Construction Management

NETWORK TECHNIQUES

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Koenigsberg, Prussia, 18th Century

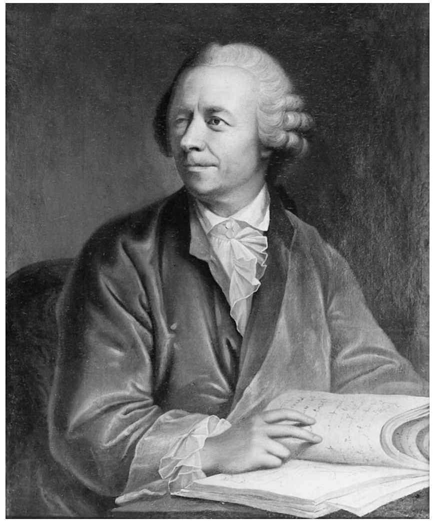
now: Kaliningrag, Russia

Problem: Is it possible to take a round trip through the city crossing each of its seven bridges once and only once?

„Seven Bridges of Koenigsberg”

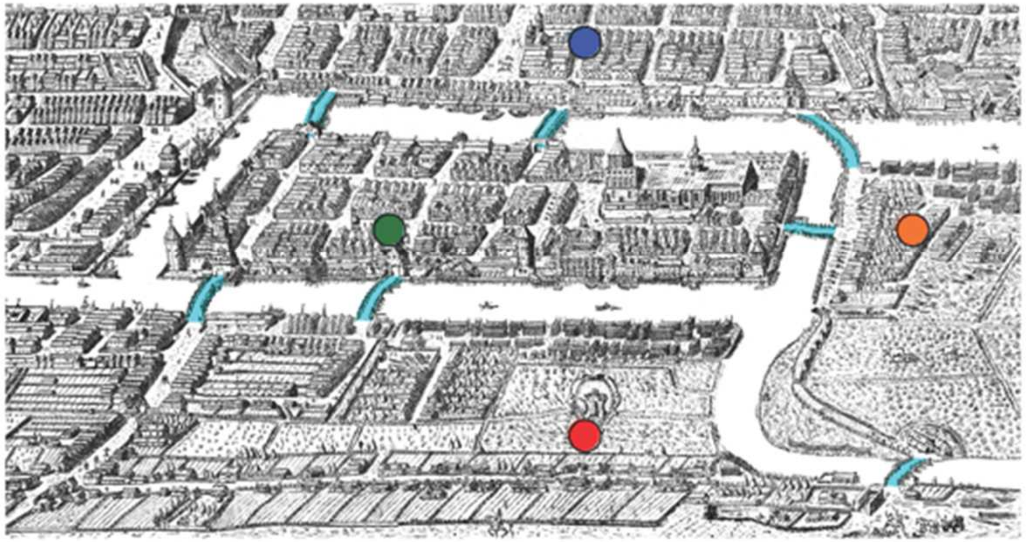
Problem: Is it possible to take a round trip through the city crossing each of its seven bridges once and only once?

Solution and Proof: Leonhard Euler, 1735
Basics of Graph Theory

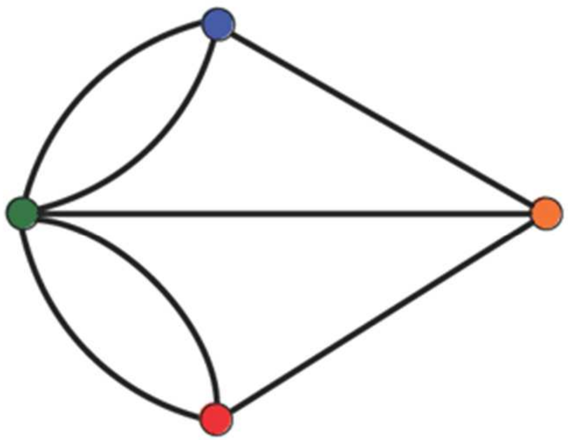


Leonhard Euler (1707-1783)

a



b



G R A P H

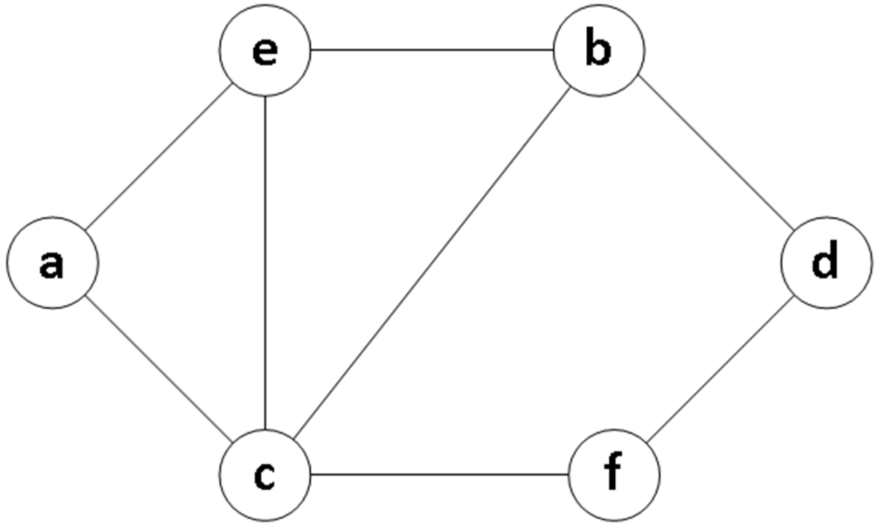
as a model structure:
well identified components and explored **pairly** relations amongst them

components:
elements, phases, processes

relations:
techno-logical dependencies

mathematically:
structured set of
nodes and edges

edge: related **pair of nodes**



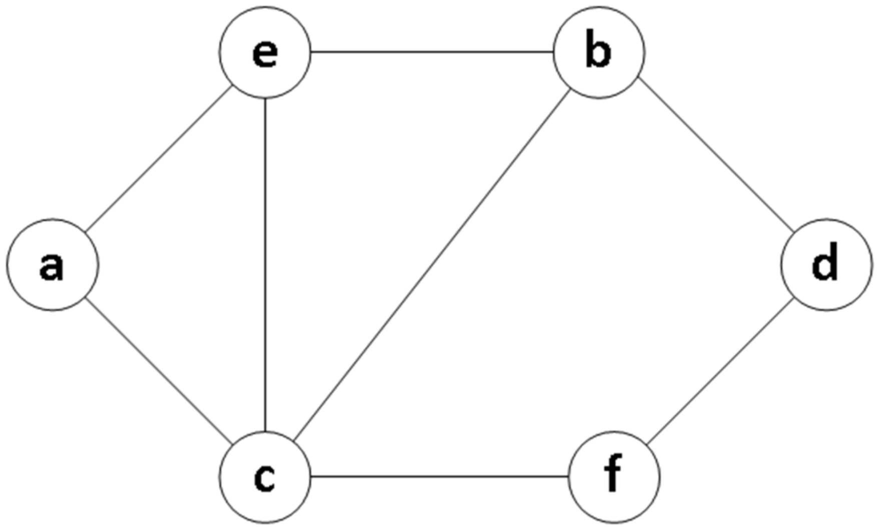
G R A P H

Set of nodes: N = { a, b, c, d, e, f } *(N=nodes)*

Set of edges: E = [{a,c},{a,e},{b,c},{b,d},{b,e},{c,e},{c,f},{d,f}] *(E=edges)*

Graph: G = [N, E]

(G=graph≅graphics)



G R A P H

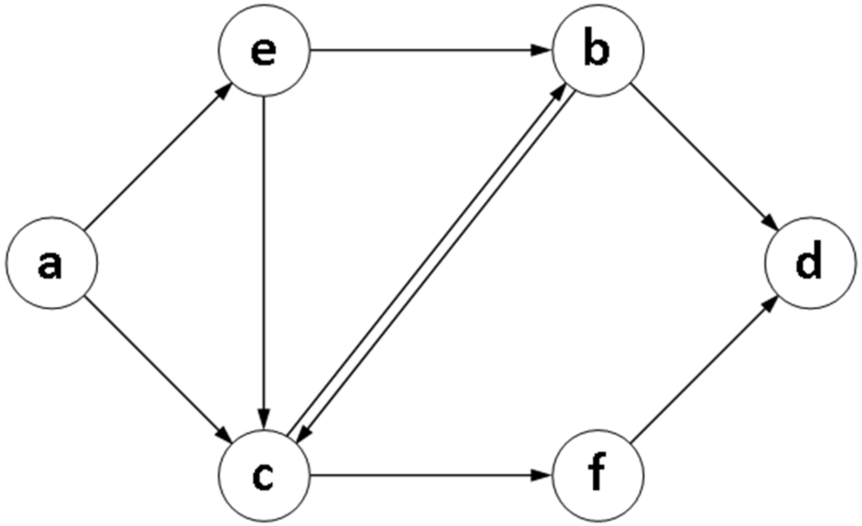
Directed Edge („Arrow”): *(A=arrows)*

dependency between the two related nodes is interpreted in one direction only

N = { a, b, c, d, e, f }

A = { (a,c),(a,e),(b,c),(b,d),(c,b),
(c,f),(e,b),(e,c),(f,d) }

G = [N, A]



Directed Graph:

(„DiGraph”=Directed Graph)

a graph with all of its edges directed

But: { i, j } = { (i, j), (j, i) }

G R A P H

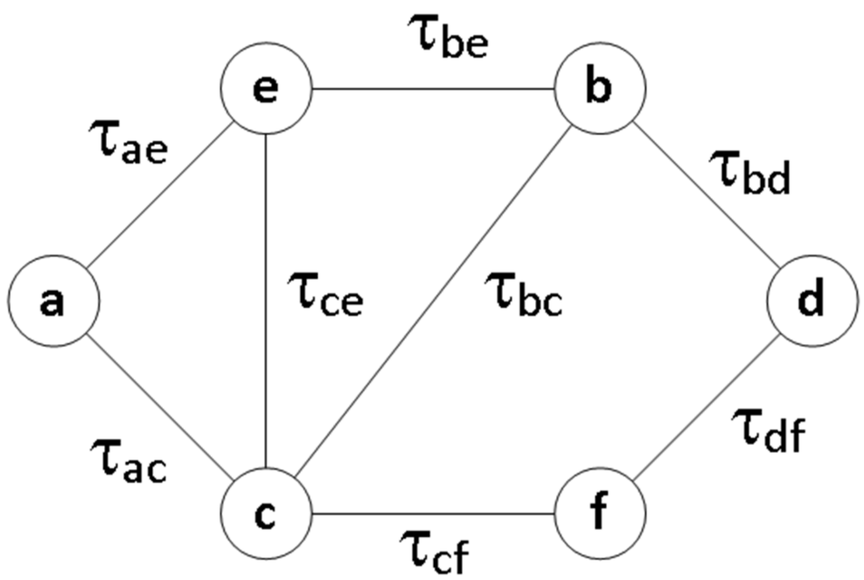
Weighted Graph:

quantitative characteristics referred as **weights** are interpreted along the edges

N = { a, b, c, d, e, f }

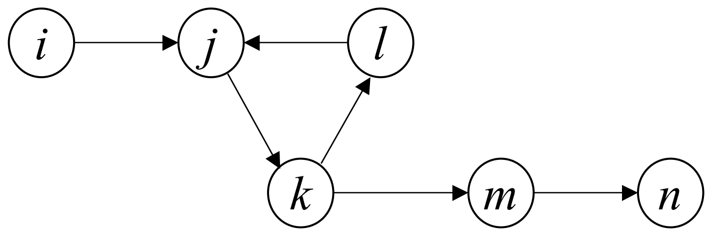
E = [$\{a,c,\tau_{ac}\},\{a,e,\tau_{ae}\},$
$\{b,c,\tau_{bc}\},\{b,d,\tau_{bd}\},$
$\{b,e,\tau_{be}\},\{c,e,\tau_{ce}\},$
$\{c,f,\tau_{cf}\},\{d,f,\tau_{df}\}$]

G = [N, E, τ]



Directed Wigthed Graph: G = [N, A, τ]

G R A P H



Basic terms of directed graphs:

Source: node with at least one leaving arrow but with no entering one e.g.: *i*

Sink: node with at least one entering arrow but with no leaving one e.g.: *n*

Route: series of nodes connected by sequence of directed edges *(R=Route)*
identified by the sequence of nodes involved e.g.: *R[i,n] = { i,j,k,l,j,k,m,n }*

