Tutorial

Fault Tree Analysis

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Contents

- Session 1: Basic Concepts
  - Fault Tree Symbols/Terminology
  - Fault Tree Construction
  - Minimal Cut Sets
  - Component Failure Models
  - Top Event Probability
  - Top Event Frequency
  - Other Top Event Parameters
  - Importance Measures

- Session 2: Advanced Features
  - Initiator/Enabler Events
  - Non-Coherent Fault Trees

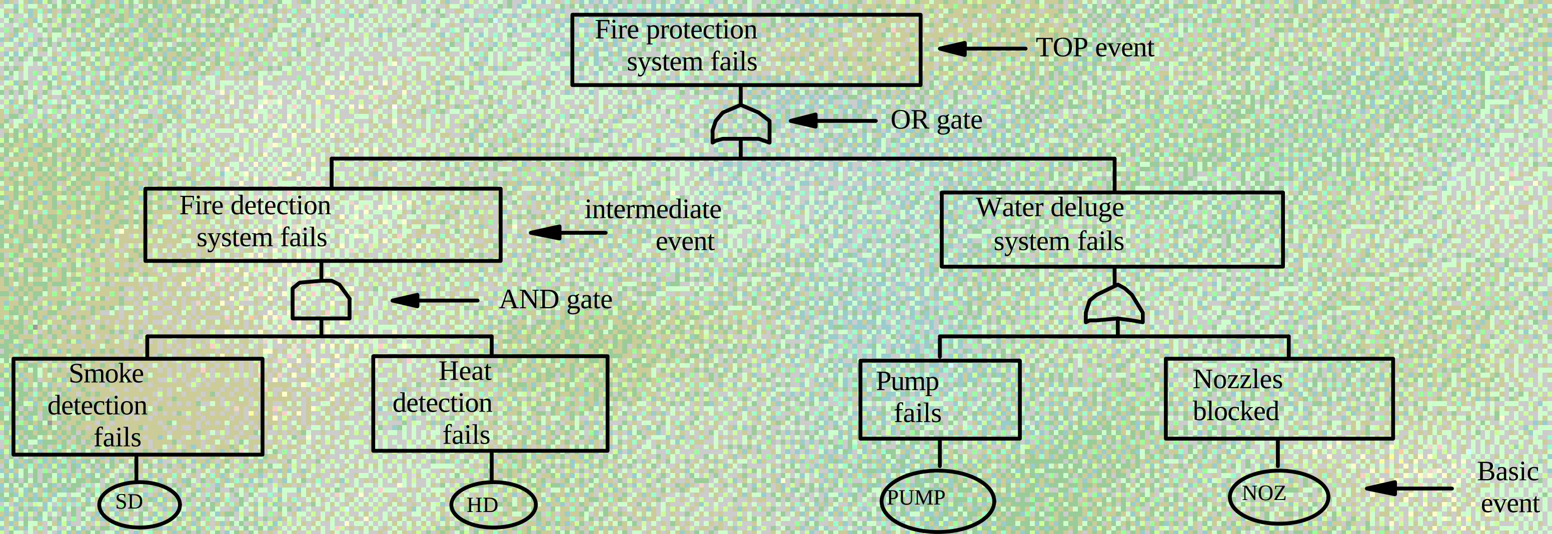
- Session 3: Current Research
  - Binary Decision Diagrams
  - Dependency Modelling
  - Optimal System Design

Session 1: Basic Concepts

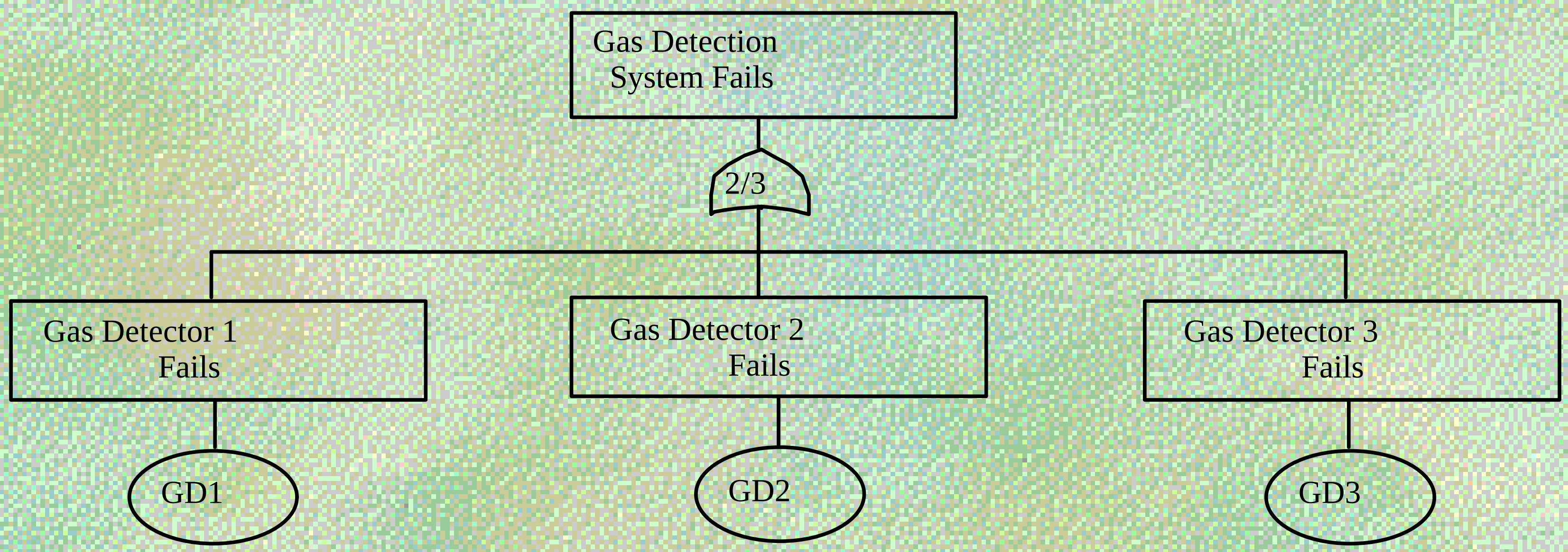
History

- 1961 - FTA Concept by H Watson, Bell Telephone Laboratories
- 1970 - Vesely - Kinetic Tree Theory
- Importance measures - Birnbaum, Esary, Proschan, Fussel, Vesely
- Initiator/Enabler Theory - Lambert and Dunglinson
- FTA on PCs with GUI’s
- Automatic Fault Tree Construction
- Binary Decision Diagrams

