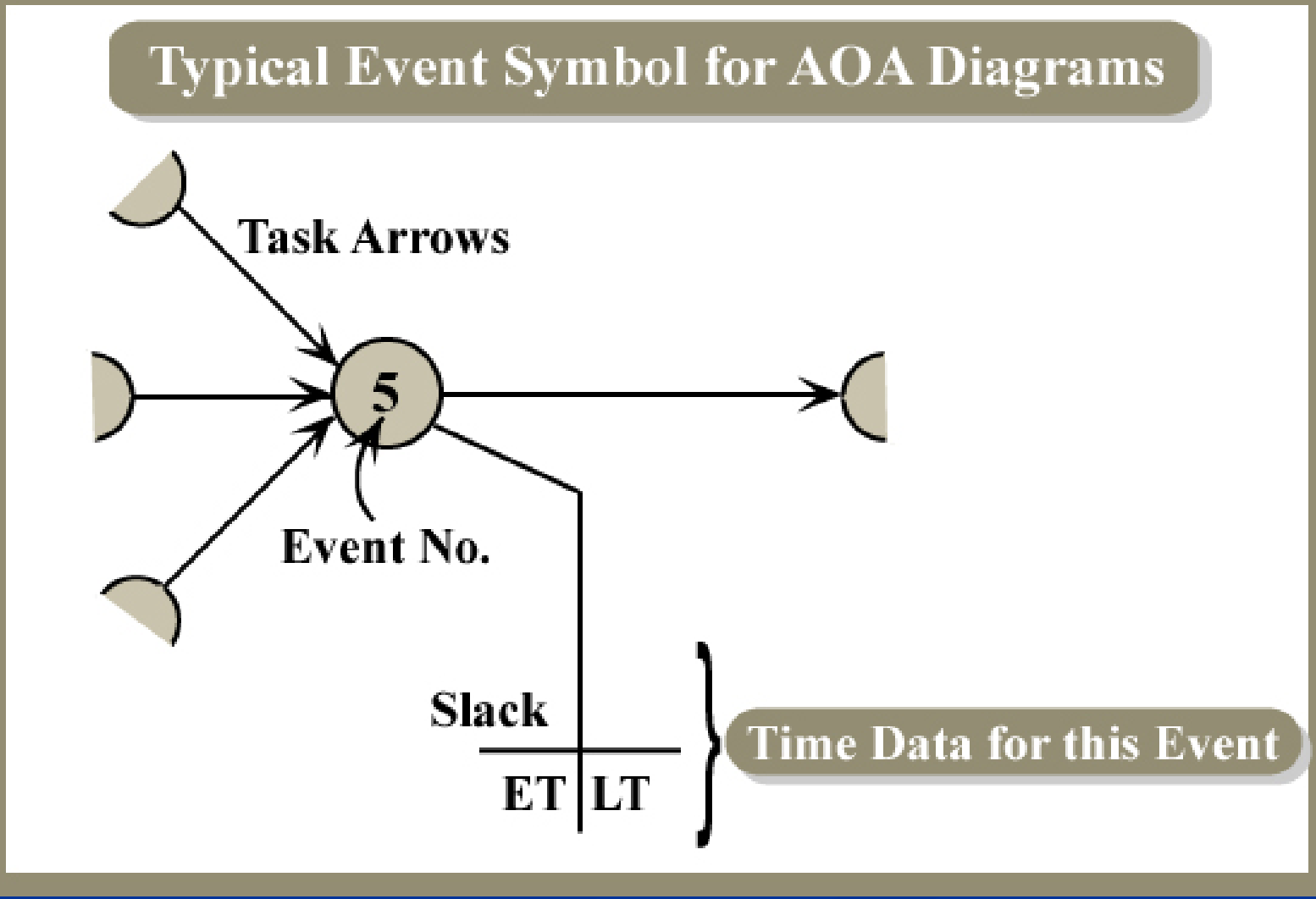
Corresponding AOA Schedule



CPM Algorithm

- Derives early, late finish/start for nodes
- Can run on AOA or AON diagrams
- O(n) [Linear time]
- NB: LF, LS are latest could start/finish *without delaying whole project*
  - These are *not* the latest could start when "keeping busy" with other activities