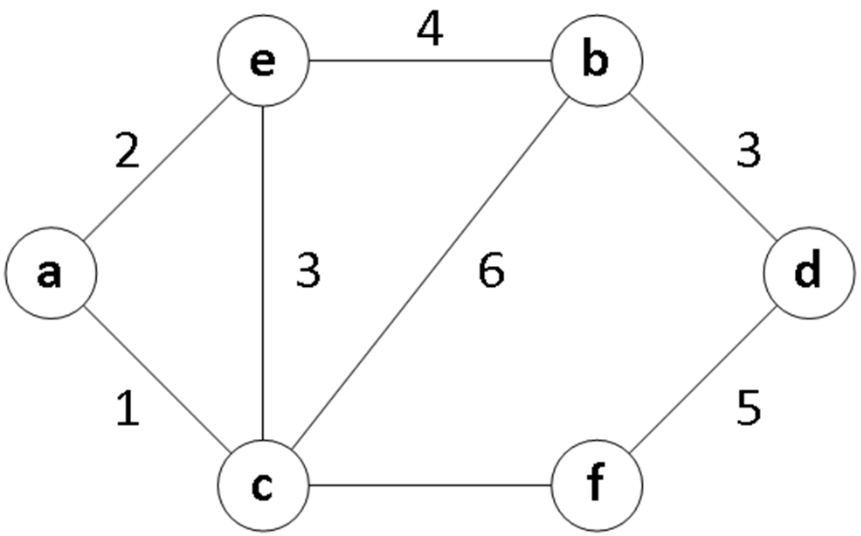
Path: sequence of directed edges with no recurring elements *(P=Path)*
identified by the sequence of nodes involved e.g.: *P[i,n] = { i,j,k,m,n }*

Loop: self-closing sequence of directed edges *(L=Loop)*
identified by the sequence of nodes involved e.g.: *L[j,j] = { j,k,l,j }*

G R A P H

Length of a Route/Path/Loop: sum of weights of its edges $|R_{in}|$ $|P_{in}|$ $|L_{jj}|$

Structure („Adjacency") Matrix

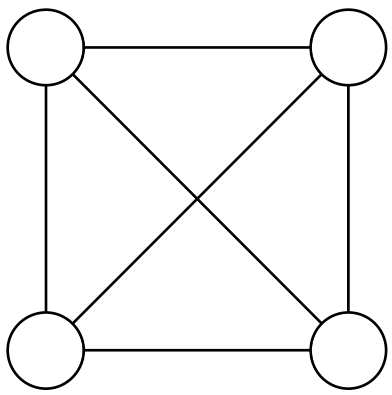


	a	b	c	d	e	f
a			1		2	
b			6	3	4	
c	1	6			3	4
d		3				5
e	2	4	3			
f			4	5		

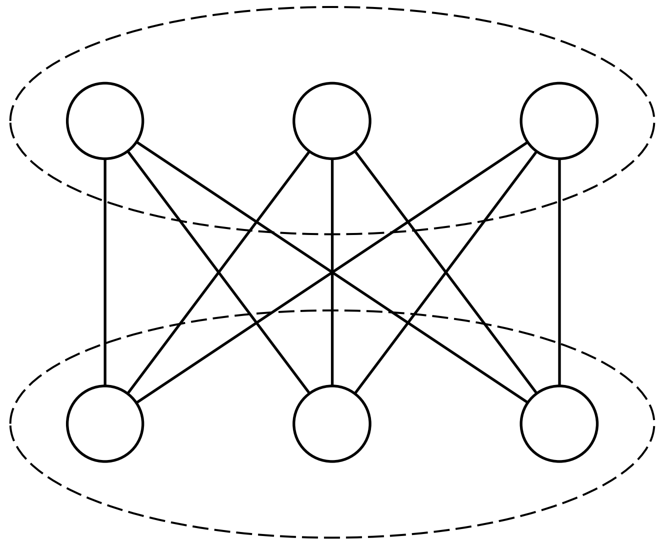
G R A P H

GRAPH – topologies (relation of nodes and edges/paths)

"complete"



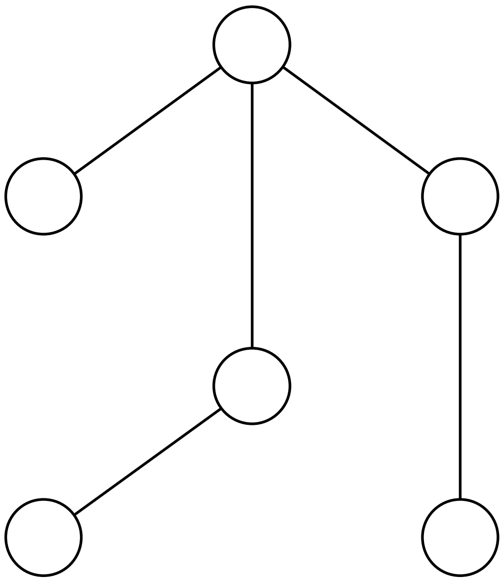
"paired"



G R A P H

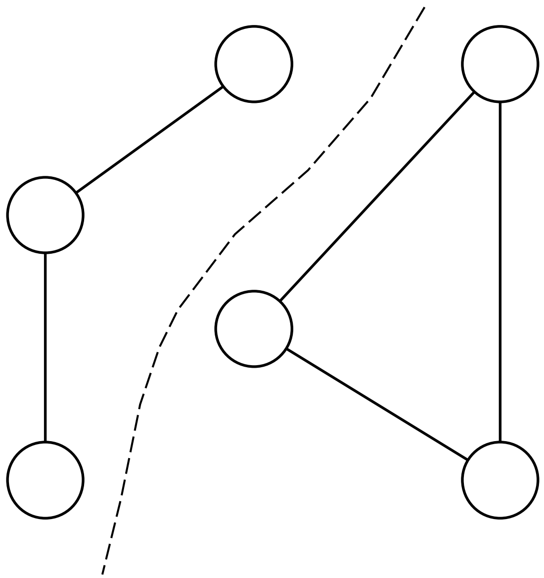
GRAPH – topologies (relation of nodes and edges/paths)

"tree"



"connected",

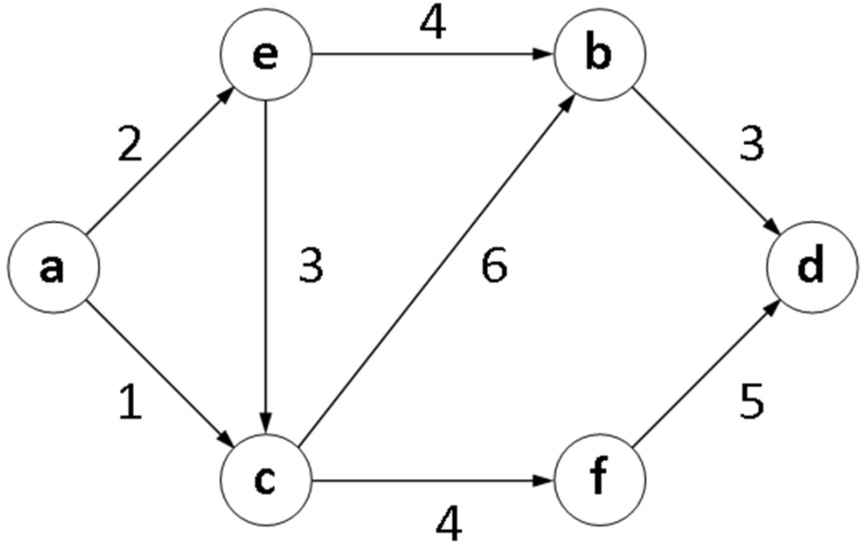
"not connected"



G R A P H

GRAPH – topologies (relation of nodes and edges/paths)

Network:
(as a special graph topology)
connected weighted directed graph, with an only source and with an only sink with no loops and with no negative weights along the edges



Network:
(as a synonym of graphs)
graph, in general, with no any restriction on topology or on any other characteristics

GRAPH TECHNIQUES – NETWORK TECHNIQUES

Basic problems (e.g.)

- Path finding
- Connectivity analysis
- Loop discovering
- Dominance analysis
- Path-variants survey
- Longest path / Shortest path
- Gravity point / Centre / Diagonal
- Maximal flow / Minimum cut
- Potentials' problem

:

Analogies in Gaph-techniques

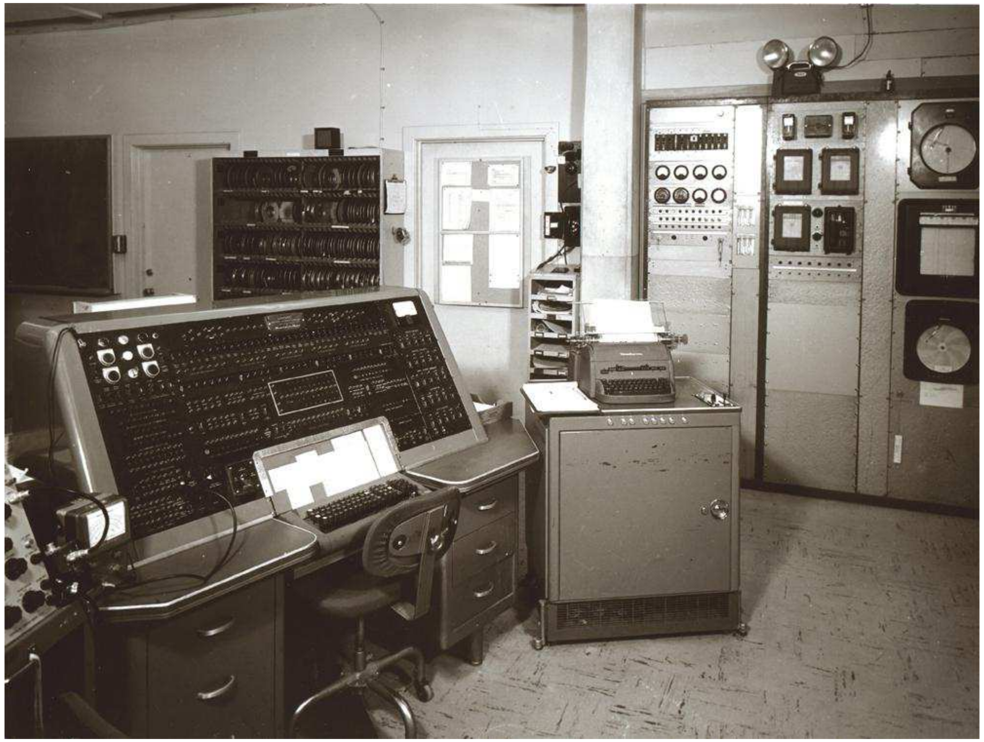
- Longest path problem
- Potentials' problem

Scheduling (Time/Cost Trade-off)

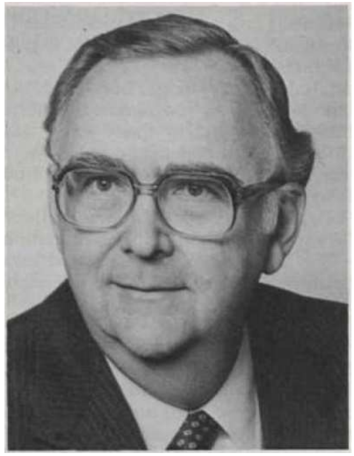
- CPM^{time}
- CPM^{cost}
- PERT^{time}
- CPM^{ladder}
- MPM^{time} / PDM^{time}
- MPM^{cost}
- GERT^{time}

Kelley-Walker Algorithm (later: CPM^{time} model)

1957 : DUPONT de NEMOURS, James E. Kelley - Morgan Walker



Remington Rand UNIVAC-I Universal Automatic Computer



James Elliot Kelley Jr.