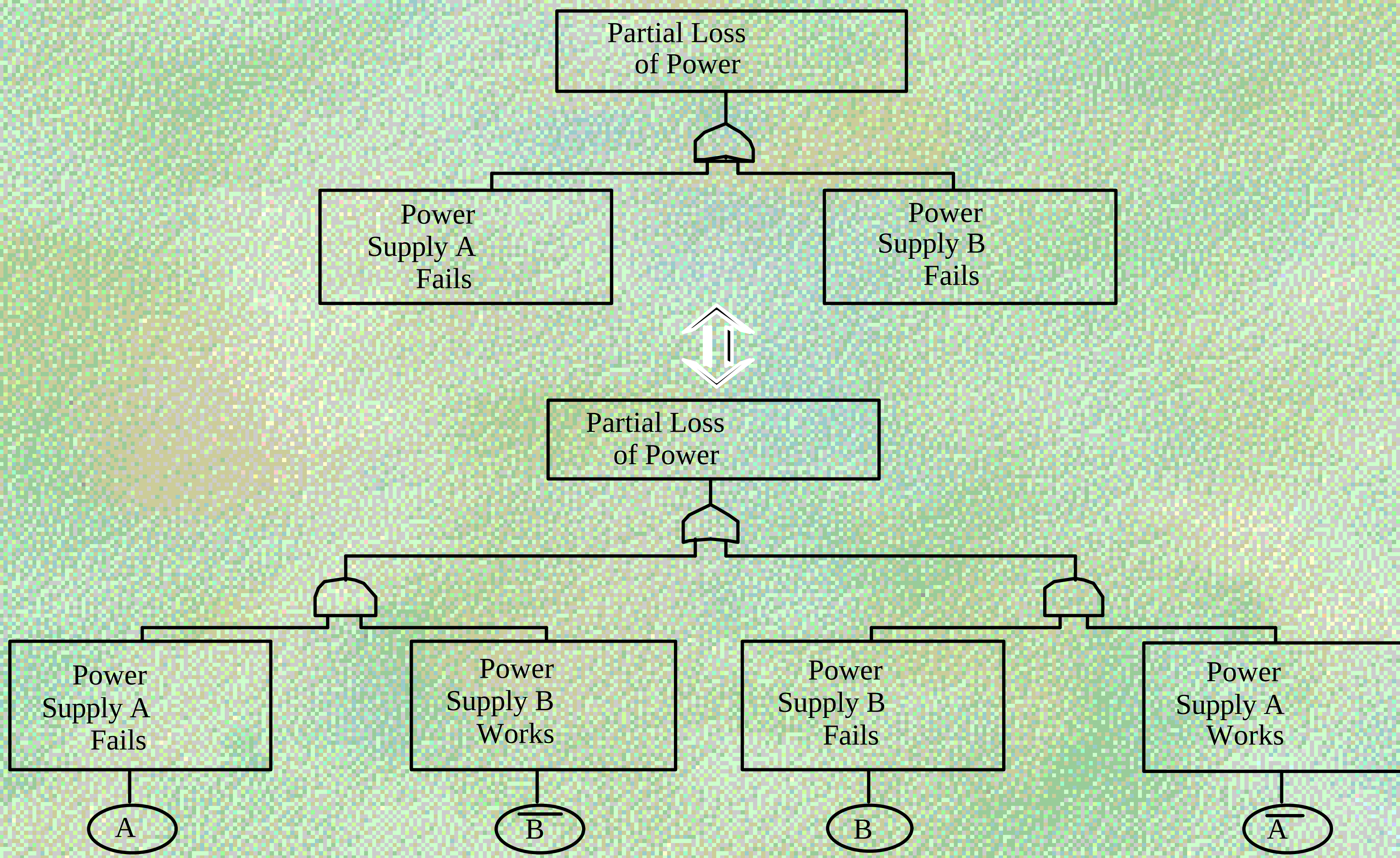
Fault Tree Example



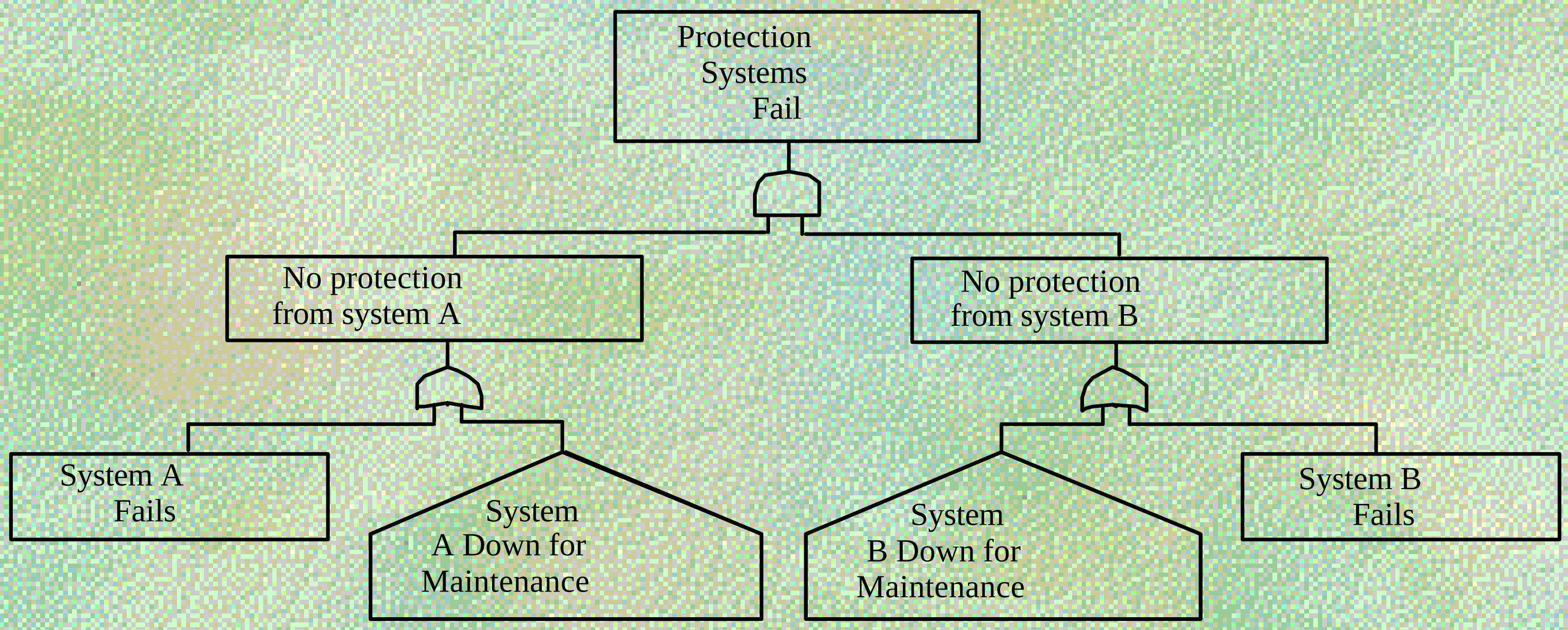
Voting Gates k/n



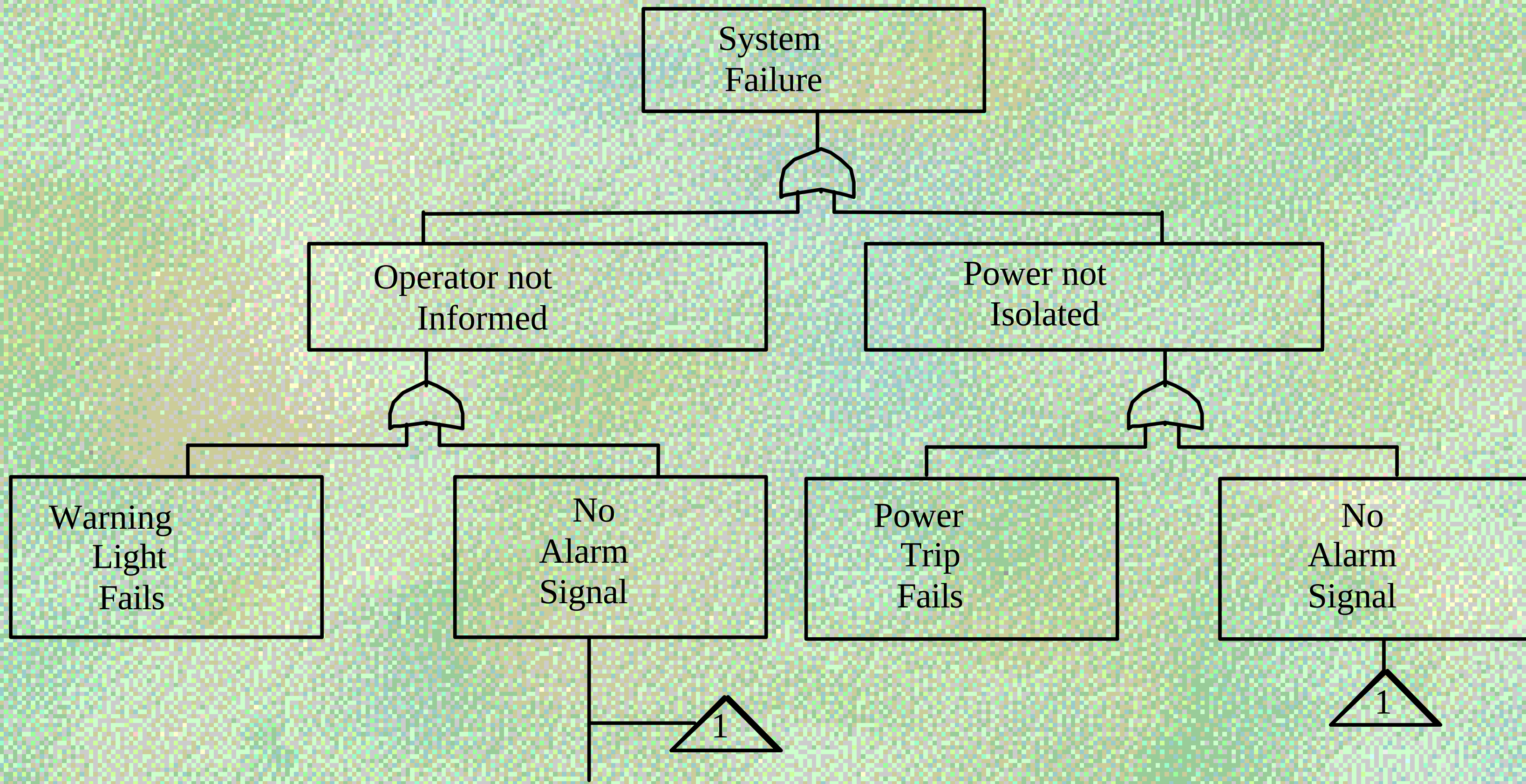
Exclusive OR Gate



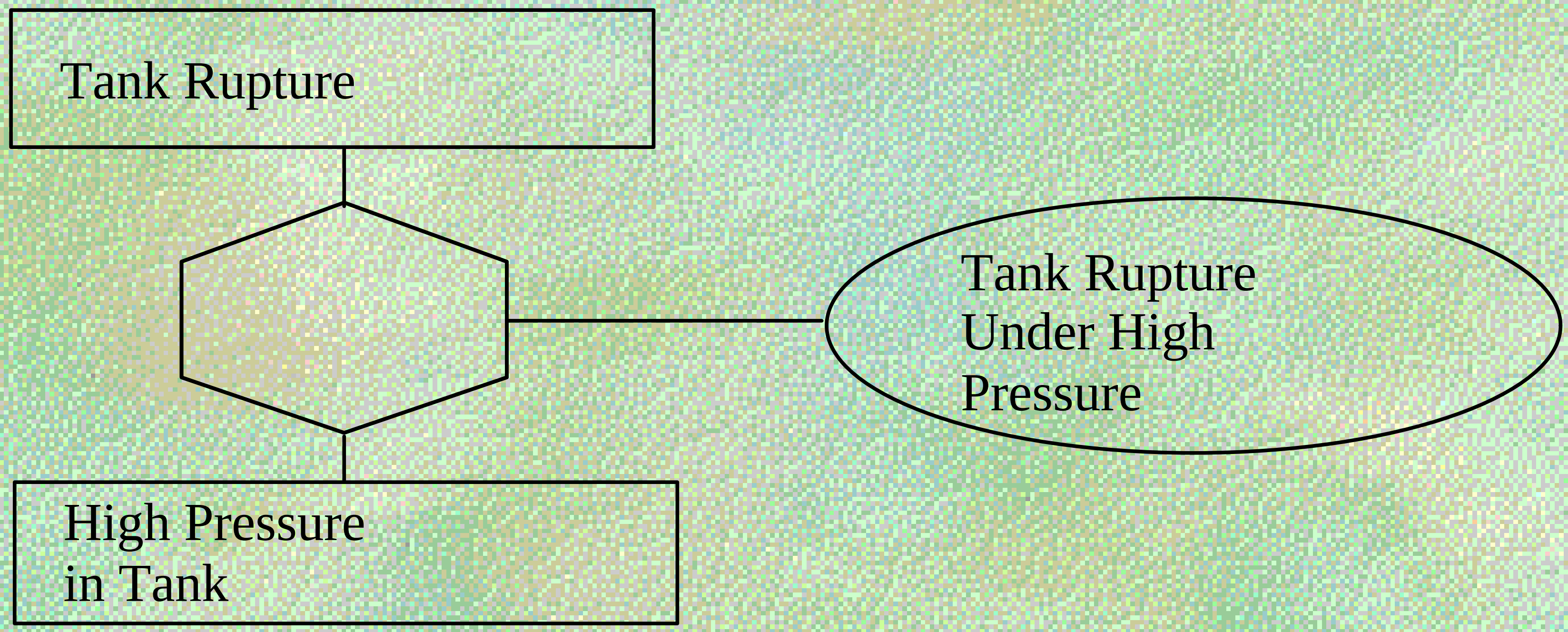
House Events



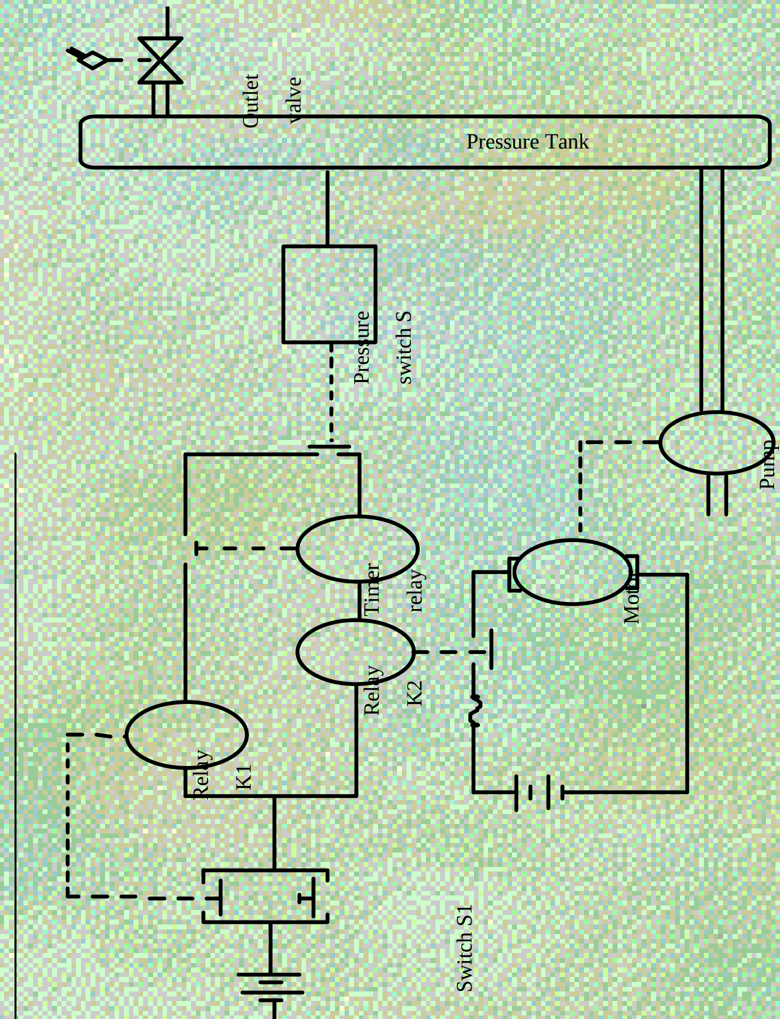
Transfer IN/OUT



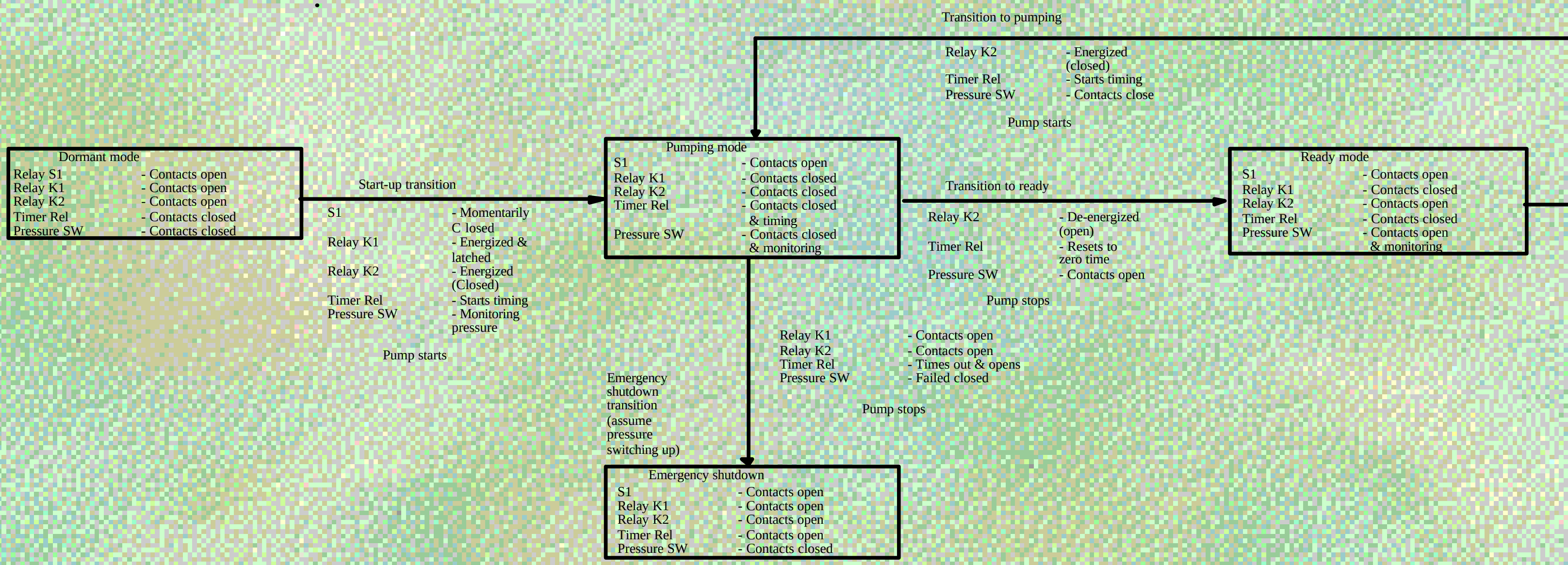
Inhibit Gate

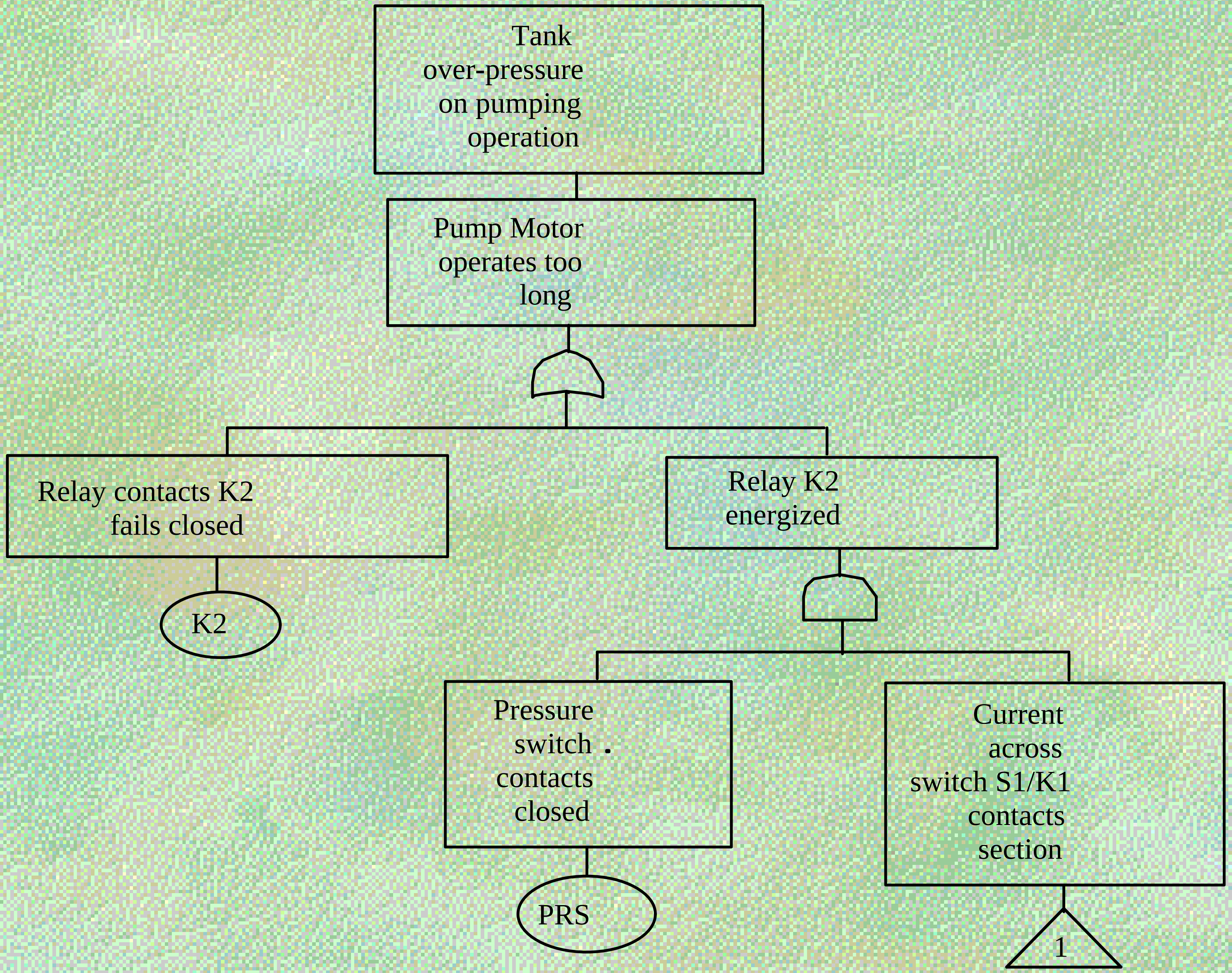


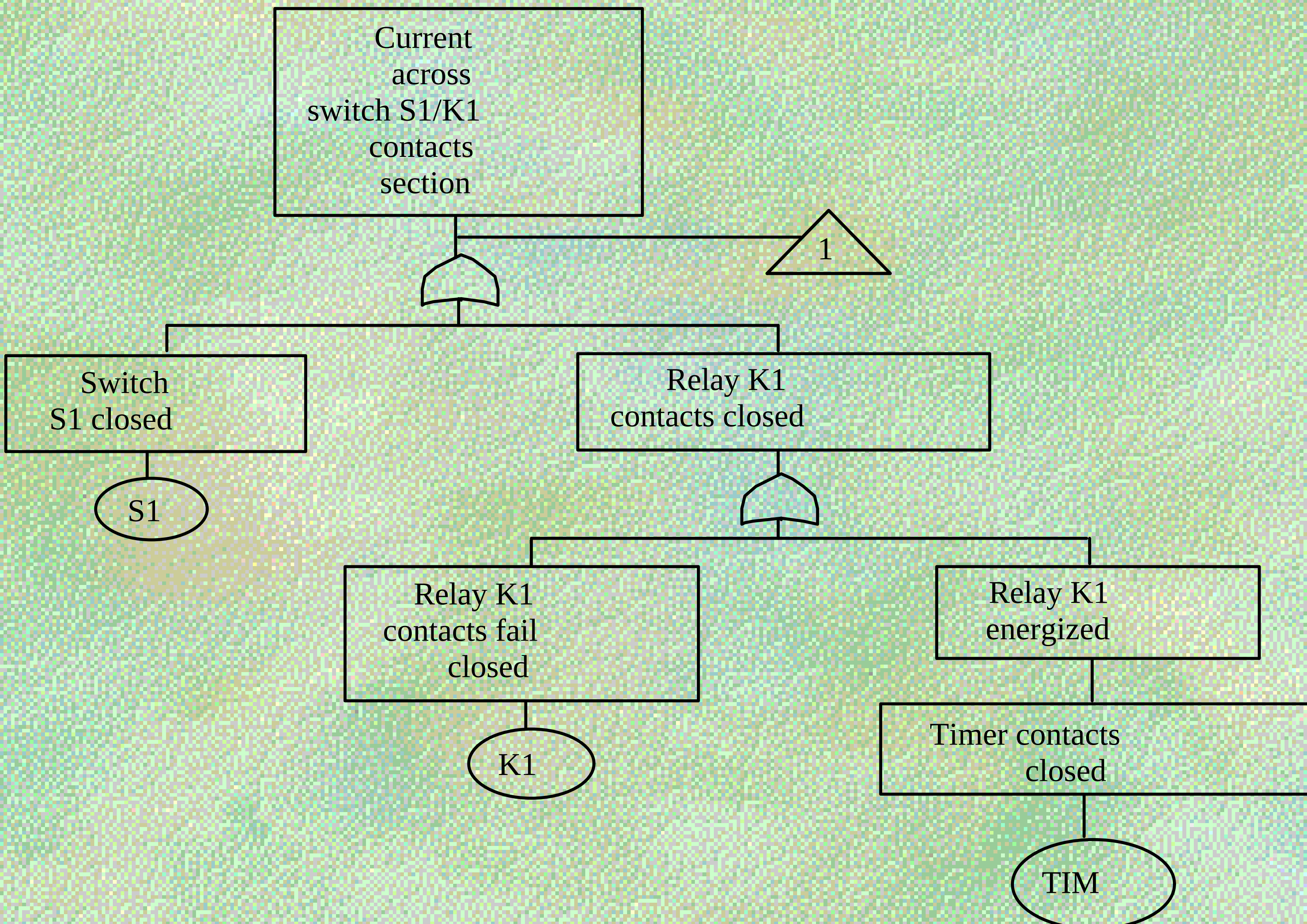
Pressure Tank Example



Circuit Actions

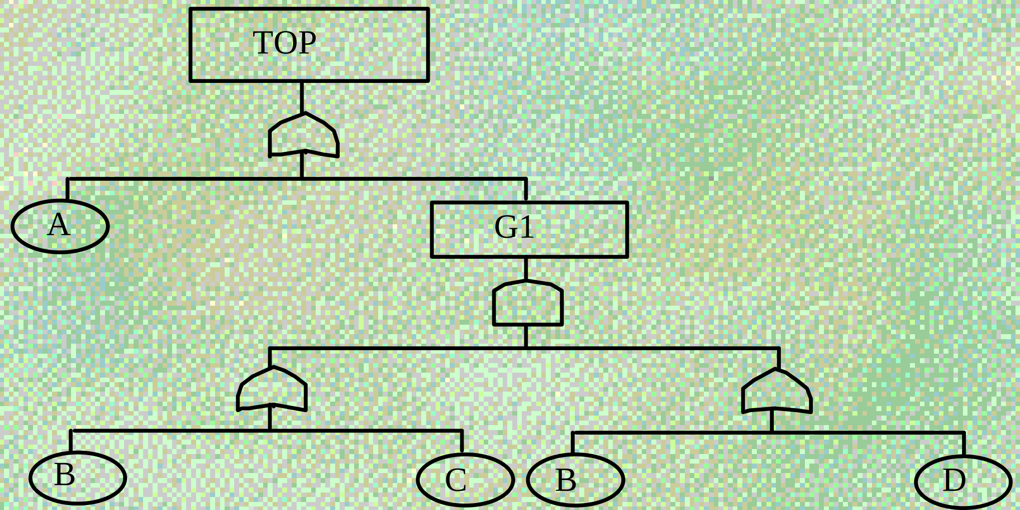



Tank over-pressure on pumping operation
Pump Motor operates too long
Relay contacts K2 fails closed
Relay K2 energized
K2
Pressure switch contacts closed
Current across switch S1/K1 contacts section
PRS
1


Current across switch S1/K1 contacts section
1
Switch S1 closed
S1
Relay K1 contacts closed
Relay K1 contacts fail closed
K1
Relay K1 energized
Timer contacts closed
TIM

Minimal Cut Sets

- Cut sets
  - A list of failure events such that if they occur then so does the top event.
- Minimal Cut Sets
  - A list of minimal, necessary and sufficient conditions for the occurrence of the top event.
- Example



List of possible failure combinations

	System State
A	F
B	F
C	W
D	W
AB	F
AC	F
AD	F
BC	F
BD	F
CD	F
ABC	F
ABD	F
ACD	F
BCD	F
ABCD	F

- Minimal Cut Sets