AOA Scheduling Notation



AON Scheduling Notation

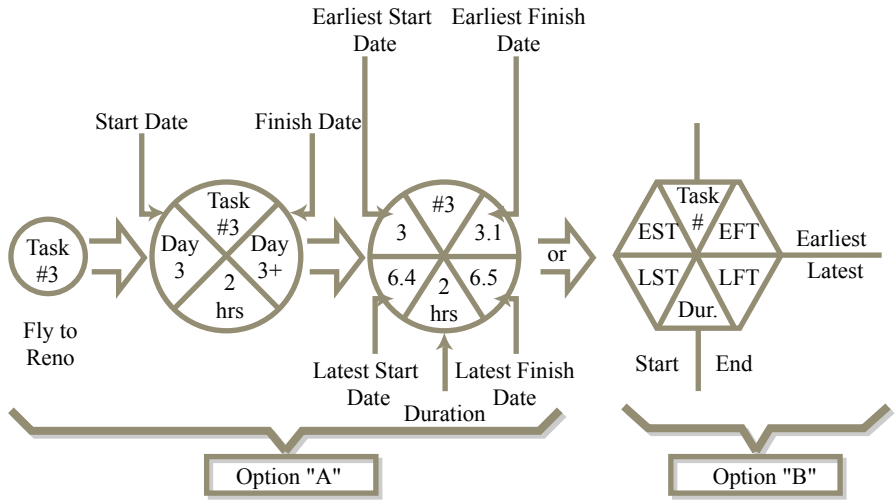
Because each node represents entire activity at one point, must specify

- Early Start (ES)
- Late Start (LS)
- Early Finish (EF)
- Late Finish (LF)

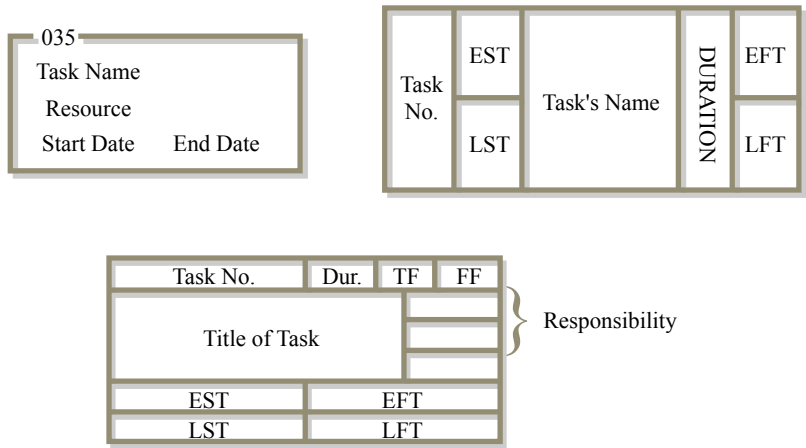
Float=(LS-ES)=(LF-EF)

Different notations typical

The Subdivided Bubble Symbol for a Task



Other Symbols for Tasks



Passes

- Forward pass
  - Because all preceding activities must finish before a successor, early start of a given node is maximum of early finishes of preceding nodes
- Overall project duration (late finish) is defined as maximum of early finishes for nodes
- Backward pass
  - Because preceding activity must finish before any following activity, Late finish of a given activity is minimum of late starts of following activity

Passes: Pseudocode (AOA)

- **Earliest Event Time Algorithm**
- *Step 1*: Let E(0) = 0.
  Step 2: For j = 1,2,3,...,n (where n is the last event), let
  E(j) = maximum {E(i) + Dij}
  where the maximum is computed over all activities (i,j) that have j as the ending event.
- **Latest Event Time Algorithm**
- *Step 1*: Let L(n) equal the required completion time of the project.
  Note: L(n) must equal or exceed E(n).
  Step 2: For i = n-1, n-2, ..., 0, let
  L(i) = minimum {L(j) - Dij}
  where the minimum is computed over all activities (i,j) that have i as the starting event.

Float/Slack Fundamentals

- Intuitively, measures leeway in scheduling
  - Degree of freedom in timing for performing task
- Length of difference between when we "have to" finish activity and how long it takes to finish
  - Types of float differ in how define "have to"
- NB: While it may be *possible* to schedule an activity at many different points, some points may be far preferable to others!