Morgan Walker

UNIVAC-I	**technical data:**
Manufacturer:	Remington Rand
Manufactured:	1951 - 1954
Installed:	46 pcs
Dimensions:	4,3 x 2,4 x 2,6 m (Σ 35,5 m^2)
Weight:	13 to
Power consumption:	125 kW
Central Unit:	5200 vacuum tubes
Clock frequency:	2,25 MHz
Processor speed:	1905 ops
Back-up store:	magnetic tape
Input device:	punch-card reader
Price:	1250-1500 US$

Kelley-Walker Algorithm (later: CPM^{time} model)

1957 : DUPONT de NEMOURS, James E. Kelley - Morgan Walker

Node: direct succession connection, precedence/sequence/reason-result relation

Edge: activity/sub-project of well defined technical content, or – by need – relation of direct succession, "dummy activity" (Activity-On-Arrow correspondence)

Edge-parameter (weight): estimated minimum time of performance, "duration" (deterministic – usually integer – variable)

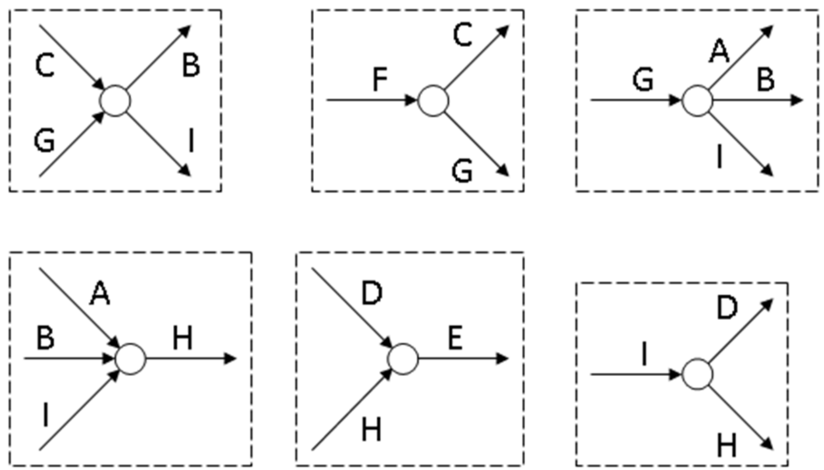
Aim: to calculate intermediate- and overall execution times ("deadlines") of the project;

later: also to identify dominant activity sequences ("critical path") and analysing effects/possibilities of activity delays ("floats") on timing other activities and/or on overall execution time

Kelley-Walker Algorithm (later: CPM^{time} model)

1957 : DUPONT de NEMOURS, James E. Kelley - Morgan Walker

Based on a set of **operative information** to elaborate a dynamic time model …



List of direct precedences:

A,B,I < H

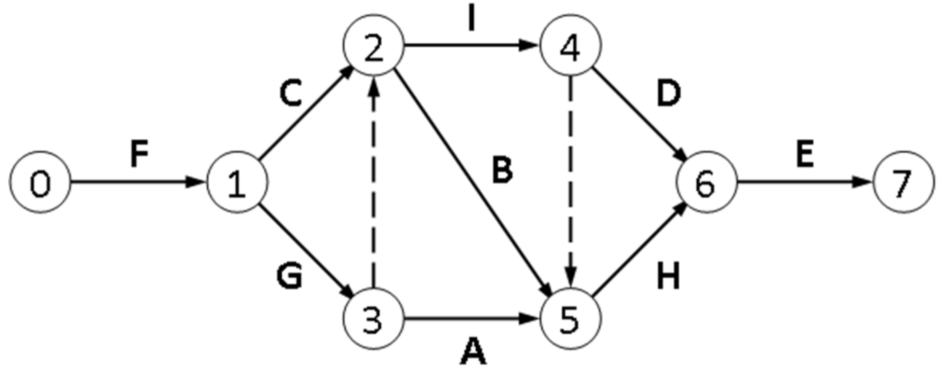
C,G < B,I

D,H < E

F < C,G

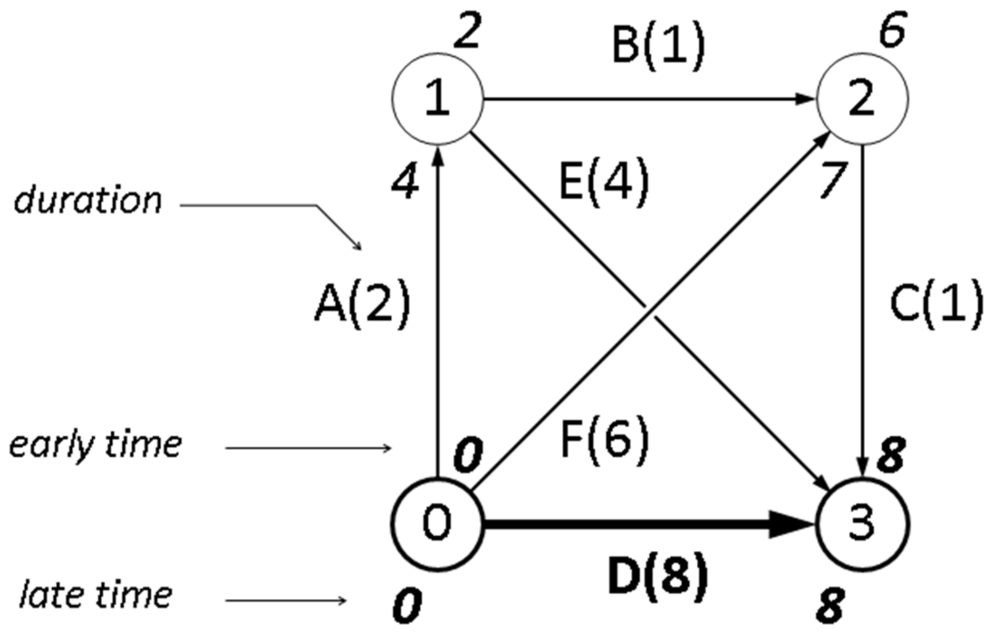
G < A,B,I

I < D,H



Kelley-Walker Algorithm (later: CPM^{time} model)

1957 : DUPONT de NEMOURS, James E. Kelley - Morgan Walker



ID	D	ES	EF	LS	LF	TF	FF	CF	IF
A	2	0	2	2	4	2	0	2	0
B	1	2	3	6	7	4	3	2	1

„CRITICAL PATH" (CP):

Subset (subgraph) of a graph composed off nodes – and off <u>dominant edges</u> among them – at which the early and the late times (potentials) equal to each other *(potentials' problem)*;

Subset (subgraph) of a graph composed off the <u>longest paths</u> leading from the source to the sink *(longest path problem)*.

ID=Identifier; D=Duration; ES=Early Start; EF=Early Finish; LS=Late Start; LF=Late Finish; TF=Total Float; FF=Free Float; CF=Conditional Float; IF=Independent Float

Kelley-Walker Algorithm (later: CPM^{time} model)

1957 : DUPONT de NEMOURS, James E. Kelley - Morgan Walker

"Total Float" (of an activity) : Acceptable increment in duration of an activity (or acceptable delay of its start) with not jeopardizing the *early finish of the project* assuming that all its (dominant) predecessors can be performed by their *early* schedules. ("… no delay before, maximum delay after …")

"Free Float" (of an activity) : Acceptable increment in duration of an activity (or acceptable delay of its start) with not jeopardizing the *early schedule of any activity* assuming that all its (dominant) predecessors can be performed by their *early* schedules. ("… no delay before, no delay after …")

"Conditional Float" (of an activity) : Acceptable increment in duration of an activity (or acceptable delay of its start) with not jeopardizing the *early finish of the project* assuming that all its (dominant) predecessors can be performed by their *late* schedules. ("… maximum delay before, maximum delay after …")

"Independent Float" (of an activity) : Acceptable increment in duration of an activity (or acceptable delay of its start) with not jeopardizing the *early schedule of any activity* assuming that all its (dominant) predecessors can be performed by their *late* schedules. ("… maximum delay before, no delay after …")
(Non-negative values concerned only !)

Critical Path Method (CPM^{cost})

1958 : DUPONT de NEMOURS, James E. Kelley - Morgan Walker

Node: direct succession connection, precedence/sequence/reason-result relation

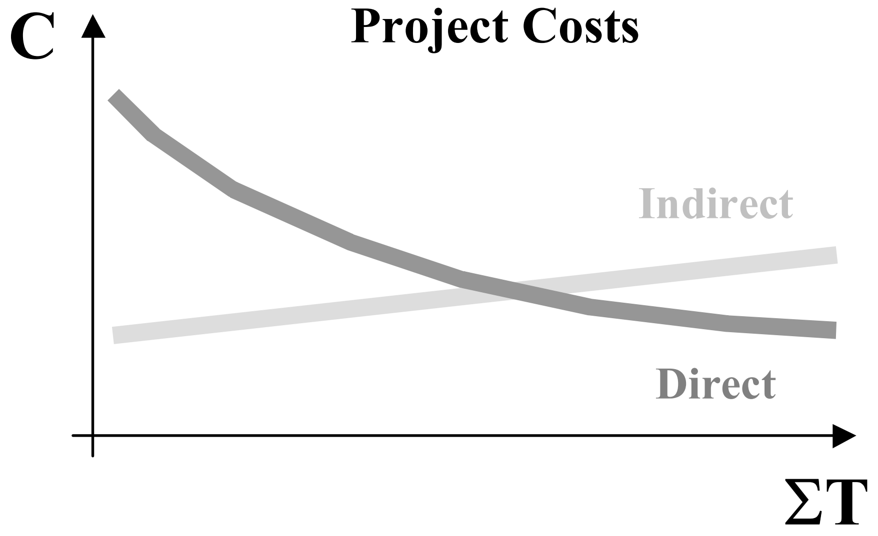
Edge: activity/sub-project of well defined technical content, or – by need – relation of direct succession, "dummy activity" (Activity-On-Arrow correspondence)

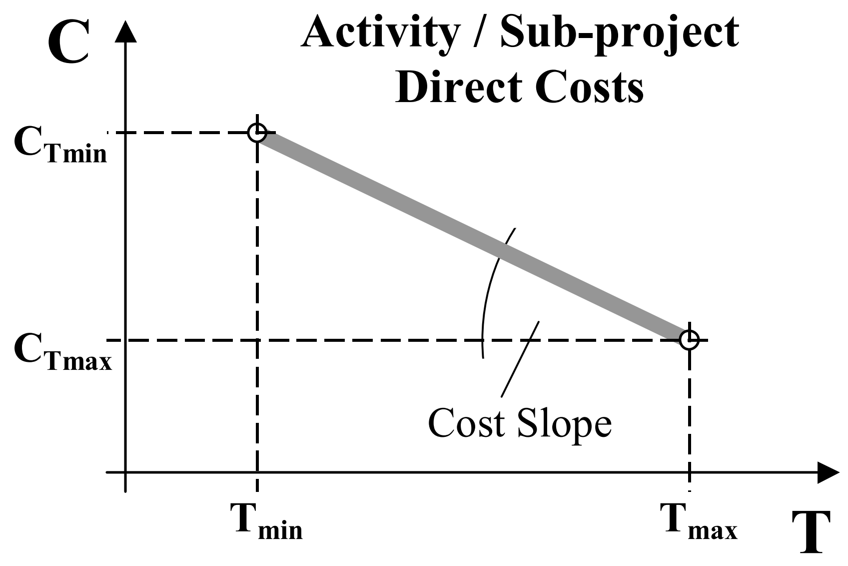
Edge-parameter (weight): estimated time-range of performance (variants of duration), with associating estimated direct costs (as function of duration)

Aim: to develop an optimal schedule with main consideration of time-cost trade-off at the activities and at the overall execution time of the project …
… via iterative steps of calculating intermediate- and overall execution times and changing activity durations (within the pre-set ranges) in a proper way to achieve an optimal solution (of minimum direct costs at a given overall exeution time)

Critical Path Method (CPM^{cost})

1958 : DUPONT de NEMOURS, James E. Kelley - Morgan Walker

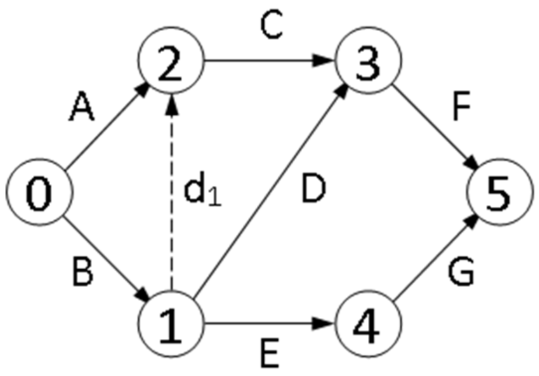




C=Cost ; T=Time; C_{Tmin}=Crash Cost; C_{Tmax}=Normal Cost ; T_{min}= Crash Time; T_{max}=Normal Time; CS=Cost Slope

Critical Path Method (CPM^{cost})

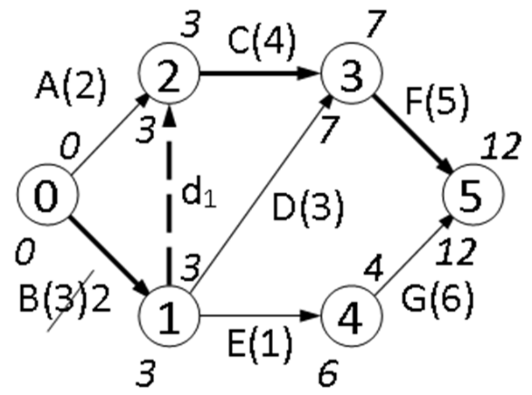
1958 : DUPONT de NEMOURS, James E. Kelley - Morgan Walker



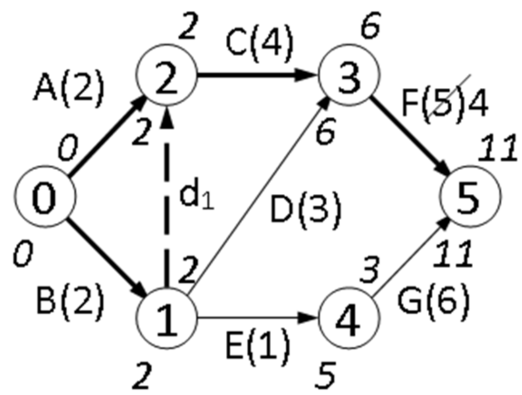
(CPM^{cost}) Problem:

What are the minimum direct costs of the project associating the scheduled overall execution time not longer than 10 time units?