  A
  B
  CD

- We want a way to produce the minimal cut sets from the fault tree structure then:

  $$T = A + B + C.D$$

Qualitative Fault Tree Analysis

- Need to identify the min cut sets whose occurrence is most likely.
- Minimal Cut Set expression for the top event.

$$T = C_1 + C_2 + C_3 + \cdots + C_N$$

$$C_I, \quad I = 1, \cdots, N$$

e.g. T = A + BC + CD are the minimal cut sets

3 minimal Cut Sets

1 first order

2 second order

Laws of Boolean Algebra

- AND

\+ OR

Distributive

$(A + B) . (C + D) = A.C + A.D + B.C + B.D$

Idempotent

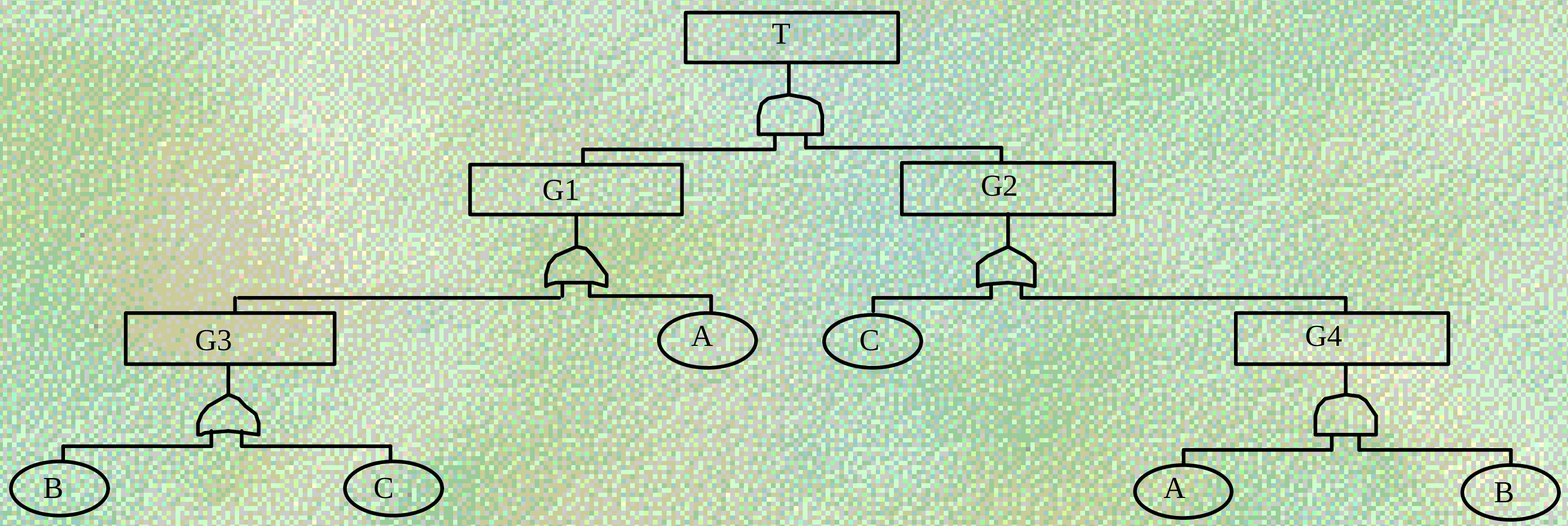
$A + A = A$

$A . A = A$

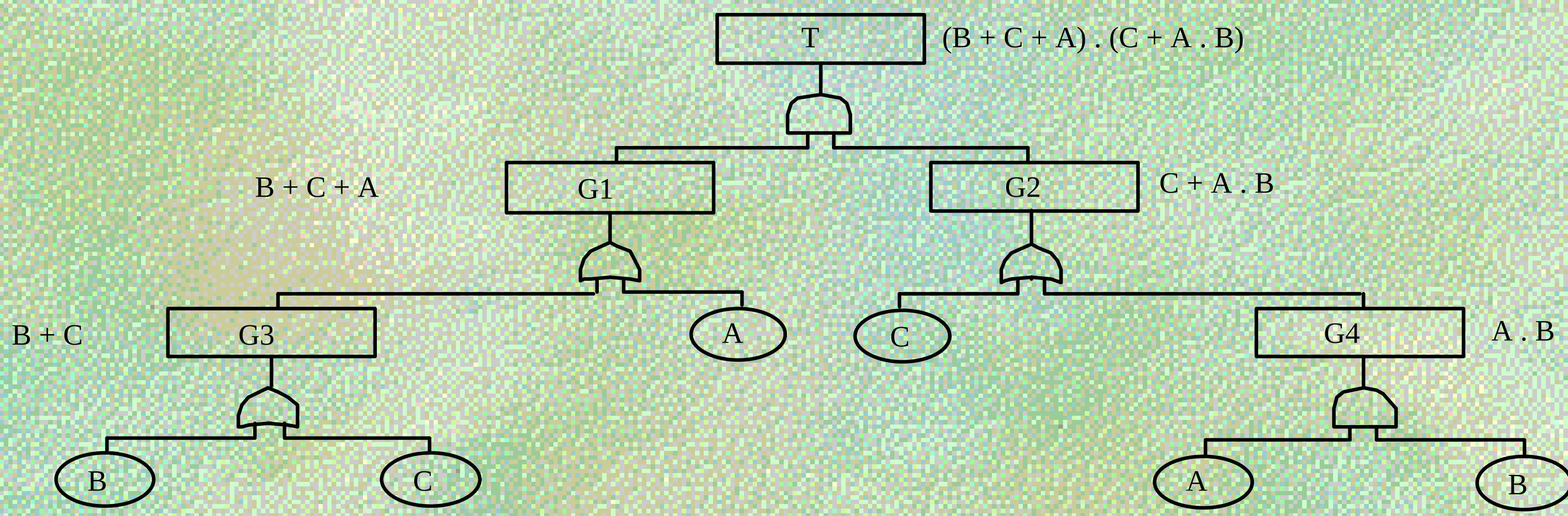
Absorption

$A + A . B = A$

Example



Bottom-up method



$$\begin{aligned} TOP &= (B + C + A) \,.\, (C + A \,.\, B) \\ &= B \,.\, C + B \,.\, A \,.\, B + C \,.\, C + C \,.\, A \,.\, B \\ &\qquad + A \,.\, C + A \,.\, A \,.\, B \end{aligned}$$

$(A \,.\, A = A)$

$$\begin{aligned} &= B \,.\, C + A \,.\, B + C + C \,.\, A \,.\, B \\ &\qquad + A \,.\, C + A \,.\, B \end{aligned}$$

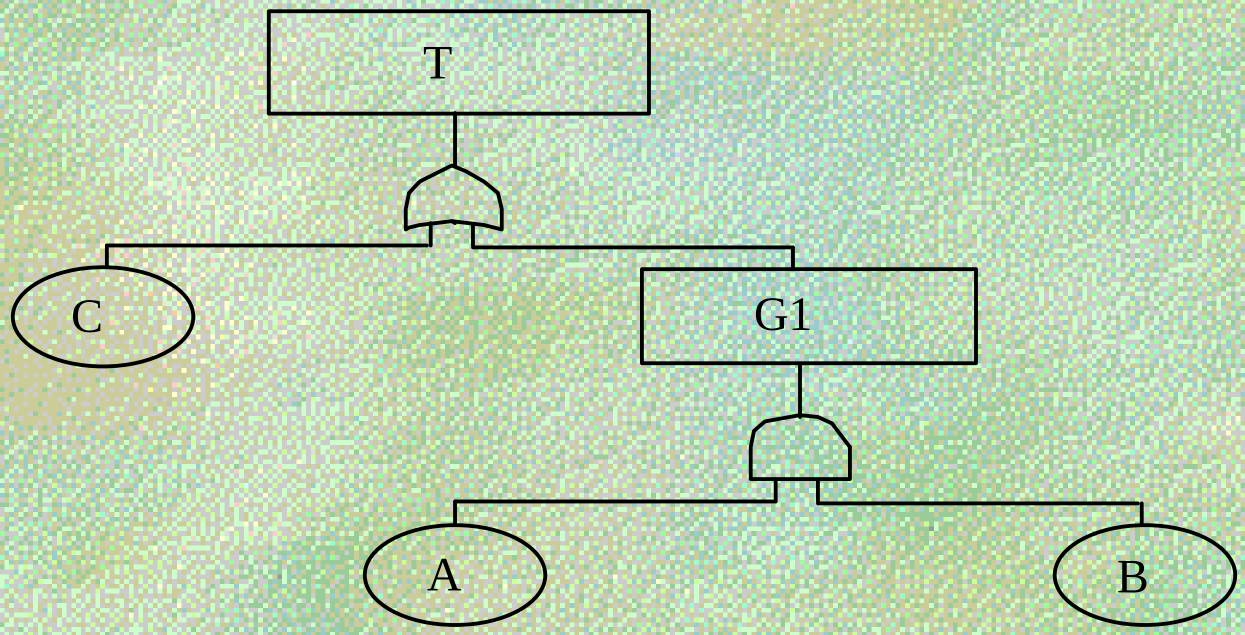
$(A + A = A)$

$$TOP = B \,.\, C + A \,.\, B + C + C \,.\, A \,.\, B + A \,.\, C$$

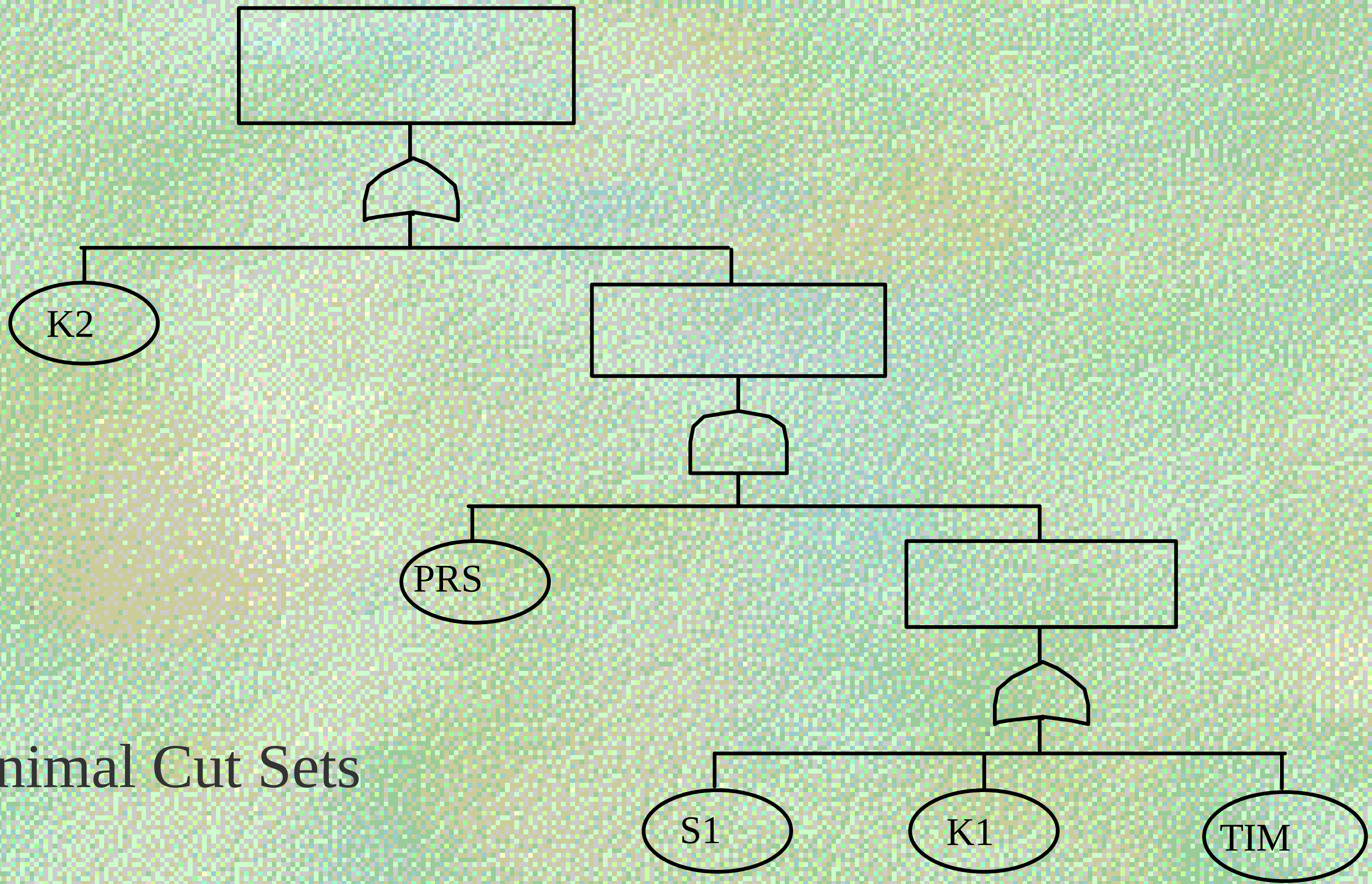
$(A + A \,.\, B = A)$

$$TOP = A \,.\, B + C$$

The tree could have been drawn:



Pump System Example

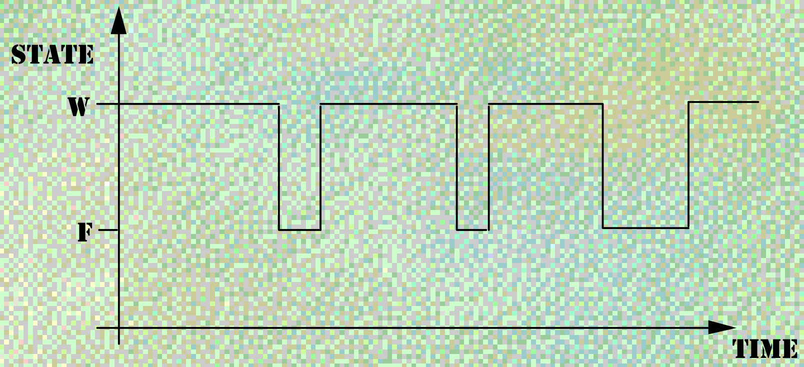


Minimal Cut Sets

K2
PRS S1
PRS K1
PRS TIM

Component Performance Characteristics

Typical History of a Repairable Component



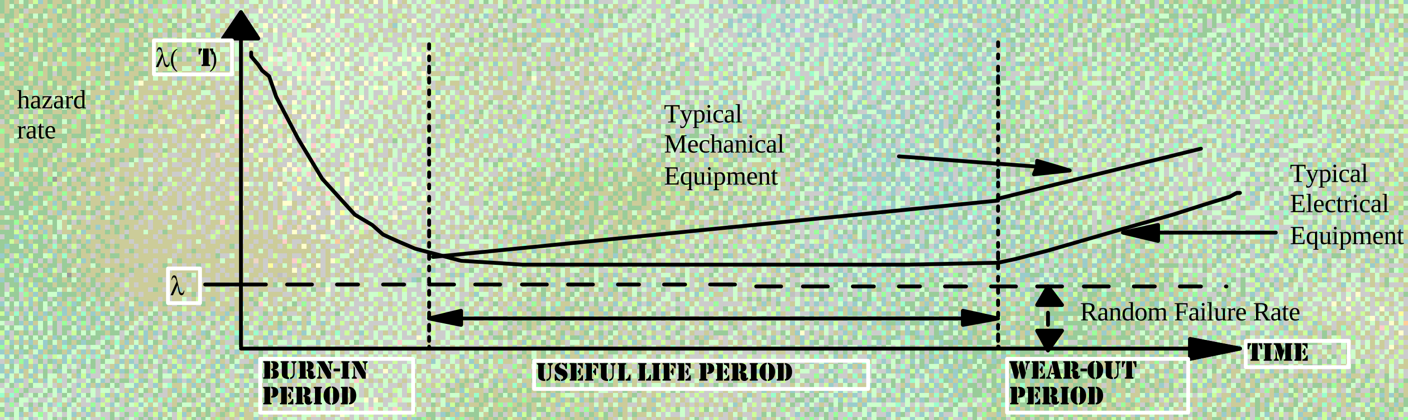
Downtime Depends on

- Failure detection time
- Availability of Maintenance team
- **REPAIR TIME** { **OBTAIN REPLACEMENT**, **INSTALLATION**
- System Test Time

Performance indicators

- Rate at which failures occur
- Measure of expected up-time

The Failure Process



For useful life period

Unreliability $F(t) = 1 - e^{-\lambda t}$

(Density Function) $f(t) = \lambda e^{-\lambda t}$

Reliability

$$R(t) = 1 - F(t)$$

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

$$= \frac{1}{\lambda}$$

Mean Time to Failure

$\lambda(t) =$ Conditional failure rate (hazard rate)

Probability that a component fails in
(t, t + dt) given that it was working at t

Maintenance Policies

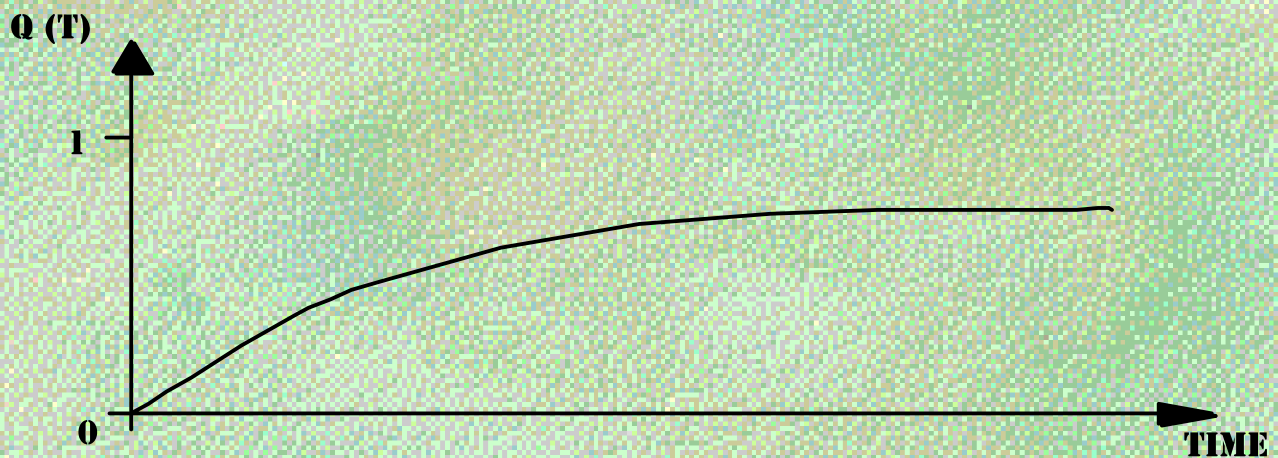
1. No Repair

Q (T) - UNAVAILABILITY

F (T) - UNRELIABILITY

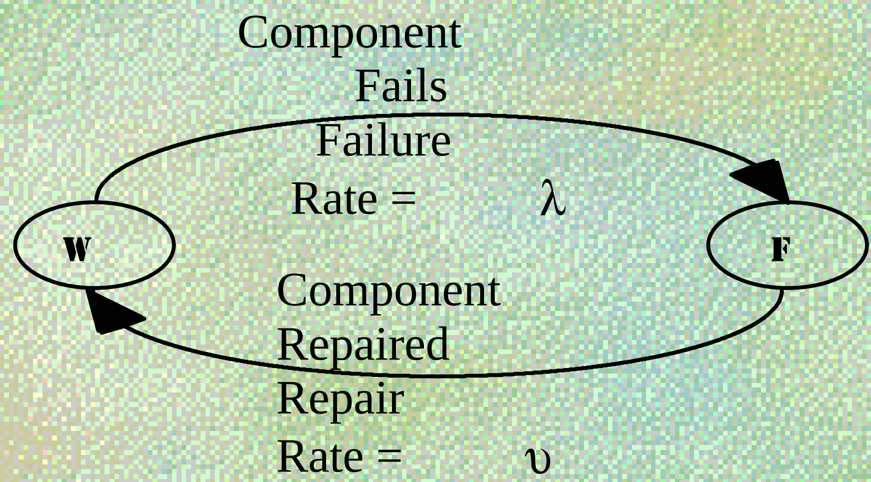
$$F(T) = 1 - E^{-\lambda T}$$

$$Q(T) = F(T)$$



Repairable Components

Failure/Repair Process



1. Only one transition can occur in a small period of time Δt.
2. Change between states is instantaneous.
3. Following repair components are as good as new.

2. Revealed Failures - unscheduled maintenance

λ - FAILURE RATE

ν - REPAIR RATE

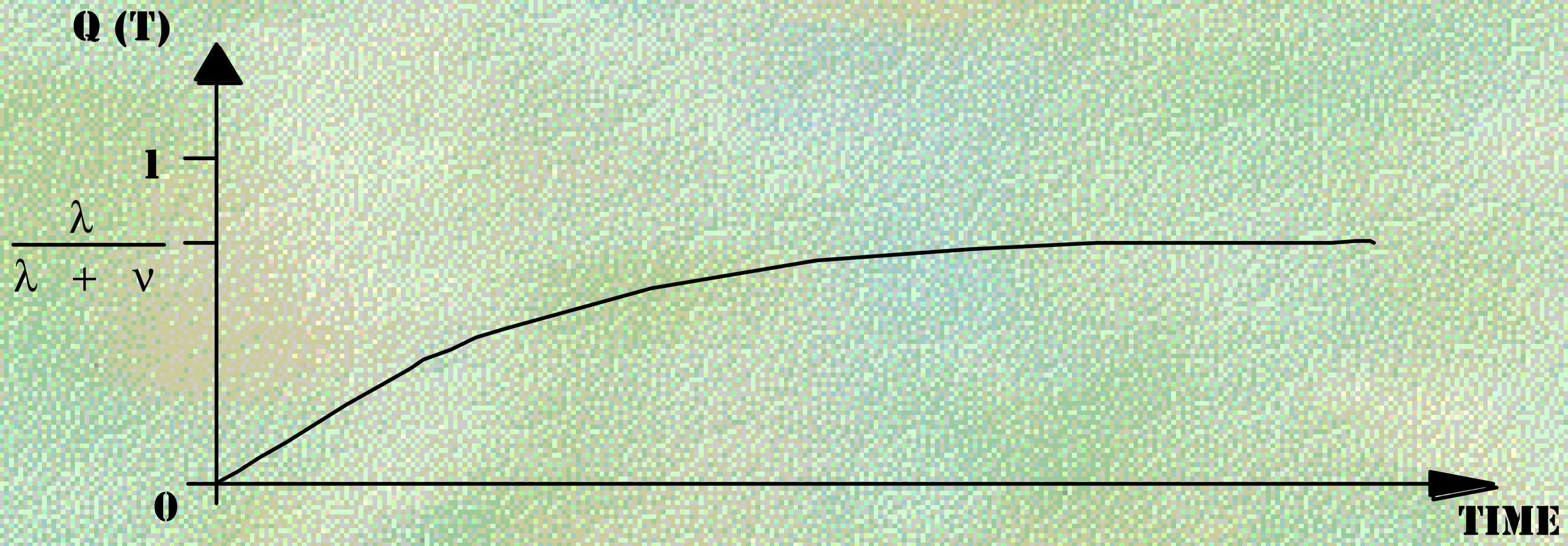
μ - MEAN TIME TO FA

τ - MEAN TIME TO RE

$Q(t)$ - UNAVAILABILITY

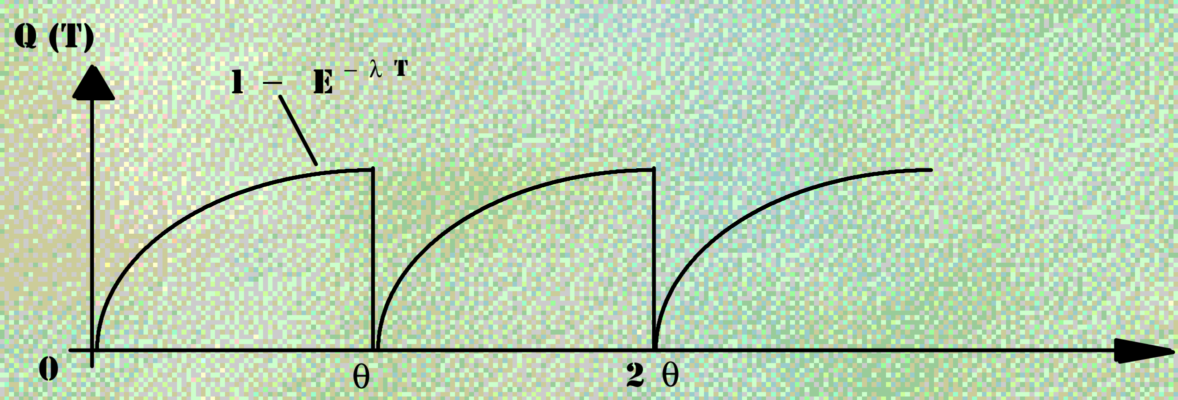
$$Q(t) = \frac{\lambda}{\lambda + \nu}\left(1 - e^{-(\lambda+\nu)t}\right)$$

AT STEADY STATE $Q = \dfrac{\lambda}{\lambda + \nu} = \dfrac{\tau}{\mu + \tau} \approx \lambda\tau$


Q (T)
1
λ
λ + ν
0
TIME

3. Unrevealed or Dormant Failures - Scheduled Maintenance

θ - TIME BETWEEN INSPECTIONS



$Q \approx \lambda\tau$

(for revealed failures)