Float

- Total float: max time can delay w/o delaying project
  - Min((L(j)-D_{ij})-E(i)) i.e. (Latest time that could start and still finish project on time)-(Earliest possible time that could start)
- Free float: max time can delay w/o delaying successors
  - Min((E(j)-D_{ij})-E(i)) :(latest time that could start but still finish before early start of next activity)-(Earliest possible time that could start)
- Independent float : Max(0,Min((E(j)-D_{ij})-L(i)))
  - Like Free float but assuming worst-case start

Topics

- ✓ Problem set background
- ✓ Planning
  - ✓ CBS
  - ✓ OBS
  - ✓ WBS
- ✓ Scheduling
  - ✓ Motivations and context
  - ✓ Gantt charts
  - ✓ CPM
    - ✓ Float
    - Critical path
    - Float ownership

Critical Path

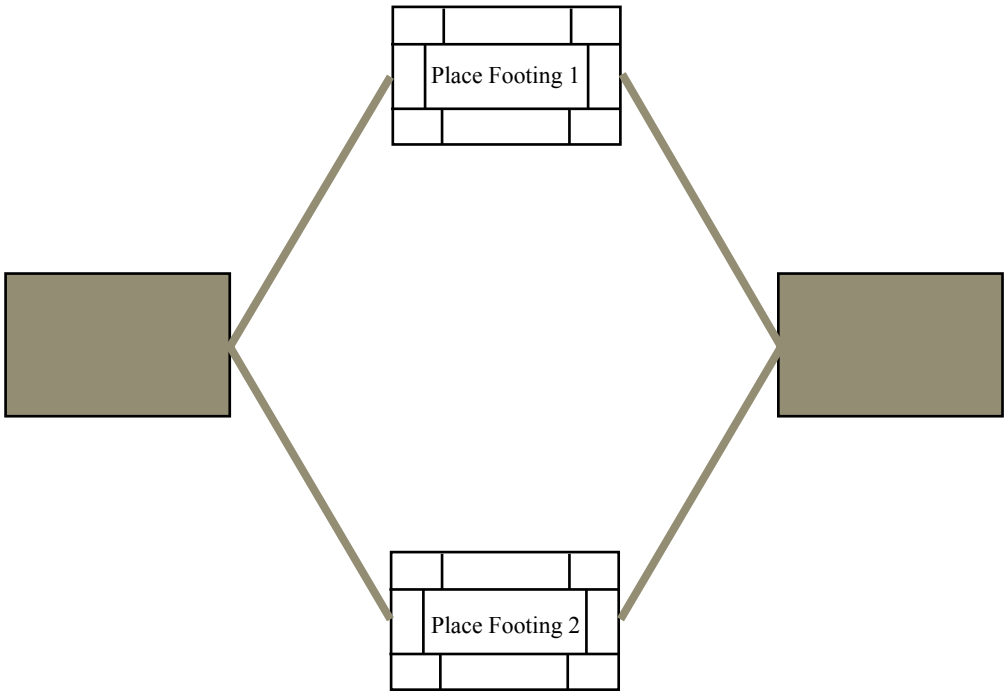
- Definition: Longest 0-float path of activities
  - For algorithm as described, at least one such path
  - Must be completed on time or entire project delayed
- Essentially indicates minimum time required for project
  - Want to consider near-critical activities as well!
- Typically evolves over time, as activity durations unfold
- No flexibility to shift for e.g. resource leveling
- Contingency buffer + Critical chain buffering

Topics

- ✓ Problem set background
- ✓ Planning
  - ✓ CBS
  - ✓ OBS
  - ✓ WBS
- ✓ Scheduling
  - ✓ Motivations and context
  - ✓ Gantt charts
  - ✓ CPM
    - ✓ Float
    - ✓ Critical path
    - ■ Float ownership

Using Float by Sequentializing Items

Arbitrary Use of Network Logic for Resource Constraint



Topics

- Problem set background
- Planning
  - CBS
  - OBS
  - WBS
- Scheduling
  - Motivations and context
  - Gantt charts
  - CPM
    - Float
    - Critical path
    - Float ownership

Float "Ownership"

- Tension between owner and contractor
- Significant legal implications
- Problem:
  - Owners seek to push contractors on tight schedule
  - Contractors seek flexibility, claims against owner

Motivations for Contractor Float Ownership

- Feel owed higher compensation b/c owner-caused delays would be much worse w/o heroics
- Seek flexibility in scheduling (e.g. for resource leveling)
  - Flexibility has value!
- Create multiple critical- or near-critical-paths
  - Deliberately inflate durations ($ charge to speed up)
  - Insert artificial precedence constraints "preferred way of doing things") ($ charge to change)
- Resent owner interference in construction

Motivations for Owner Float Ownership

- Seeks to lower risk by getting work done earlier
  - Too many late starts risks overall project duration
- May seek to impose unrealistically short schedule on contractor
- May contractually limit flexibility of contractor
  - Specify owner rights to use float
  - Right of owner to select scheduling procedure
  - Right to object to "unreasonable" durations
  - Right to remove artificial constraints from diagram
  - Force redrawing of critical path if contractor behind