ID	Normal		Crash		
	time	cost	time	cost	CS
A	2	120	1	200	80
B	3	80	1	200	60
C	4	100	2	350	125
D	3	150	3	150	-
E	1	250	1	250	-
F	5	130	2	460	110
G	6	80	5	110	30



$C_{11}=C_{12}+CS_B=910+60=970$

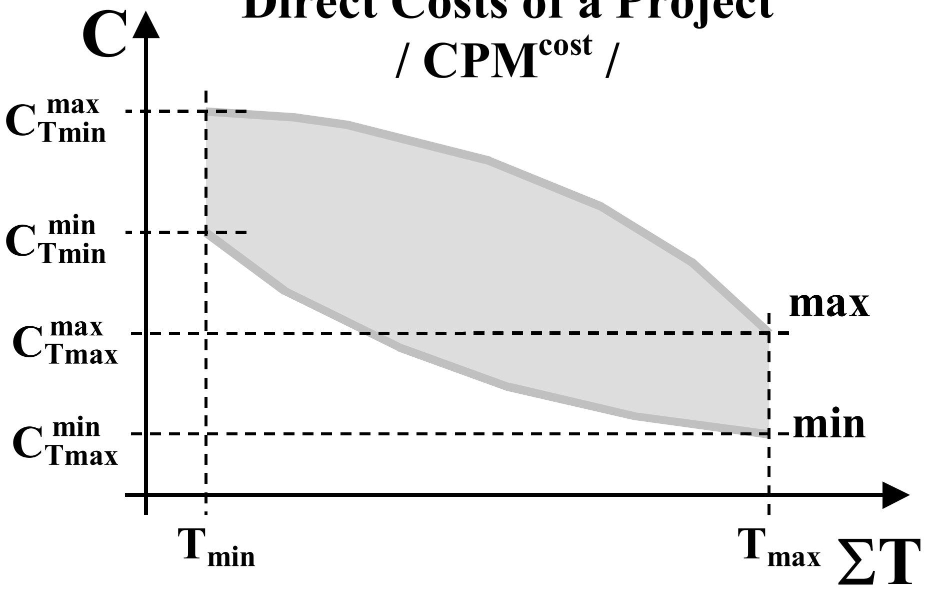


$C_{10}=C_{11}+CS_F=970+110=1080$

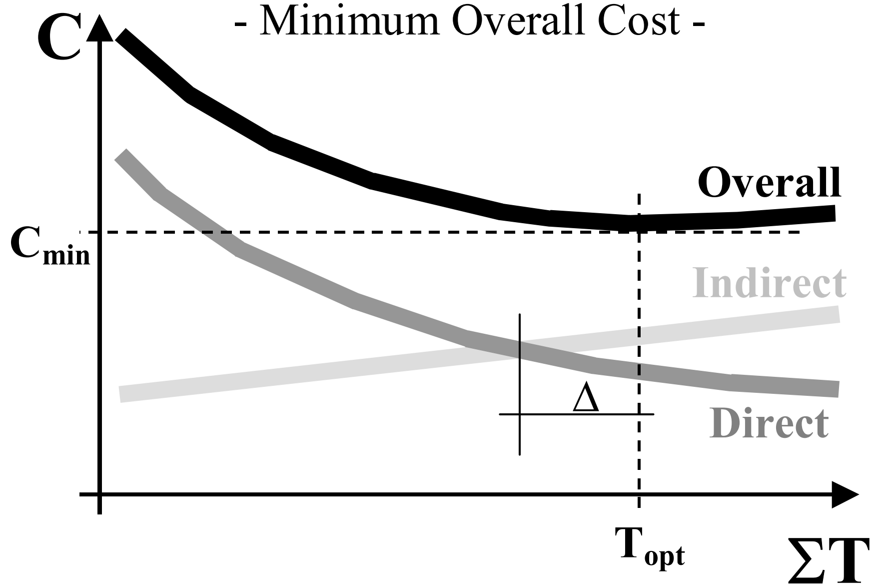
Critical Path Method (CPM^{cost})

1958 : DUPONT de NEMOURS, James E. Kelley - Morgan Walker

Direct Costs of a Project
/ CPM^{cost} /



Optimal Project Duration
- Minimum Overall Cost -



Sputnik-1

First artificial satellite (companion) of Earth, Baikonur, Sovietunion, 04.10.1957

US NAVY, Polaris Project

First successful underwater launch of a missile, USS George Washington 20.07.1960

Program Evaluation & Review Technique (PERT)

1958 : US NAVY, SPO, Polaris Project, Willard Fazar

Node: event, state, "mile-stone", phase of progression

Edge: activity ("sub-projects") with closely not identified (technical) contents ("R&D") (Activity-On-Arrow correspondence)

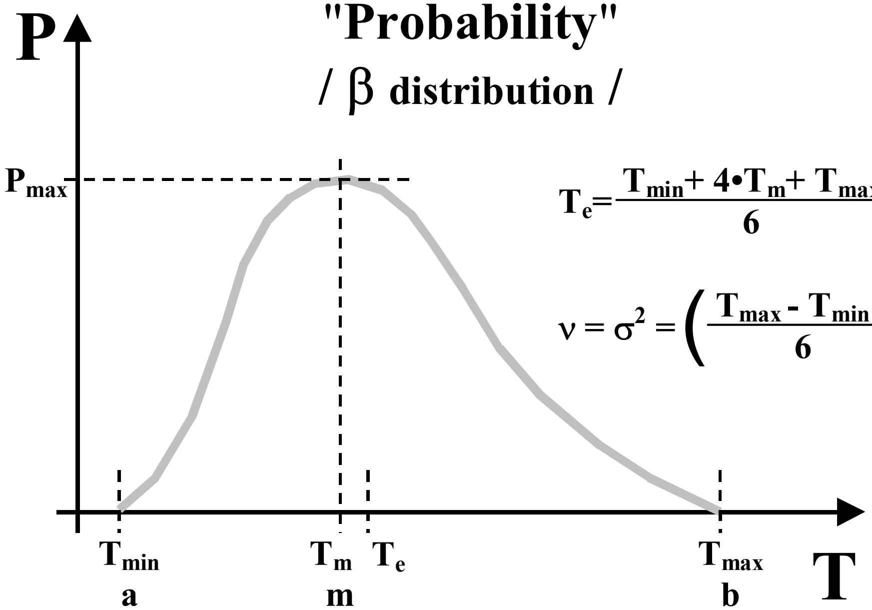
Parameter (weight): likely "time-span" of the activity, probabilistic variable of β **distribution**, predicted by triplex estimates (stochastic model)

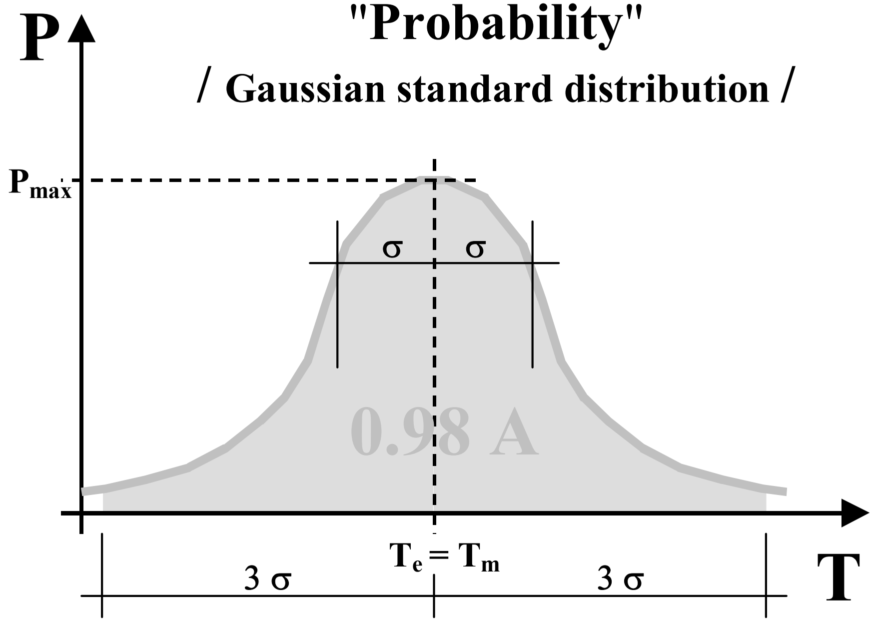
Aim: to predict timing of milestones and overall execution time of the project, together with indices of uncertainty ("deviation");
also to check feasibility of a schedule

Program Evaluation & Review Technique (PERT)

1958 : US NAVY, SPO, Polaris Project, Willard Fazar

Why β distribution? Why 6? : limited range, asymmetry, tolerable error



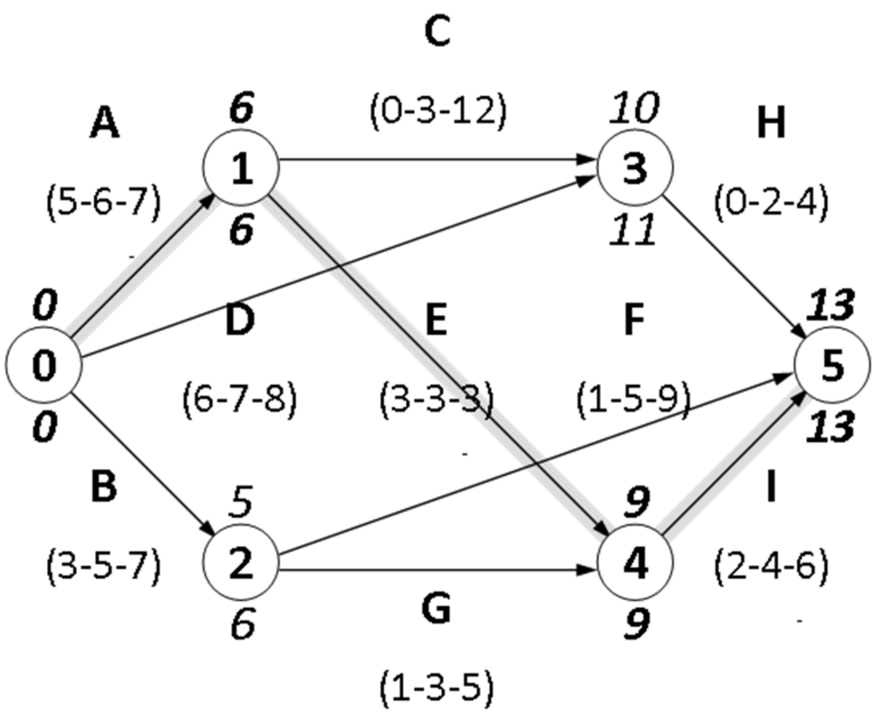


$T_e = \mu_e$ = expected value; $T_m = \mu_m$ = modus; ν = variance (or: deviation square); σ = deviation; P = propability (density)

Program Evaluation & Review Technique (PERT)

1958 : US NAVY, SPO, Polaris Project, Willard Fazar

PERT problem : What is the probability of completing the project below in a scheduled period not longer than 12 time units?