Mean time to restore

$=$ MEAN DETECTION TIME + MEAN TIME TO REP

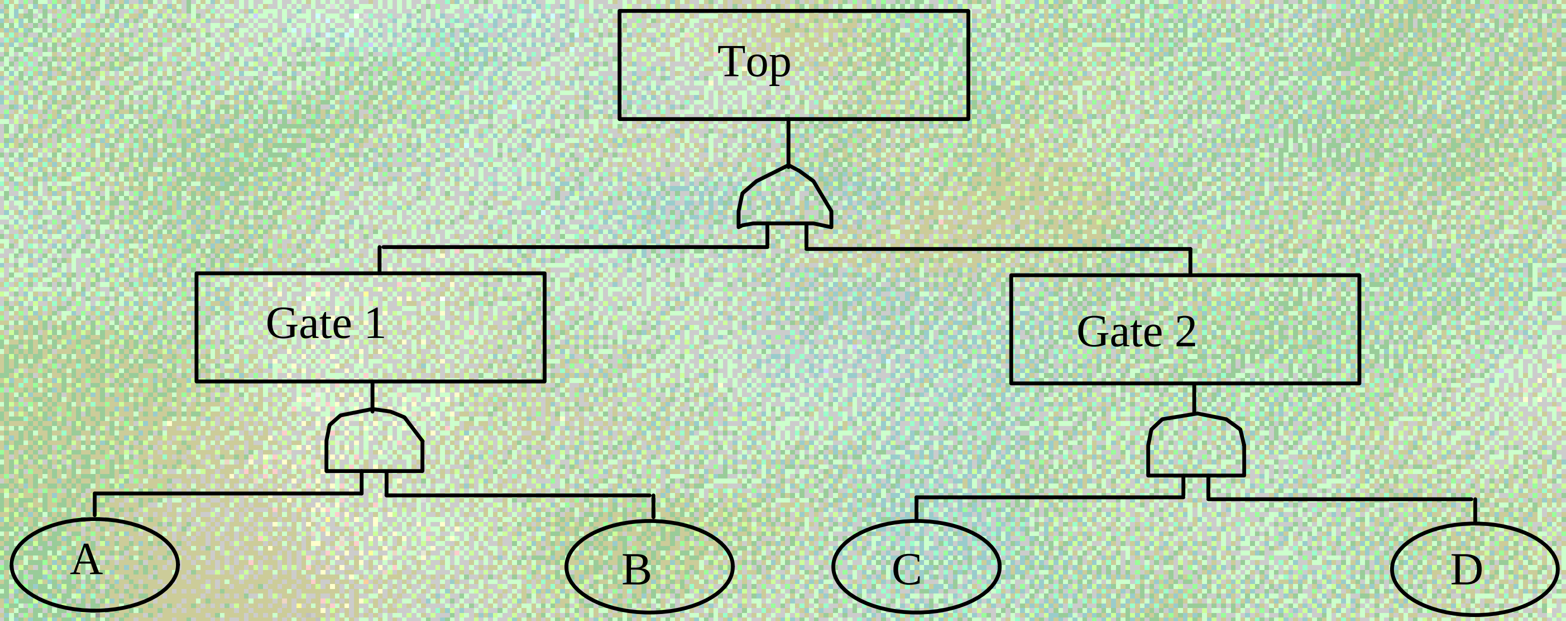
$$= \quad \frac{\theta}{2} \quad + \quad \tau$$

$$\therefore \quad Q_{AV} = \lambda\left(\frac{\theta}{2} + \tau\right)$$

IN GENERAL $\theta >> \tau$ $\qquad Q_{AV} \approx \dfrac{\lambda\theta}{2}$

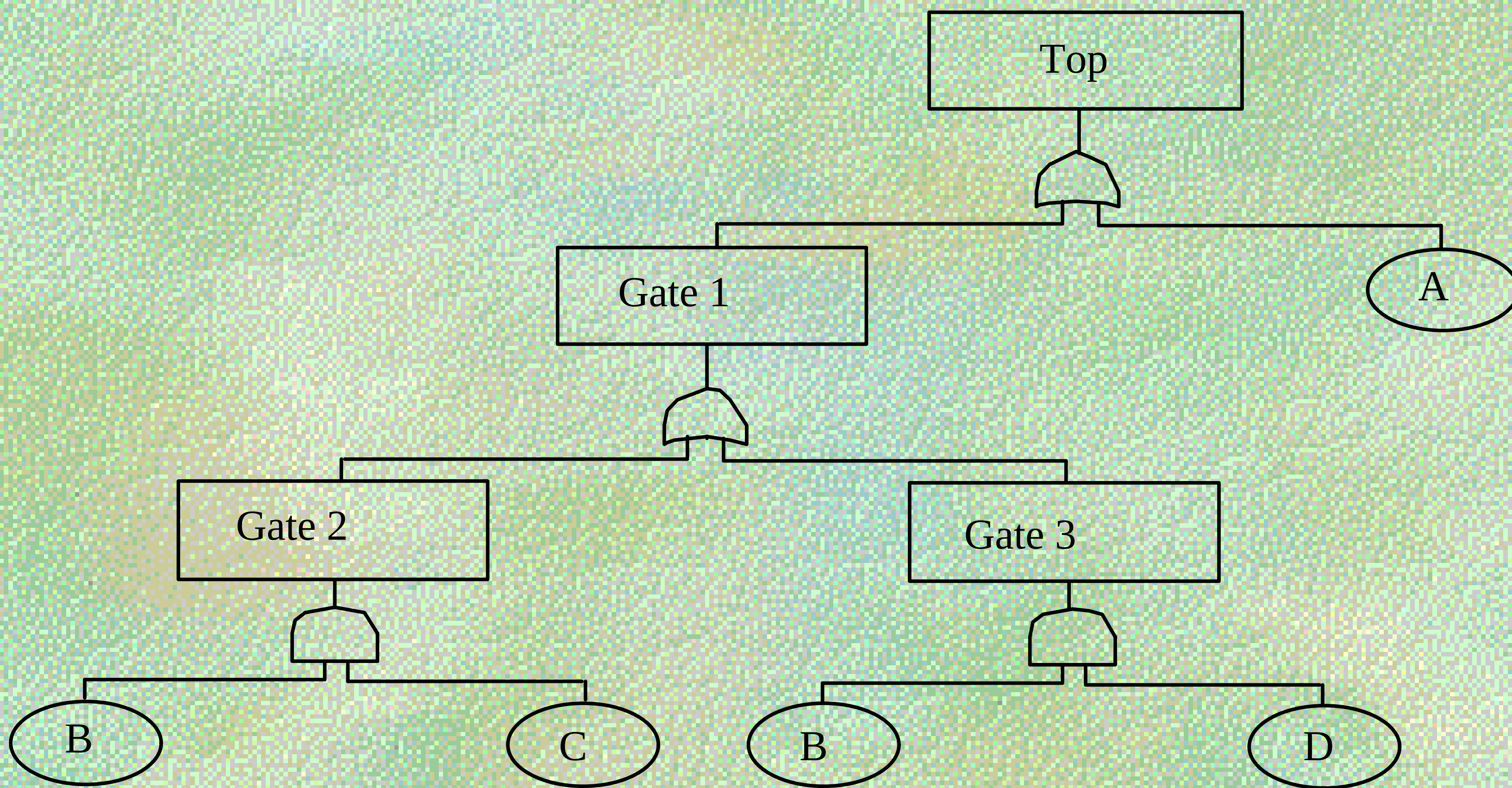
$$\left[\text{MORE ACCURATE ALTERNATIVE } Q_{AV} = 1 - \frac{(1 - e^{-\lambda\theta})}{\lambda\theta}\right]$$

Top Event Probability



All basic event independent with prob 0.1

P(Gate 1) = P(A) . P(B) = 0.01
P(Gate 2) = P(C) . P(D) = 0.01
And P(TOP) = P(Gate 1 OR Gate 2)
= P(Gate 1) + P(Gate 2) -
P(Gate 1) . P(Gate 2)
= 0.01 + 0.01 - 0.0001
= 0.199



all basic events are independent and

$$Q_A = Q_B = Q_C = Q_D = 0.1$$

The minimal cut sets of the fault tree are:

$$\begin{array}{ll} A & \\ B & C \\ B & D \end{array}$$

$$T = A + BC + BD$$

$$Q_S(T) = P(T) = P(A + BC + BD)$$

Using three terms of the inclusion-exclusion expansion gives:

$$= \underbrace{[P(A) + P(BC) + P(BD)]}_{\text{1ST TERM}}$$

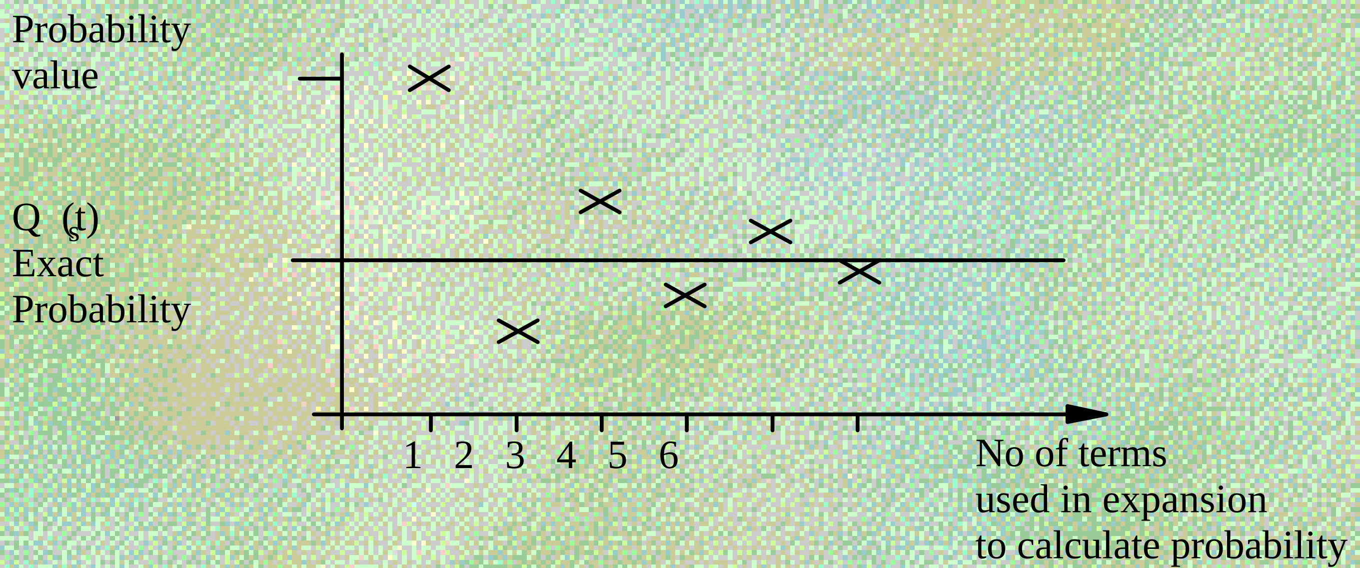
$$- \underbrace{[P(ABC) + P(ABD) + P(BCD)]}_{\text{2ND TERM}}$$

$$+ \underbrace{[P(ABCD)]}_{\text{3RD TERM}}$$

$$= [0.1 + 0.01 + 0.01] - [0.001 + 0.001 + 0.001] + [0.0001]$$

$$= [0.12] - [0.003] + [0.0001]$$

$$= 0.1171$$



Probability
value
Q (t)
s
Exact
Probability
1 2 3 4 5 6
No of terms
used in expansion
to calculate probability

Convergence of Inclusion-Exclusion Expansion

$$P(T) = \sum_{i=1}^{N_c} P(C_i) - \sum_{i=2}^{N_c} \sum_{j=1}^{i-1} P(C_i \cap C_j) + \cdots (-1)^{N_c - 1} P(C_1 \cap C_2 \cap \cdots \cap C_{N_c})$$

$$Q_{\text{RARE EVENT}} = \sum_{i=1}^{N_c} P(C_i)$$

$$Q_{\text{LOWER}} = \sum_{i=1}^{N_c} P(C_i) - \sum_{i=2}^{N_c} \sum_{j=1}^{i-1} P(C_i \cap C_j)$$

N_C – NO OF MIN CUT SETS

$$Q_{EXACT} = 0.1171$$

$$Q_{RARE\ EVENT} = 0.12$$

$$Q_{LOWER} = 0.117$$

Minimal Cut Set Upper Bound

$$
\begin{aligned}
Q_{MCSU} &= 1 - \prod_{I=1}^{N_c} (1 - P(C_I)) \\
&= 1 - (1 - 0.1)(1 - 0.01)(1 - 0.01) \\
&= 0.11791
\end{aligned}
$$

$$Q_{LOWER} \le Q_{EXACT} \le Q_{MCSU} \le Q_{RARE\ EVE}$$

Pump System Example

Component probabilities

Relay K1 contacts	K1	1×10^{-4}
Relay K2 contacts	K2	1×10^{-4}
Pressure switch	PRS	5×10^{-4}
Timer relay	TIM	3×10^{-4}
Switch	S1	5×10^{-3}

Minimal Cut Sets

K2		1×10^{-4}
PRS	S1	2.5×10^{-6}
PRS	K1	5.0×10^{-8}
PRS	TIM	1.5×10^{-7}

Top Event Probability

Rare Event

$$Q_{SYS} = \sum_{I=1}^{N_C} Q_{C_I}$$

$$= 1.027 \times 10^{-4}$$

Minimal Cut Set Upper Bound

$$Q_{SYS} = 1 - \prod_{I=1}^{N_C} (1 - Q_{C_I})$$

$$= 1.027 \times 10^{-4}$$

Exact

$$Q_{SYS} = 1.026987 \times 10^{-4}$$

Importance Measures

- Critical System State

  For component i is a state of the remaining (n - 1) components such that the failure of component i causes the system to go from a working to a failed state.

- Birnbaums Measure (I_B)

  The probability that the system is in a critical state for the component.

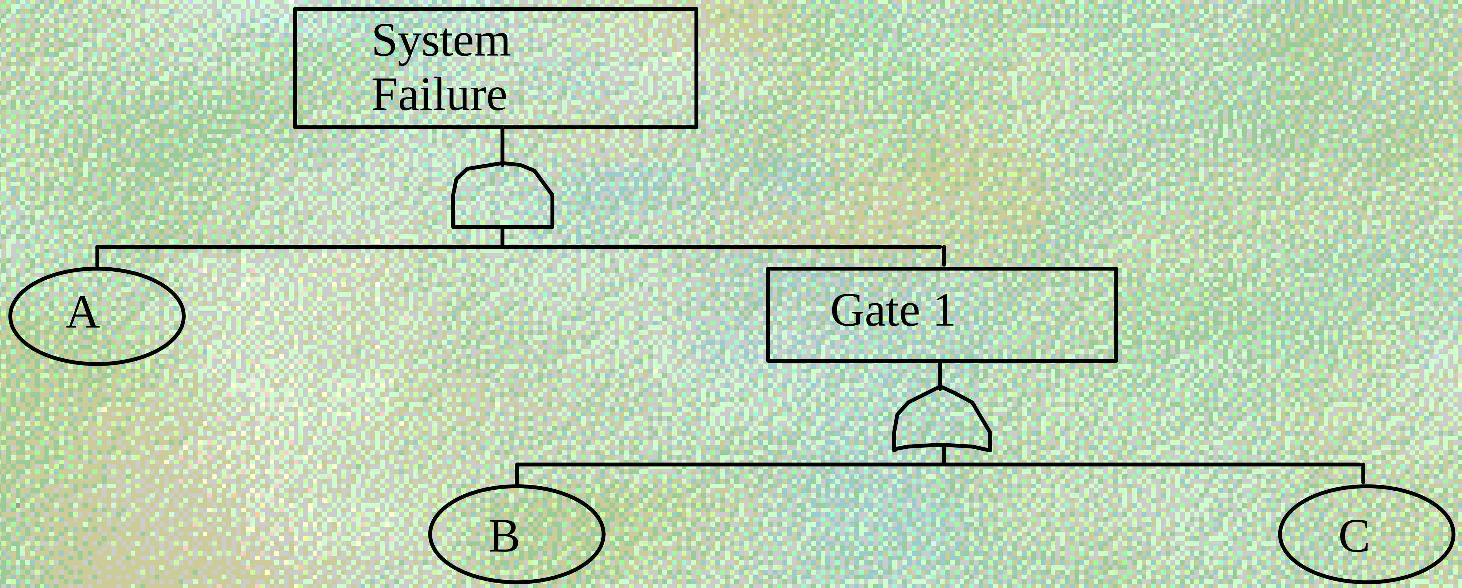
$$I_{B_I} = \frac{\partial Q_{SYS}}{\partial Q_I}$$

I_{B_I} - Birnbaum importance measure for component i

Q_{SYS} - System unavailability

Q_I - Component unavailability

Example



$q_A = q_B = q_C = 0.1$

Minimal Cut Sets

AB
AC

$$Q_{SYS} = P(AB + AC)$$

$$= Q_A Q_B + Q_A Q_C - Q_A Q_B Q_C \qquad = 0.019$$

$$I_{B_A} = \frac{\partial Q_{SYS}}{\partial Q_A} = Q_B + Q_C - Q_B Q_C \qquad = 0.19$$