ID
(a-m-b)

$$\mu_e = \frac{a + 4 \bullet m + b}{6}$$

$$\nu = \sigma^2 = \left(\frac{b - a}{6}\right)^2$$

$\mu_T = 13$

$\nu_T = 5/9$

$\mu_A = 6 \quad \nu_A = \frac{1}{9} \qquad \mu_F = 5 \quad \nu_F = \frac{16}{9}$

$\mu_B = 5 \quad \nu_B = \frac{4}{9} \qquad \mu_G = 3 \quad \nu_G = \frac{4}{9}$

$\mu_C = 4 \quad \nu_C = \frac{36}{9} \qquad \mu_H = 2 \quad \nu_H = \frac{4}{9}$

$\mu_D = 7 \quad \nu_D = \frac{1}{9} \qquad \mu_I = 4 \quad \nu_I = \frac{4}{9}$

$\mu_E = 3 \quad \nu_E = \frac{0}{9}$

$$\nu_5 = \nu_A + \nu_E + \nu_I = \frac{1}{9} + \frac{0}{9} + \frac{4}{9} = \frac{5}{9}$$

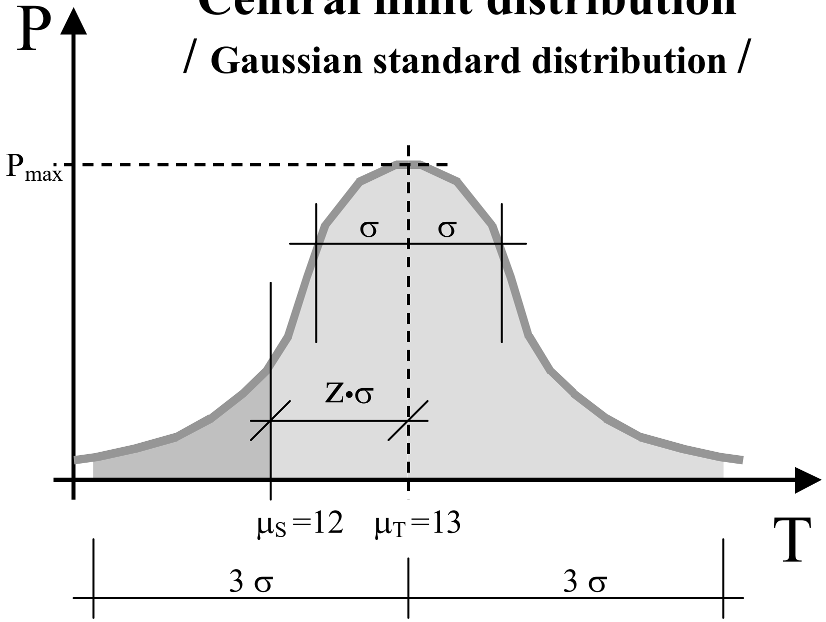
Program Evaluation & Review Technique (PERT)

1958 : US NAVY, SPO, Polaris Project, Willard Fazar

PERT problem : What is the probability of completing the project below in a scheduled period not longer than 12 time units?

Central limit distribution

/ Gaussian standard distribution /



$$Z = \frac{\mu_S - \mu_T}{\sqrt{\nu_T}} = \frac{12-13}{\sqrt{5/9}} = -1.3416$$

Z	CP	Z	CP
- 2.0	0.02	+ 0.1	0.54
- 1.5	0.07	+ 0.2	0.58
- 1.3	0.10	+ 0.3	0.62
- 1.0	0.16	+ 0.4	0.66
- 0.9	0.18	+ 0.5	0.69
- 0.8	0.21	+ 0.6	0.73

CP ≈ 9 %

μ_S = scheduled time; μ_T = expected length of the longest path; ν_T = variance associating μ_T; CP = cummulative probability

Vostok-1, Yuri Gagarin

On an orbit around the Earth, first man in space, 12.04.1961 09:07 (108 minute mission)



Alan Bartlett Shepard

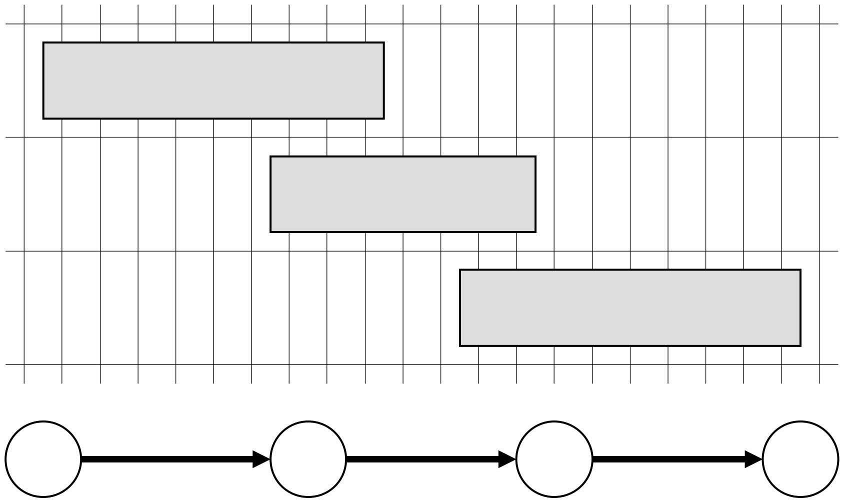
First american in space, on a suborbital trajectory, 05.05.1961 (15 minute „space-jump”)
Fifth american astronaut stepping on the surface of the Moon, Apollo-14, 31.01 - 09.02.1971

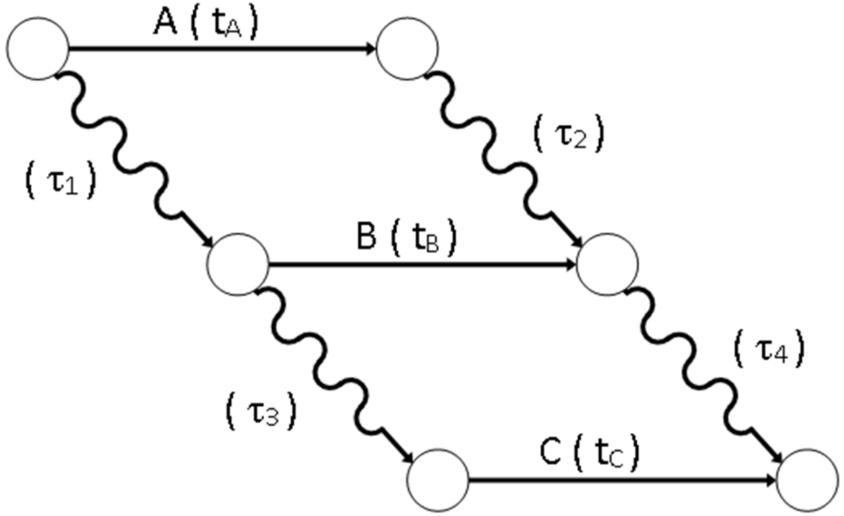
CPM^{ladder} Convention

1961..: BTM / ICT, UK, J. Grant, P. A. Rhodes, H. S. Woodgate, ..

CPM/PERT: modelling overlapped time positions is unsolved or too complicated

Proposal: inserting further dummy- ("ladder" and "hammock") activities



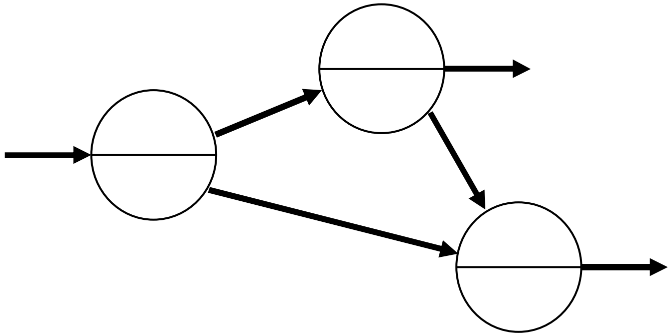


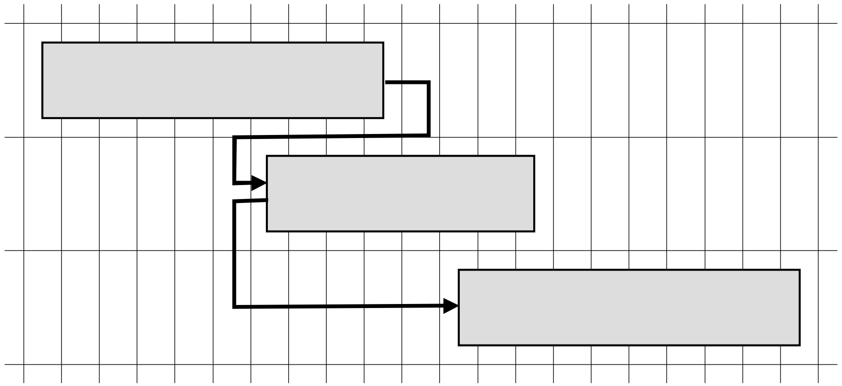
still Activity-On-Arrow ("AOA") correspondence

Precedence Diagramming Method (PDM)

Activity On Node correspondence

1962 : Stanford University, John W. Fondahl





John W. Fondahl

IBM, MicroSoft, „Bar-chart – PERT-chart" projection, USA, 1964-

METRA – Potentials' Method (MPM)

1958-61 : SEMA-METRA, France, Construction Projects, Bernard Roy

Chinon Nuclear Power Plant, Loire valley, France, 1962

Bernard Roy

METRA – Potentials' Method (MPM)

1958-61 : SEMA-METRA, France, Construction Projects, Bernard Roy

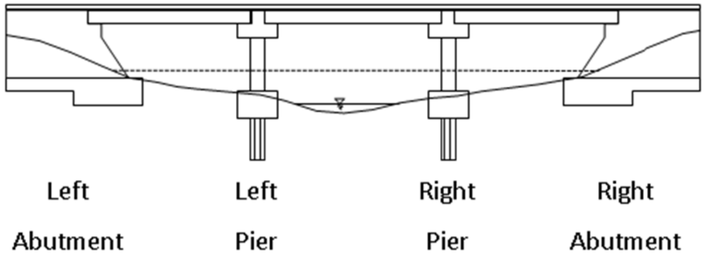
Node: activity of fixed duration (0 duration for events or for milestones)
(Activity-On-Node correspondence)

Edge: techno-logical or resource-based quantified relation

Parameter (weight): lead- or lag time, duration
(usually integer typed deterministic variable)

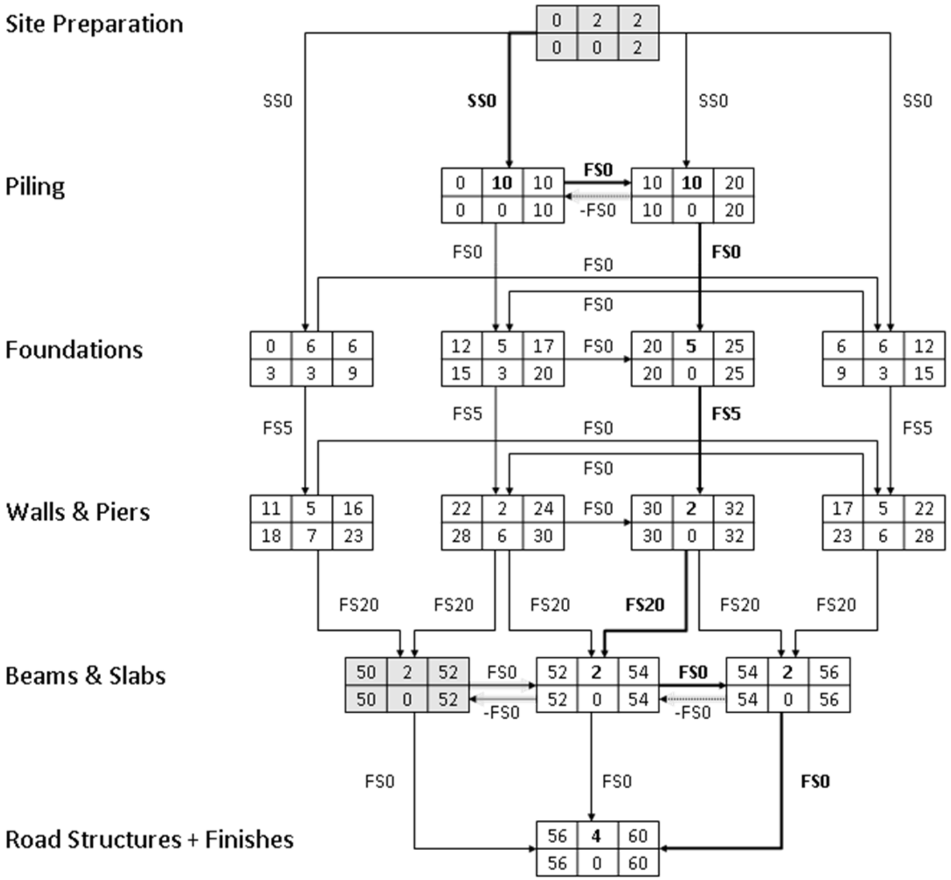
Aim: modelling technologies, production management, controlling/monitoring, change management …

… modelling arbitrary relative time positions (e.g. overlapping), lower/upper bounds for timing (minimum/maximum typed relations)…



METRA Potentials' Method (MPM)

1958-61 : SEMA-METRA, France, Construction Projects, Bernard Roy



MPM time model of the on-site works of a bridge construction project

METRA – Potentials' Method (MPM)

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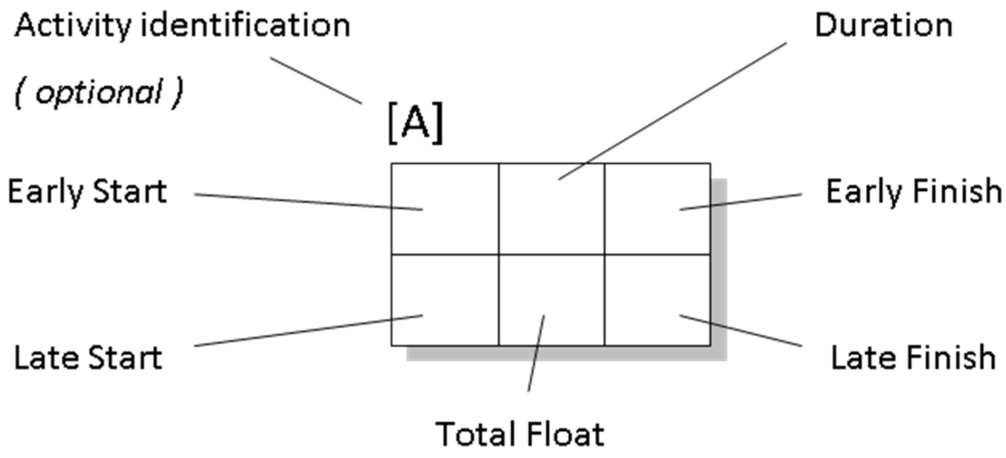
**Arranging data in an activity box/shield (Node)
for manual calculations**



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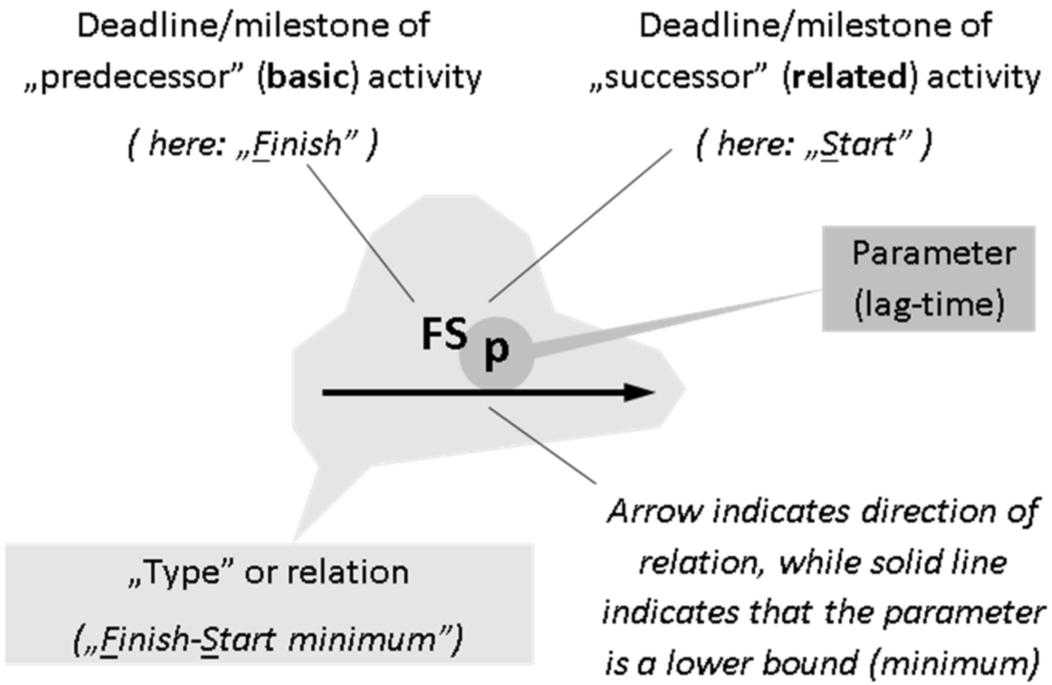
Graphic representation of lower bound (minimum) typed relations



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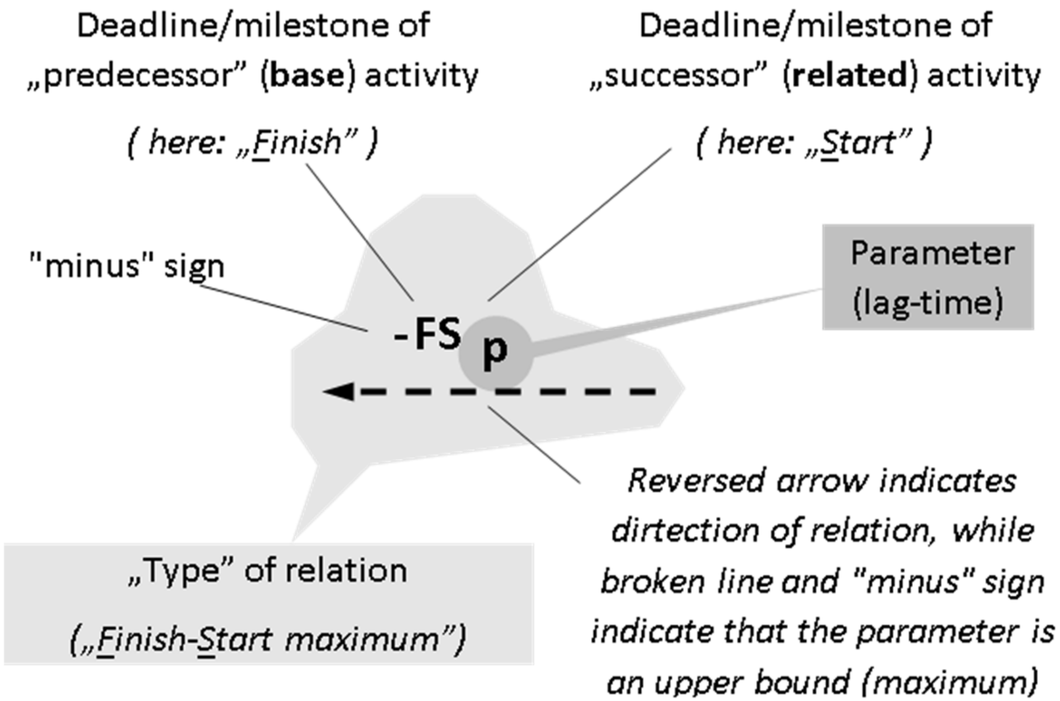
Graphic representation of upper bound (maximum) typed relations



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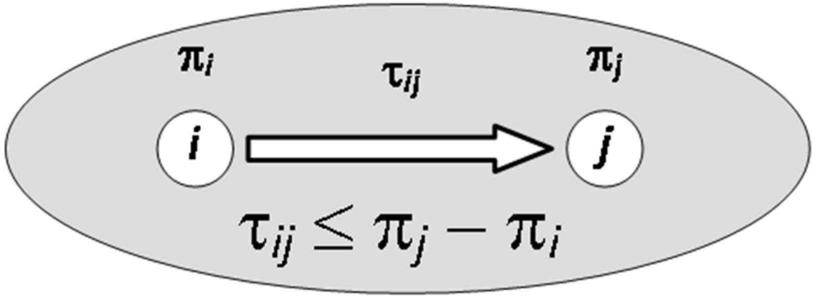
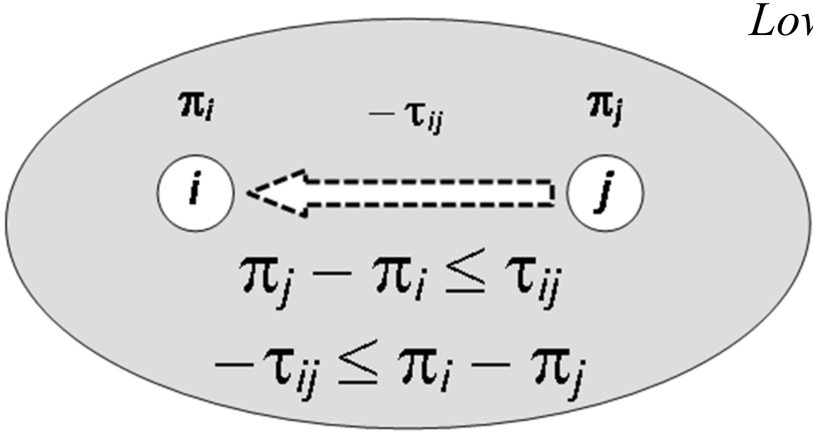
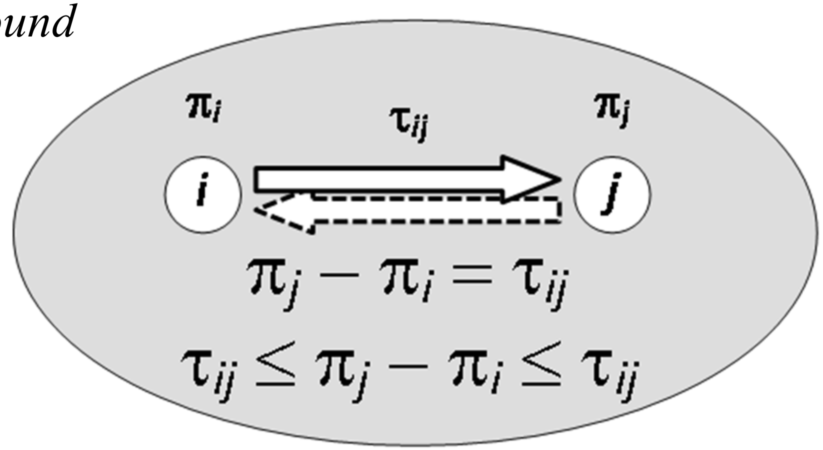
"Homogenizing" relations (bounds) – keeping analogy of the "longest path" problem



Lower bound



Upper bound



Fixed value

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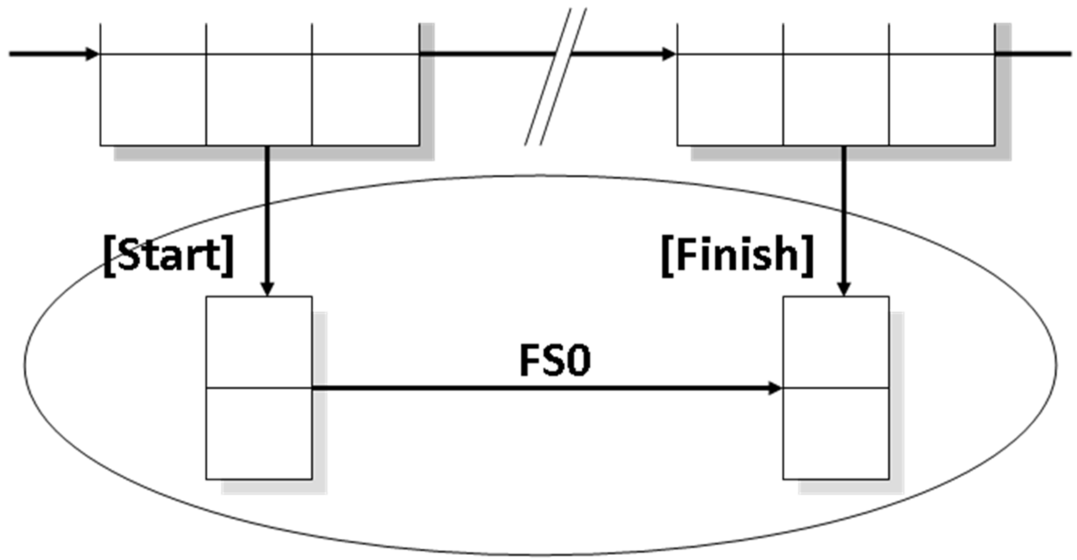
"Hammock" ("summary" or "embracing") activity