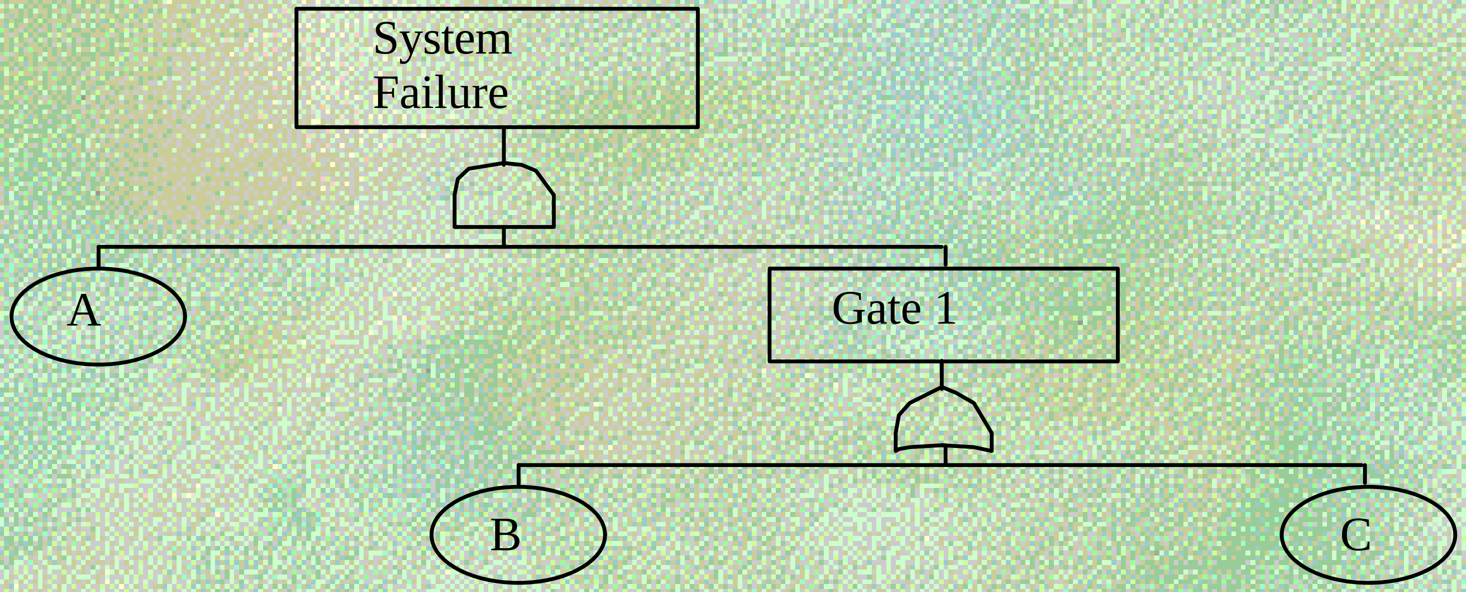
$$I_{B_B} = \frac{\partial Q_{SYS}}{\partial Q_B} = Q_A (1 - Q_C) \qquad = 0.09$$

$$I_{B_C} = \frac{\partial Q_{SYS}}{\partial Q_C} = Q_A (1 - Q_B) \qquad = 0.09$$

Fussell-Vesely Measure (I_{FV})

Probability of the union of all Minimal Cut Sets containing the component given that the system has failed.

Example



$q_A = q_B = q_C = 0.1$

Minimal Cut Sets

AB
AC

$$I_{FV_A} = \frac{P(AB + BC)}{Q_{SYS}} = \frac{Q_{SYS}}{Q_{SYS}} = 1.0$$

$$I_{FV_B} = \frac{P(AB)}{Q_{SYS}} = \frac{Q_A Q_B}{Q_{SYS}} = \frac{0.01}{0.019} = 0.526$$

$$I_{FV_C} = \frac{P(AC)}{Q_{SYS}} = \frac{Q_A Q_C}{Q_{SYS}} = \frac{0.01}{0.019} = 0.526$$

Pump System Example

Importance Measures

	Fussell Vesely	Birnbaum
K2	0.974	0.9999
PRS	0.026	5.397×10^{-3}
S1	0.024	4.9975×10^{-4}
TIM	0.0015	4.974×10^{-4}
K1	0.0005	4.973×10^{-4}

Session 2: Advanced Features

Minimal Cut Set Failure Frequency

$W_{C_K}(T)$ – UNCONDITIONAL FAILURE

OF CUT SET K

N – COMPONENTS IN MIN CUT S

$$W_{C_K}(T) = \sum_{I=1}^{N} W_I(T) \left(\prod_{\substack{J=1 \\ J \neq I}}^{N} Q_J(T) \right)$$

Example Min Cut Set 1 = ABC

$$W_{C_1} = W_A Q_B Q_C + W_B Q_A Q_C + W_C Q_A Q_B$$

w(t) - unconditional failure intensity

The probability that a component fails in
(t, t + dt)

$$w(t) = \lambda(t)[1 - Q(t)]$$

Expected Number of Failures W(0, t)

$$W(0,t) = \int_0^t w(u)\,du$$

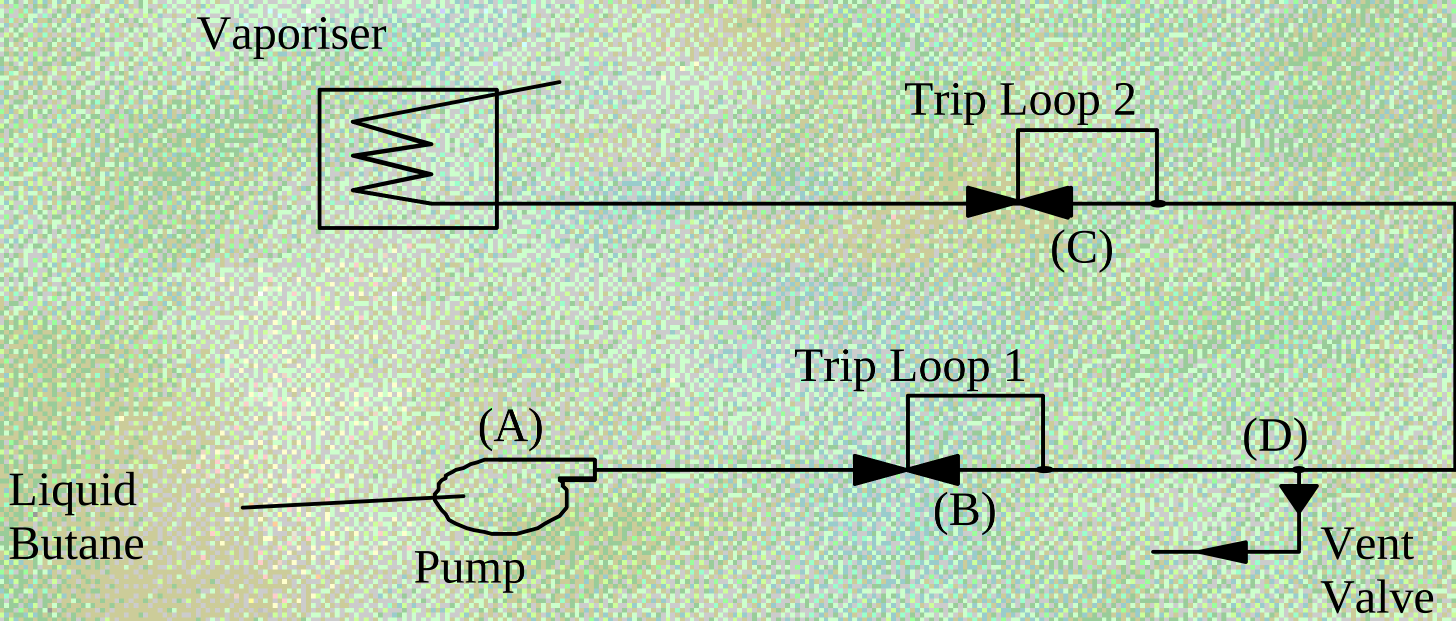
Top Event Failure Frequency

(upper bound approximation)

$$W_{SYS} = \sum_{I=1}^{N_C} W_{C_I} \left(1 - \prod_{\substack{J=1 \\ J \neq I}}^{N_C} (1 - Q_{CJ})\right)$$

N_C – NO OF MIN CUT SETS

Initiator/Enabler Theory



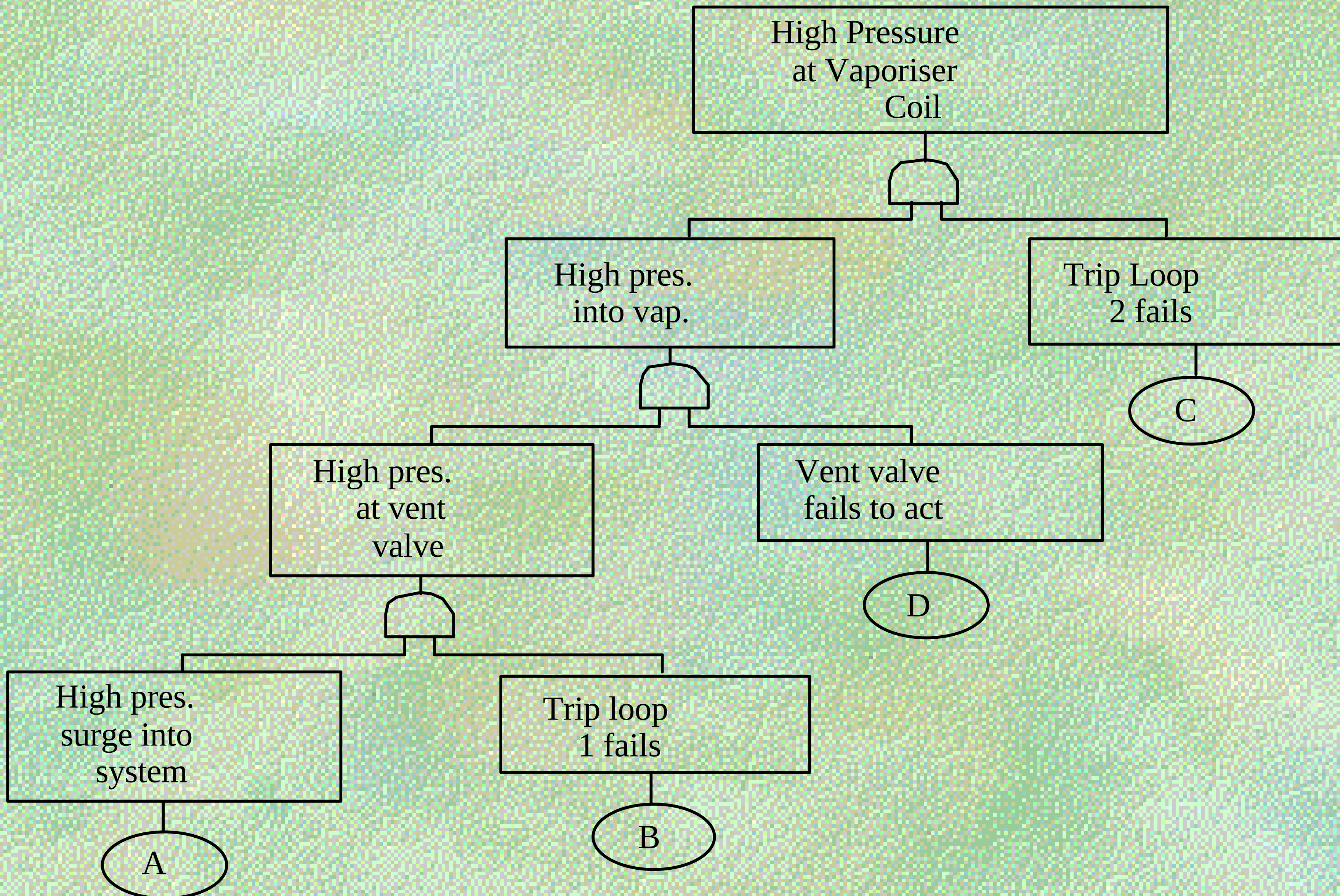
Failure Modes:	Pump Surge (control system failure)	A
	Trip Loop 1 fails to act	B
	Trip Loop 2 fails to act	C
	Vent Valve fails to act	D

Component Data

	λ	τ	$W = \lambda(1 - Q)$
A			6.667×10^{-3}
B			9.091×10^{-3}
C			9.091×10^{-3}
D			9.091×10^{-3}

$+ \quad Q = \dfrac{\lambda\tau}{\lambda\tau + 1}$

$* \quad Q = \lambda(\tau + \dfrac{\theta}{2})$


High Pressure at Vaporiser Coil
High pres. into vap.
Trip Loop 2 fails
C
High pres. at vent valve
Vent valve fails to act
D
High pres. surge into system
Trip loop 1 fails
A
B

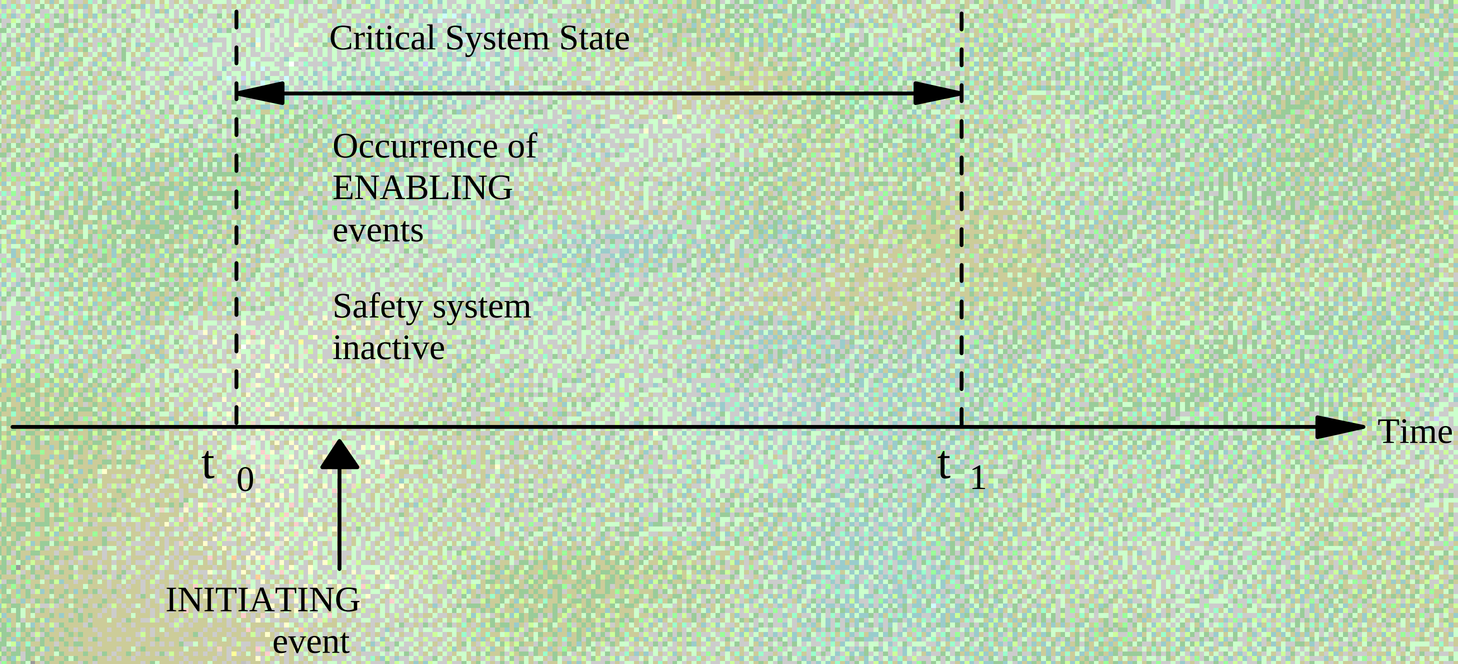
Conventional Approach

$$
\begin{aligned}
W_S(t) &= W_{C_1}(t) \\
&= \sum_{j=1}^{4} W_j(t) \prod_{\substack{i=1 \\ i \neq j}}^{4} Q_i(t) \\
&= W_A Q_B Q_C Q_D + W_B Q_A Q_C Q_D + W_C Q_A Q_B Q_D \\
&\quad + W_D Q_A Q_B Q_C \\
&= 5.0075 \times 10^{-6} + 2.5037 \times 10^{-5} \\
&\quad + 2.5037 \times 10^{-5} + 2.5037 \times 10^{-5} \\
&= 8.012 \times 10^{-5}
\end{aligned}
$$

Expected number of failures over 10 years

$$
\begin{aligned}
W(0,87600) &= \int_0^{87600} 8.012 \times 10^{-5}\, dt \\
&= 7.02
\end{aligned}
$$

The Window for Initiating Events



Initiating Events

Initiating events perturb system variables and place a demand on control/protection Systems to respond.