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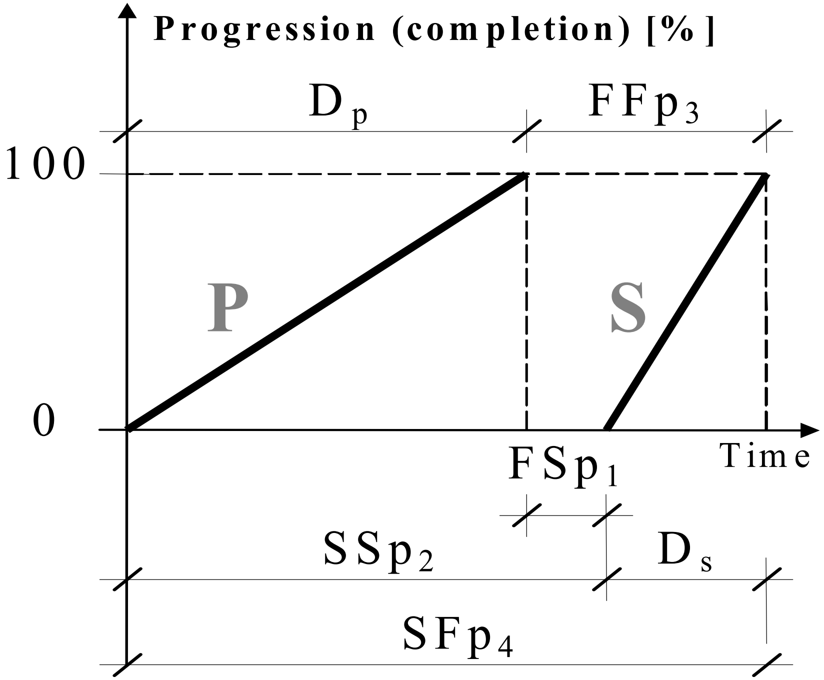
The four basic types of relations



Conversion of basic types of relations

	FFq	FSq	SFq	SSq
FFp		$q = p - D_s$	$q = p + D_p$	$q = p + D_p - D_s$
FSp	$q = p + D_s$		$q = p + D_p + D_s$	$q = p + D_p$
SFp	$q = p - D_p$	$q = p - D_p - D_s$		$q = p - D_s$
SSp	$q = p + D_s - D_p$	$q = p - D_p$	$q = p + D_s$	

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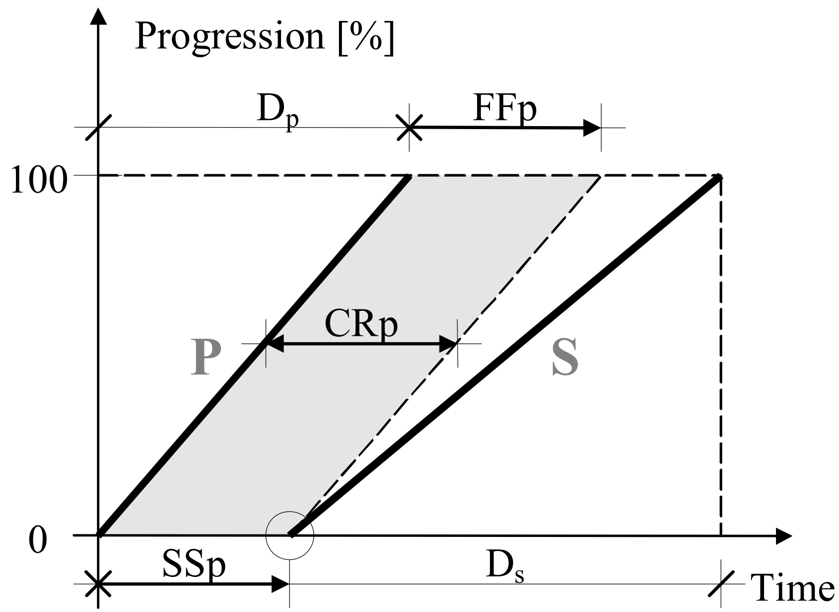
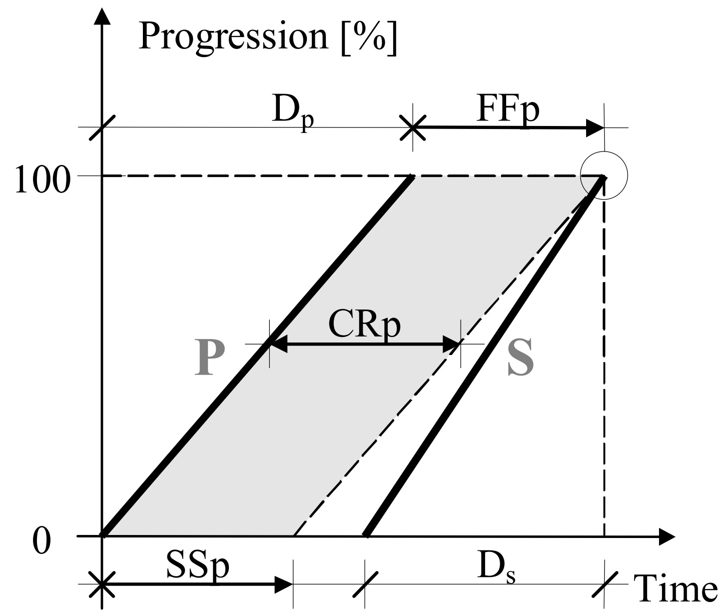
Providing (minimum) lead in time („technological break") between overlapped activities





METRA – Potentials' Method (MPM)

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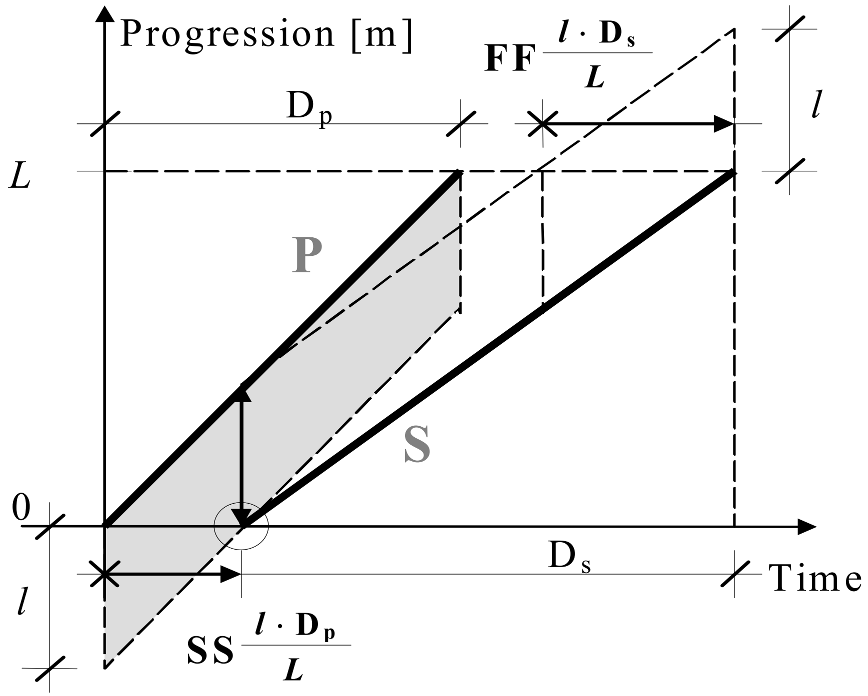
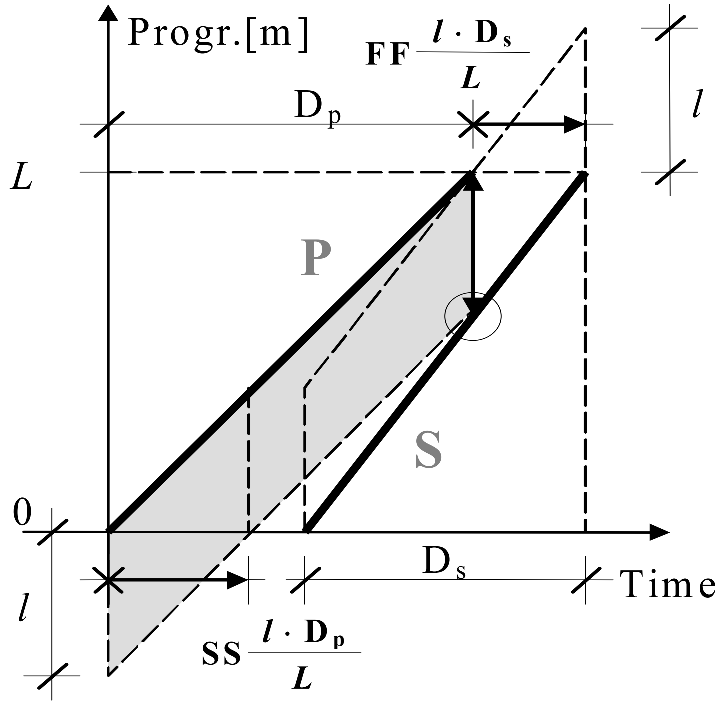
Providing (minimum) lead in progression („safety distance”) between overlapped activities





METRA – Potentials' Method (MPM)

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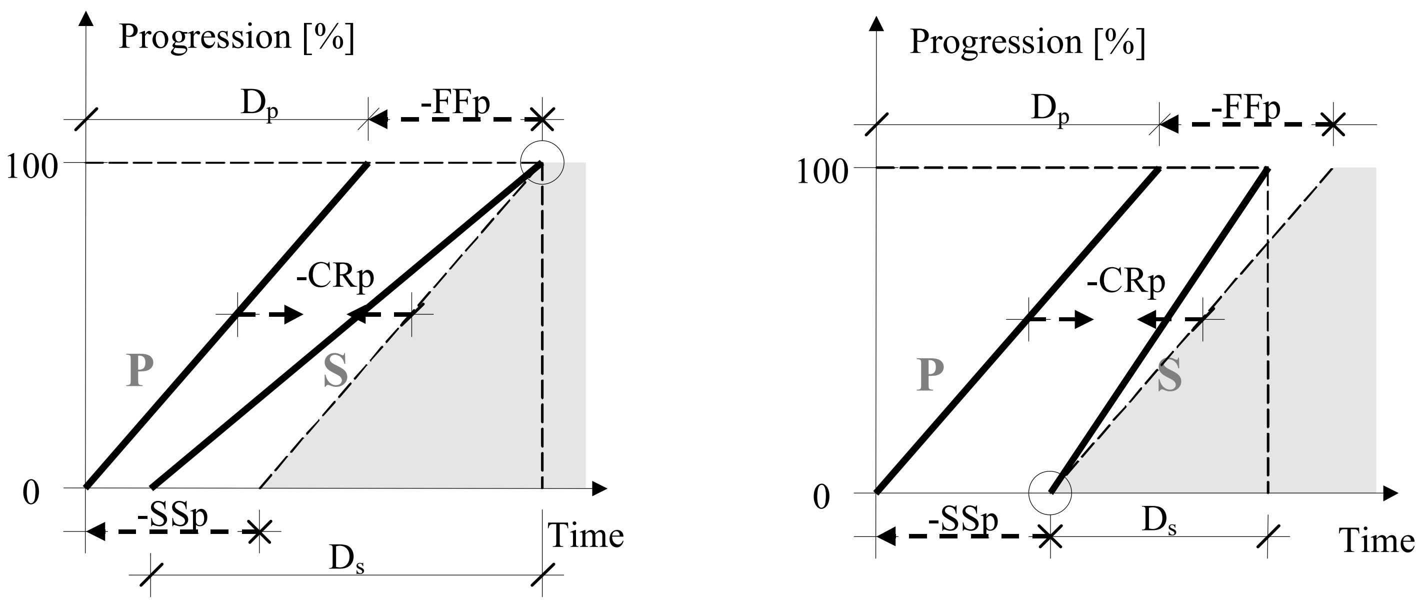
Limiting (maximum) lag in time („sensitive conditions") between overlapped activities



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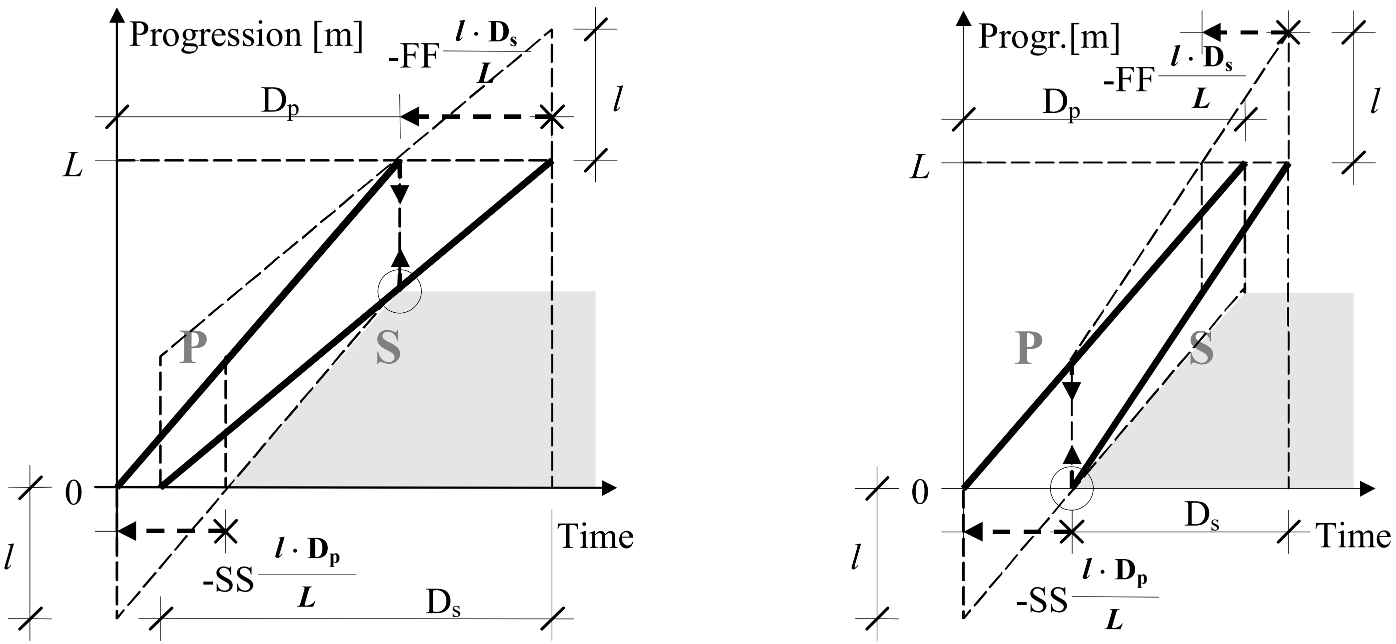
Limiting (maximum) lag in progression („distance") between overlapped activities



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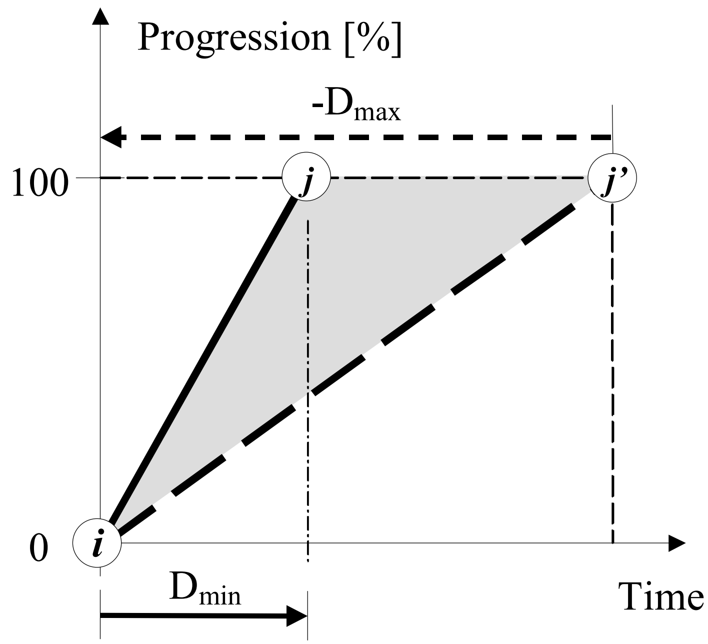
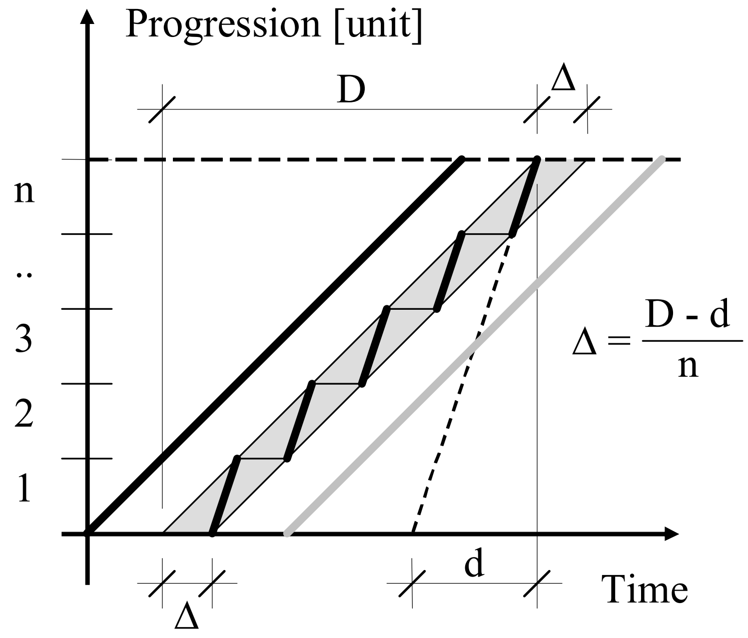
Bounding flexible duration



Resolving duration paradox



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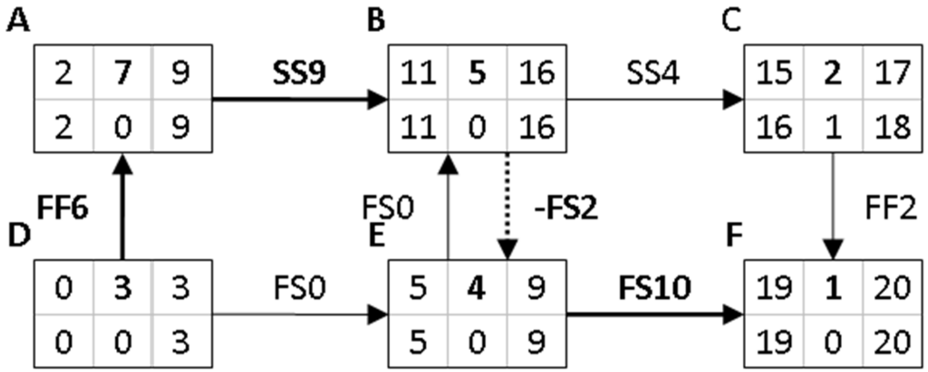
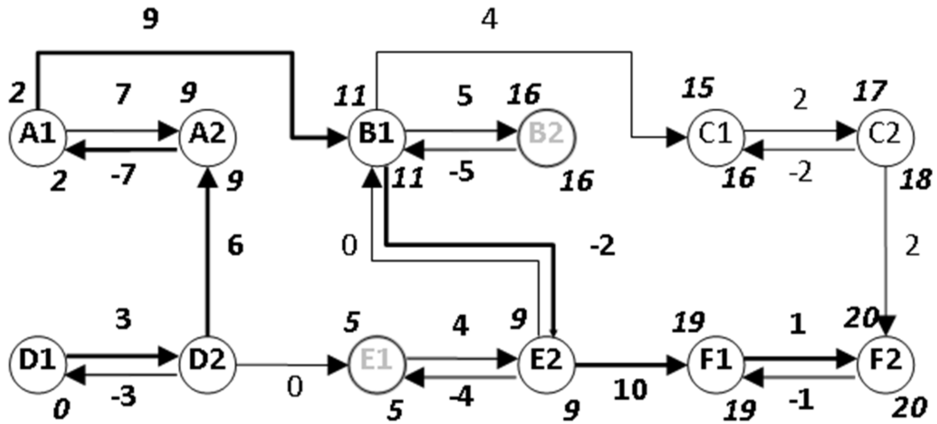


An MPM time model … **… and its DiGraph equivalent**



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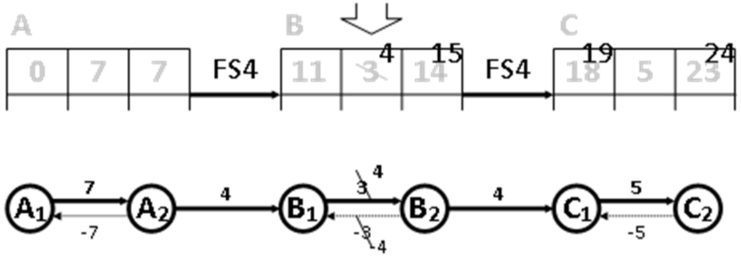
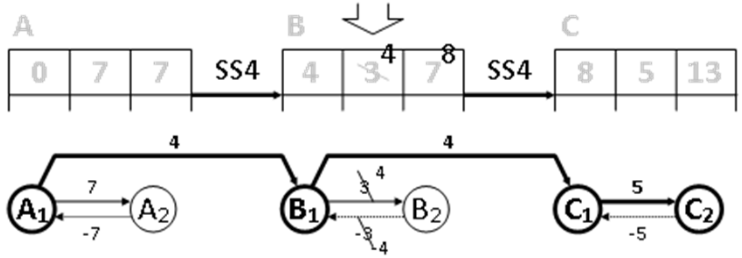
BEHAVIOUR OF CRITICAL ACTIVITIES (SOME TYPES OF DOMINANCE)

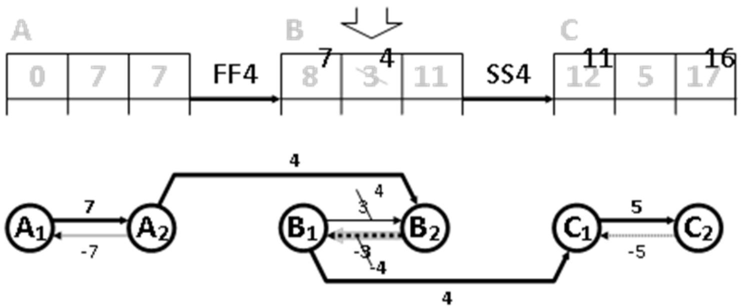
Positive critical



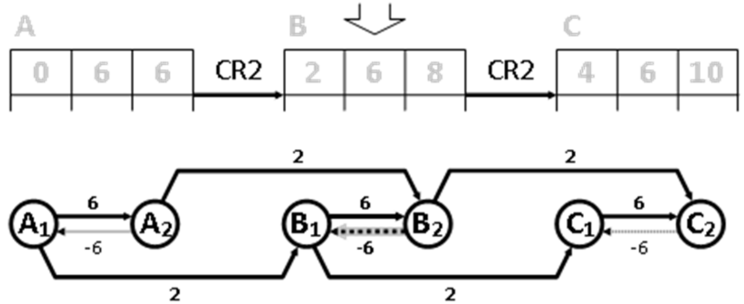
Quasi or Zero (here: start) critical



Negative critical



Absolute critical



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COMPREHENSION: FOUR RIDDLES ON NETWORK TIME MODELS

1., Duration of an activity having no float in an activity-on-arrow typed network time model get increased by δ. What will be its effect on the overall execution time of the project ?

2., Duration of an activity having no float in an activity-on-arrow typed network time model get decreased by δ. What will be its effect on the overall execution time of the project ?

3., Duration of an activity having no float in an activity-on-node typed network time model get increased by δ. What will be its effect on the overall execution time of the project ?

4., Do explain a situation when changing the duration of an activity that has no any float in a network time model will surely increase the overall execution time of the project.