Enabling Events

Enabling events are inactive control/ Protection systems which permit initiating Events to cause the top event.

Using initiator/enabler theory

$$
\begin{aligned}
W_S(T) &= W_{C_1}(T) \\
&= W_A Q_B Q_C Q_D \\
&= 5.0075 \times 10^{-6}
\end{aligned}
$$

Expected Number of Failures over 10 years

$$
\begin{aligned}
W(0,87600) &= \int_0^{87600} 5.0075 \times 10^{-6} DT \\
&= 0.4387
\end{aligned}
$$

Not Logic

Noncoherent Fault Trees

Barlow - “A physical system would be quite unusual (or poorly designed) if improving the performance of a component (ie by replacing a failed component by a functioning component) causes the system to deteriorate (ie change from a functioning to a failed state)”

Example

Min Cut Set $AB\overline{C}$

Is not a coherent structure as

$AB\overline{C} \rightarrow$ SYSTEM FAILS

$ABC \rightarrow$ SYSTEM WORKS

Coherent structure consist of only:

- AND gates
- OR gates

Noncoherent Structures

Are those which do not conform to the definition of a coherent structure

This occurs if the NOT operator is used or implied

eg XOR

Laws of Boolean Algebra - Not Logic

$$A + \overline{A} = 1$$

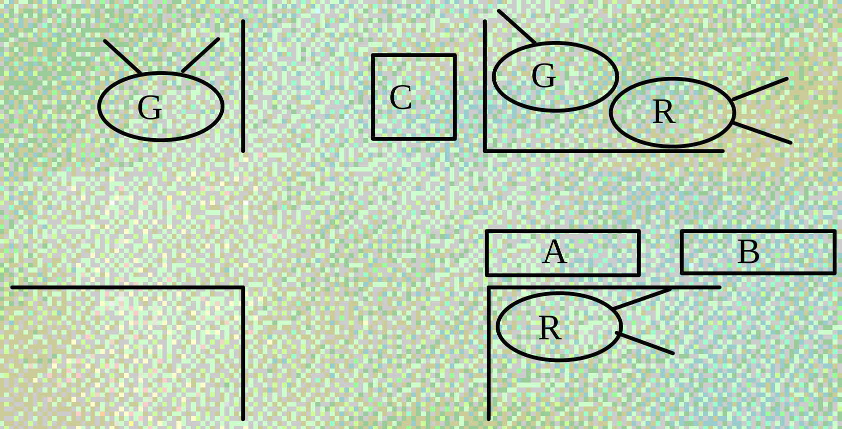
$$A . \overline{A} = 0$$

De Morgan's Laws

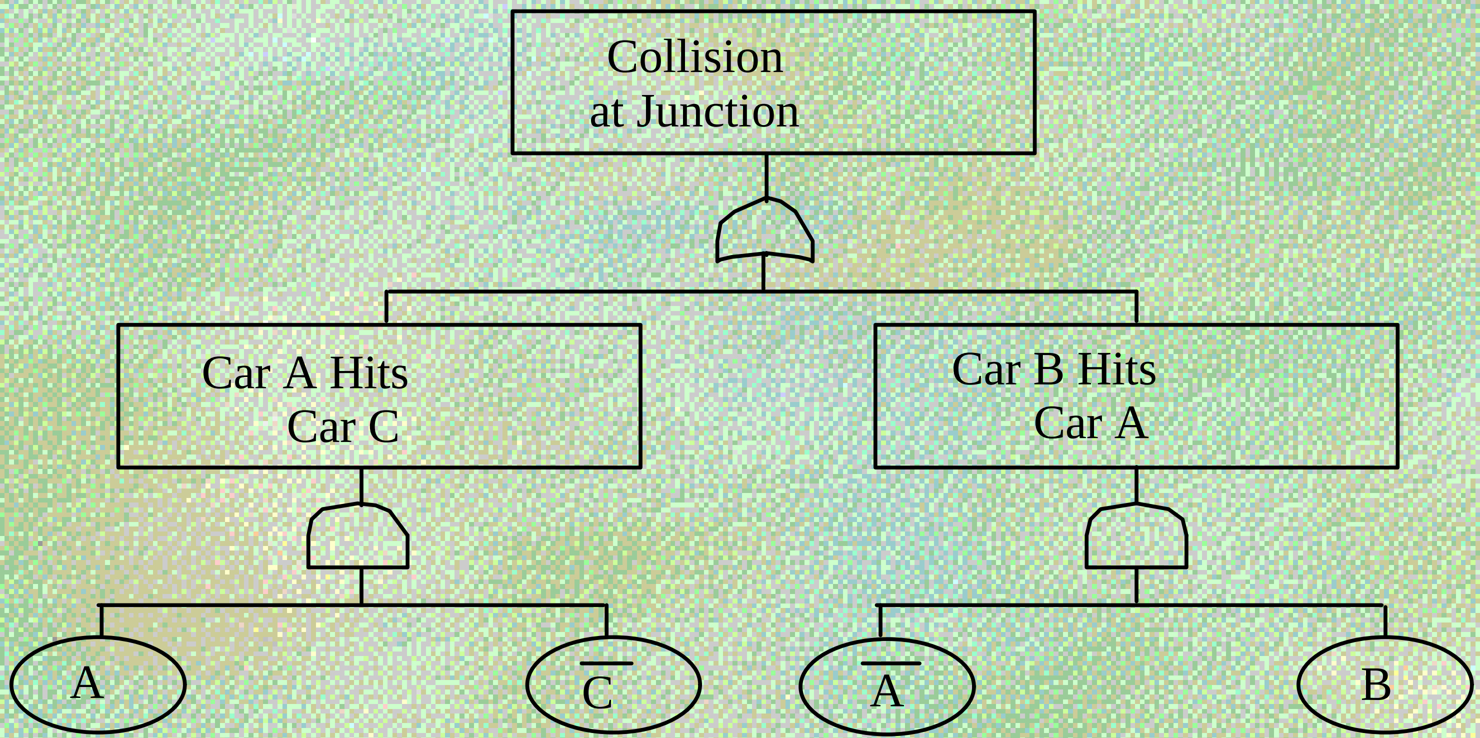
$$\overline{(A + B)} = \overline{A} . \overline{B}$$

$$\overline{(A . B)} = \overline{A} + \overline{B}$$

Road Junction Example



A - Car A fails to stop
B - Car B fails to stop
C - Car C stops



TOP = AC + AB

Implicant Set is a combination of basic events (success or failure) which produces the top event.

Prime Implicant Set is a combination of basic events (success of failure) which is both necessary and sufficient to cause the top event.

$$\text{TOP} = A\,\overline{C} + \overline{A}\,B$$

What about $\overline{C}B$

it is a prime implicant

Conventional approaches to fault tree reduction do not deliver all prime implicants for every non-coherent tree

so:

$$\text{TOP} = A\,\overline{C} + \overline{A}\,B + \overline{C}\,B$$

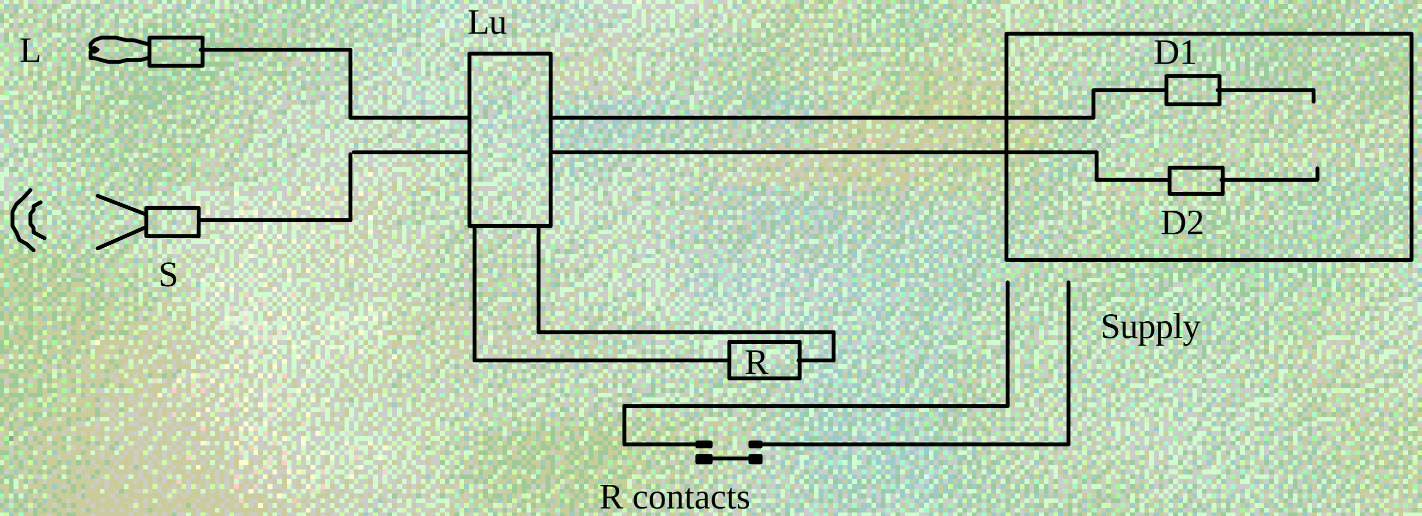
Coherent approximation

$$\text{TOP} = A + B$$

OK if

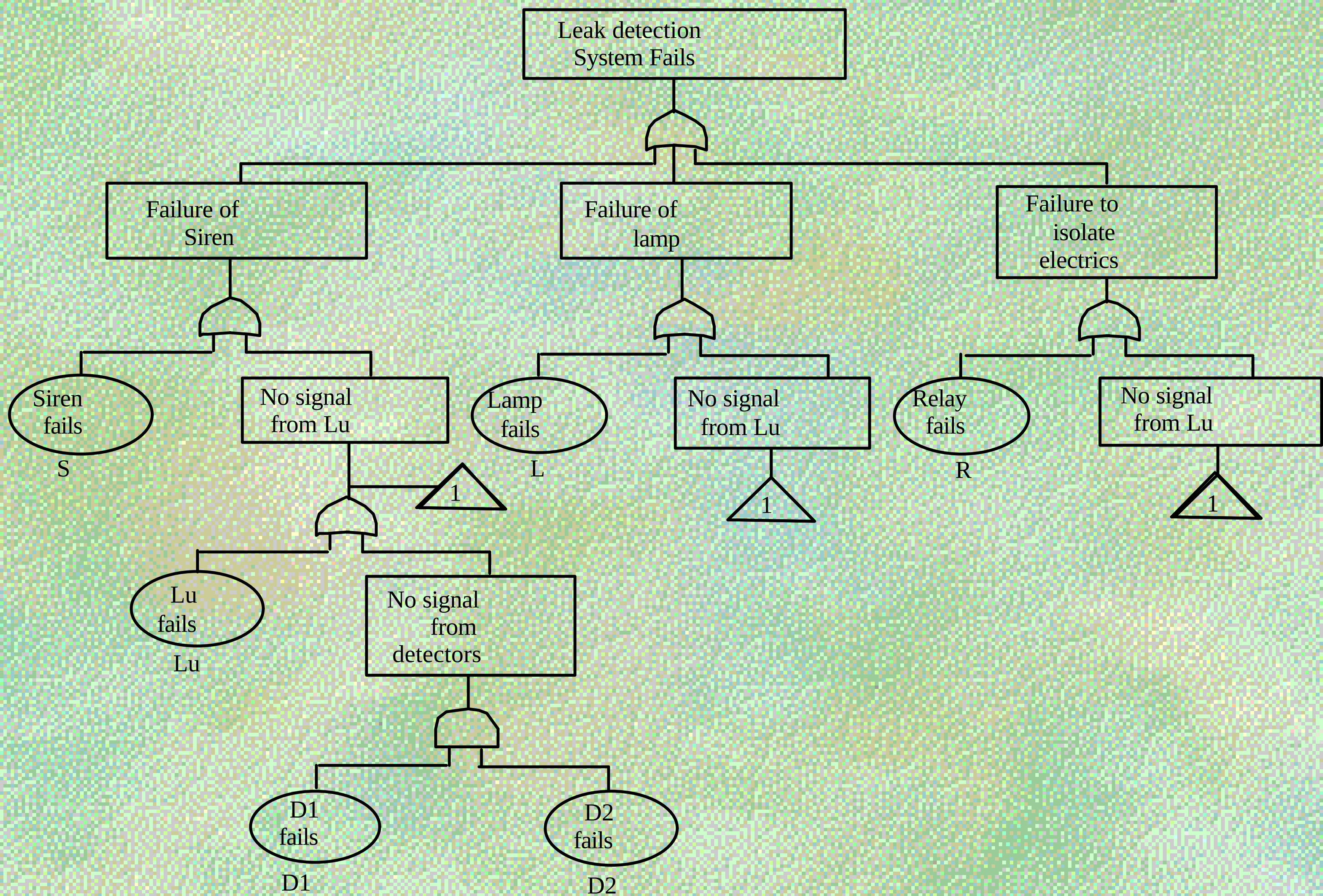
$$P(\overline{C}) \approx 1$$

Example



System Functions - on detecting gas

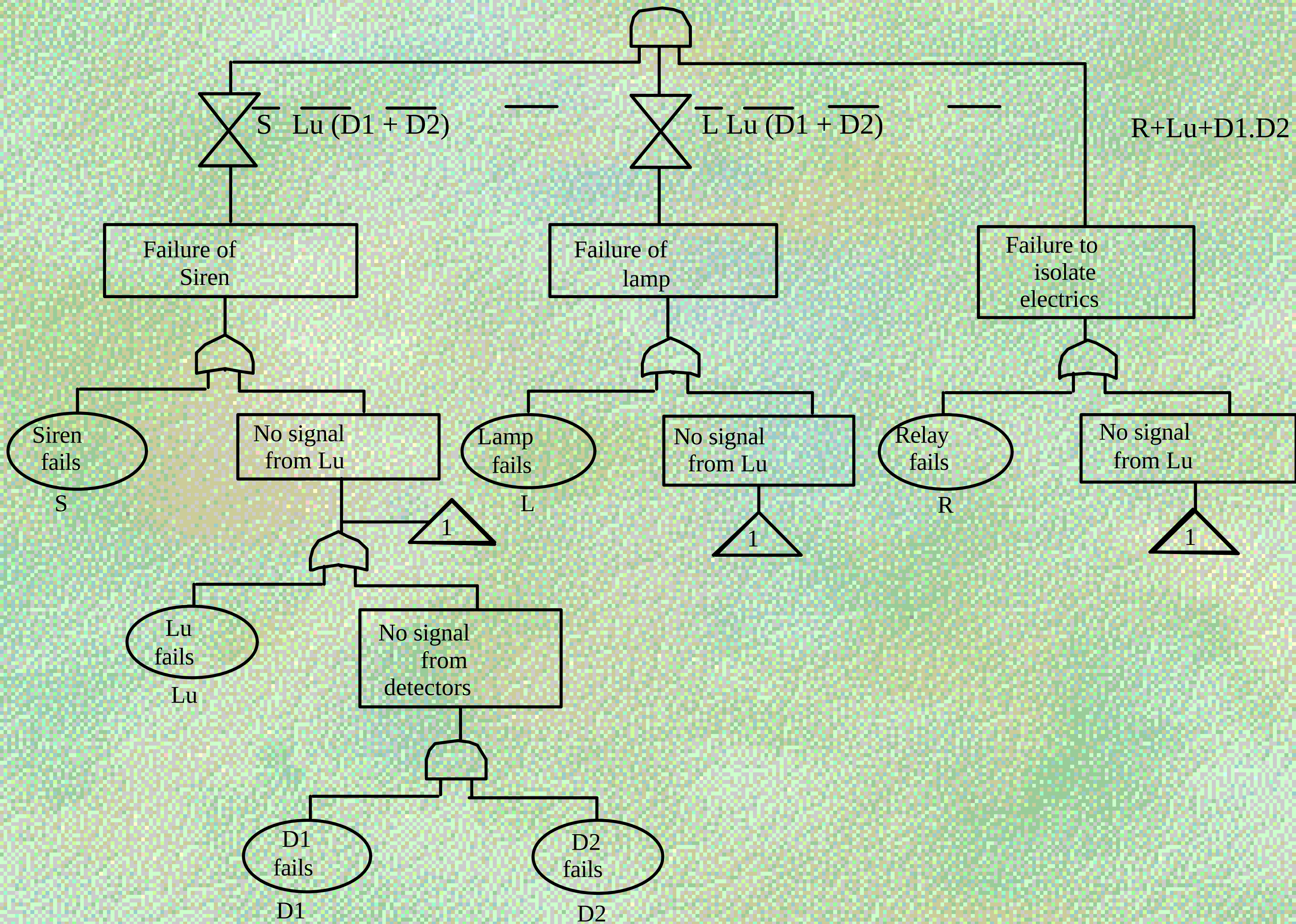
a) to alert the operator via a lamp
b) to alert the operator via a siren
c) to isolate electrical ignition sources


Leak detection System Fails
Failure of Siren
Failure of lamp
Failure to isolate electrics
Siren fails
S
No signal from Lu
1
Lamp fails
L
No signal from Lu
1
Relay fails
R
No signal from Lu
1
Lu fails
Lu
No signal from detectors
D1 fails
D1
D2 fails
D2

System Outcomes

	SIREN	LAMP	ISOLATION	SYSTEM
1	W	W	W	?
2	W	W	F	
3	W	F	W	
4	W	F	F	
5	F	W	W	
6	F	W	F	
7	F	F	W	
8	F	F	F	

Operator alerted of spill (Siren and Lamp) But electric circuits active



$$
\begin{aligned}
TOP &= (\overline{S}\,\overline{LU}\,(\overline{D1} + \overline{D2})).(\overline{L}\,\overline{LU}\,(\overline{D1} + \overline{D2})).(R + LU + D1.D2) \\
&= \overline{S}\,\overline{L}\,\overline{LU}\,(\overline{D1} + \overline{D2}).(R + LU + D1.D2) \\
&= \overline{S}\,\overline{L}\,\overline{LU}\,(\overline{D1} + \overline{D2}).R
\end{aligned}
$$

Coherent Approximation

TOP = R

Session 3: Current Research

Problem areas in conventional Fault Tree Analysis

- Qualitative Analysis

  For very large fault trees it may not be possible to produce a complete list of minimal cut sets.

  Solution

  Evaluate only those minimal cut sets which have the most significant contribution to system failure

  - Order culling
  - Probability or Frequency culling

- Quantitative Analysis
  - Requires minimal cut sets
  - Calculations are too computer intensive to perform fully

Solution

- Use most significant minimal cut sets
- Use approximate calculation techniques.

Binary Decision Diagrams

BDD's

1 Developed over last 5 years.

2 Fault Tree - Good representation of engineering failure logic

- Poor efficiency/accuracy in mathematical calculations

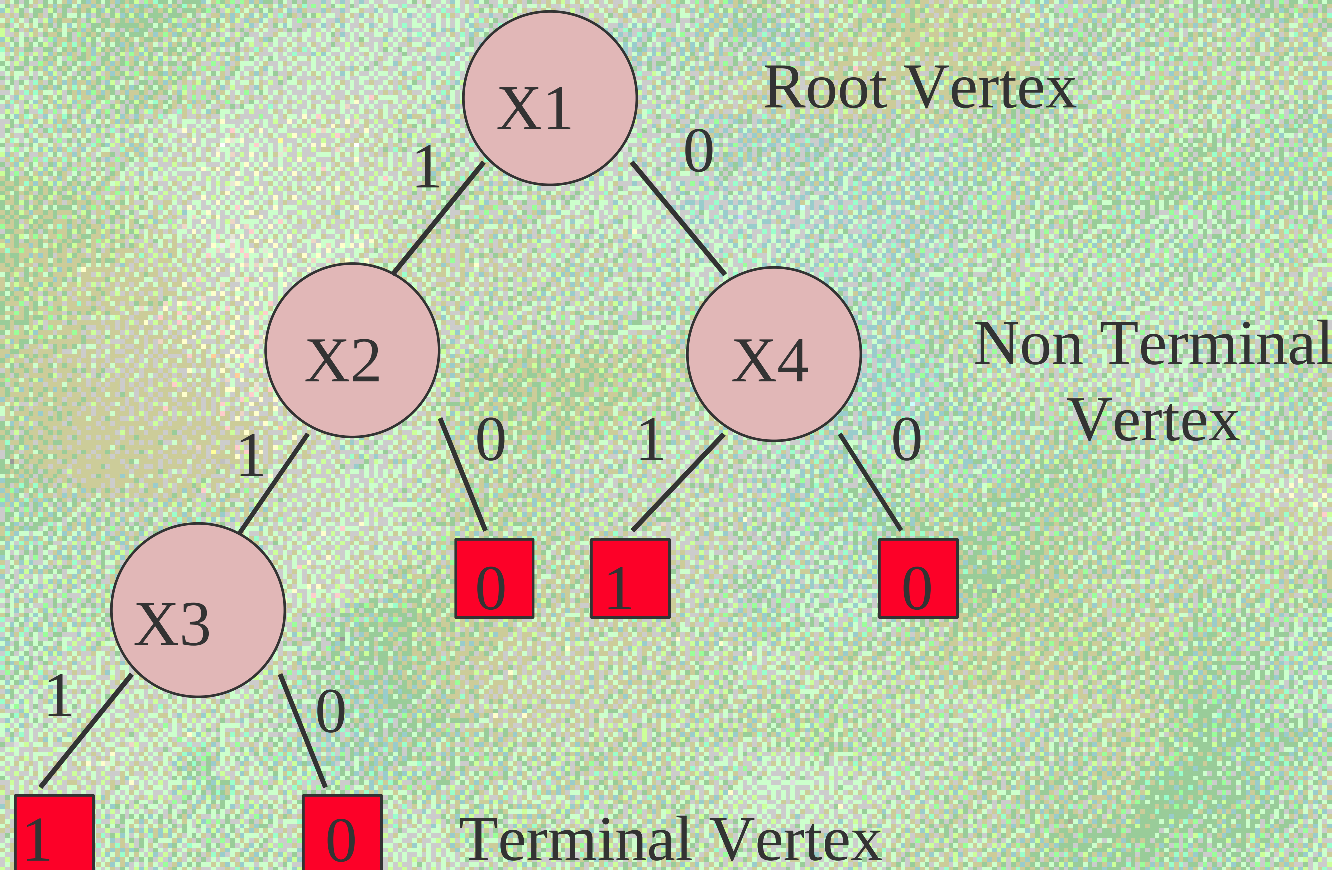
BDD - Poor representation of engineering failure logic

- Good efficiency/accuracy in mathematical calculations.

3 Trade-off for improved efficiency/accuracy is conversion between FT $\rightarrow$ BDD.

4 Minimal cut sets not required to perform quantification.

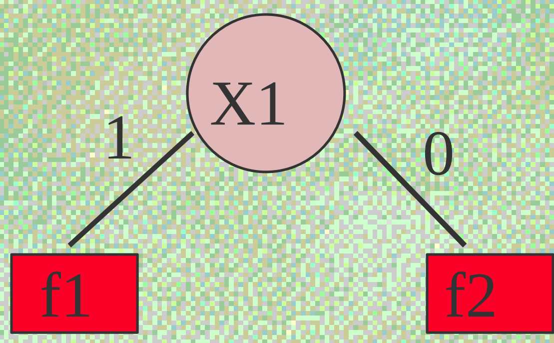
B.D.D. Structure



Fault Tree -> B.D.D

1. Initially requires basic events in the fault tree to be placed in an ordering.
2. Most common method - If-Then-Else Structure

   * ITE(X1, f1, f2) means
     if X1 fails
       then consider f1
       else consider f2



Simple Conversion - ite method

Rules : G = ite (x, g1, g2), H = ite (y, h1, h2)

G*H=

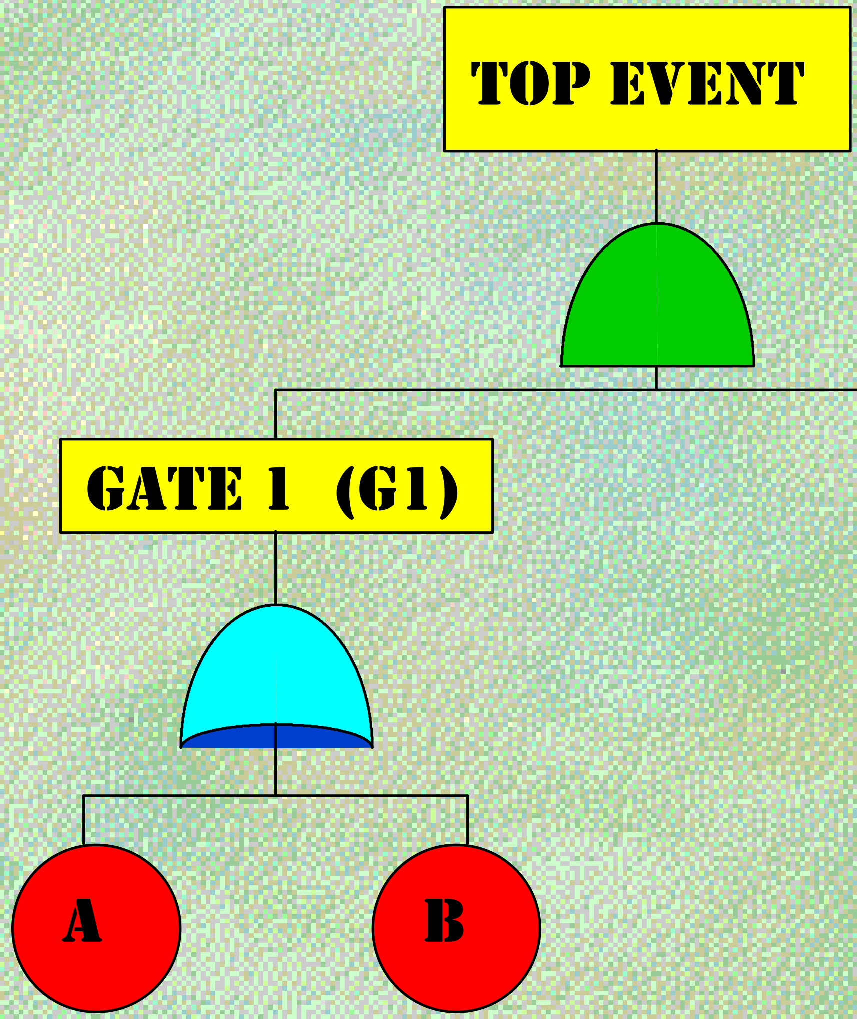
if (x < y) => ite (x, g1*H, g2*H)

if (x = y) => ite (x, g1*h1, g2 *h2)

if * = AND => 1 * G = G, 0 * G = 0

if * = OR => 1 * G = 1, 0 * G = G

Fault Tree Structure



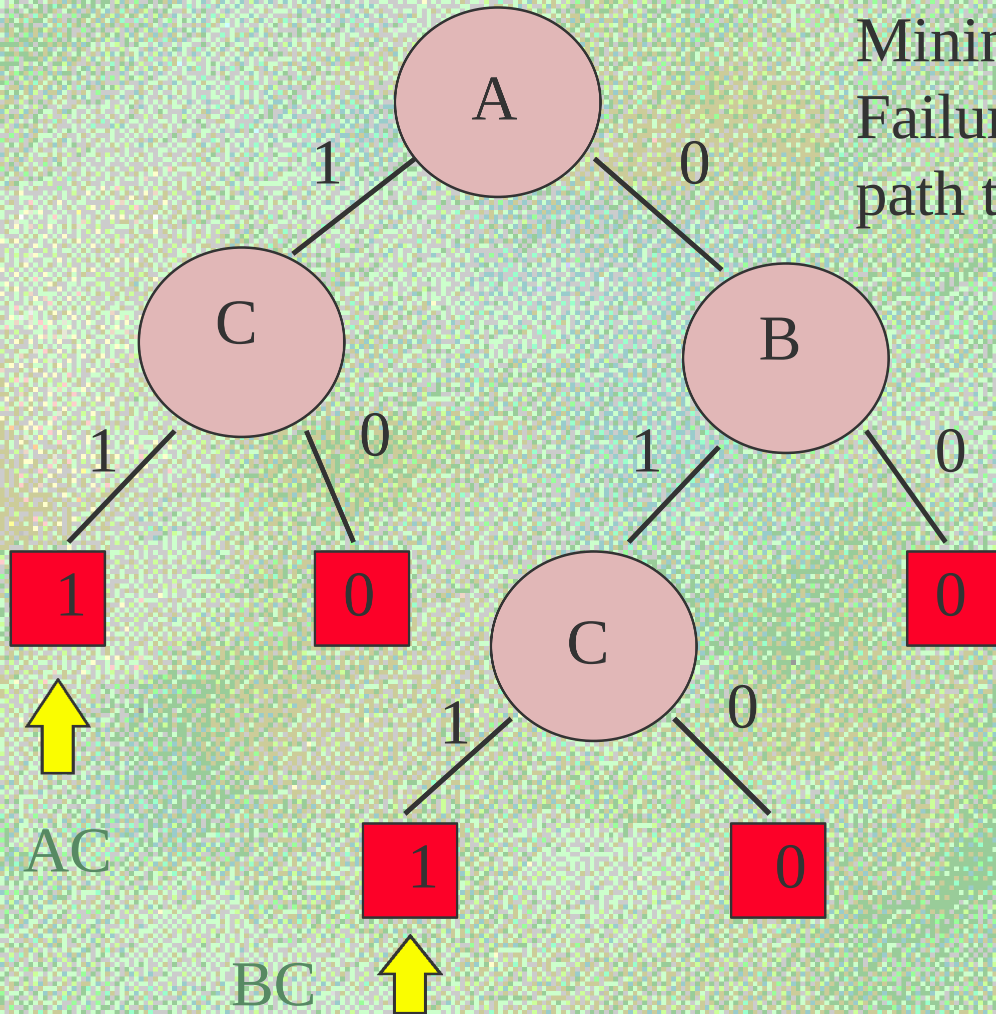
A = ite (A, 1, 0)
B = ite (B, 1, 0)
C = ite (C, 1, 0)

Simple Conversion cont...

Order	A < B < C
G1 = A + B	= ite(A, 1, 0) + ite(B, 1, 0)
	= ite(A, 1+ite(B, 1, 0), 0+ite(B, 1, 0))
	= ite(A, 1, ite(B, 1, 0))
TOP = G1.C	= ite(A, 1, ite(B, 1, 0)).ite(C, 1, 0)
	= ite(A, 1.ite(C, 1, 0), ite(B, 1, 0).ite(C, 1, 0))
	= ite(A, ite(C, 1, 0), ite(B, 1.ite(C, 1, 0), 0.ite(C, 1, 0)))
	= ite(A, ite(C, 1, 0), ite(B, ite(C, 1, 0), 0))

Root Vertex 1 branch 0 branch

Resulting Diagram



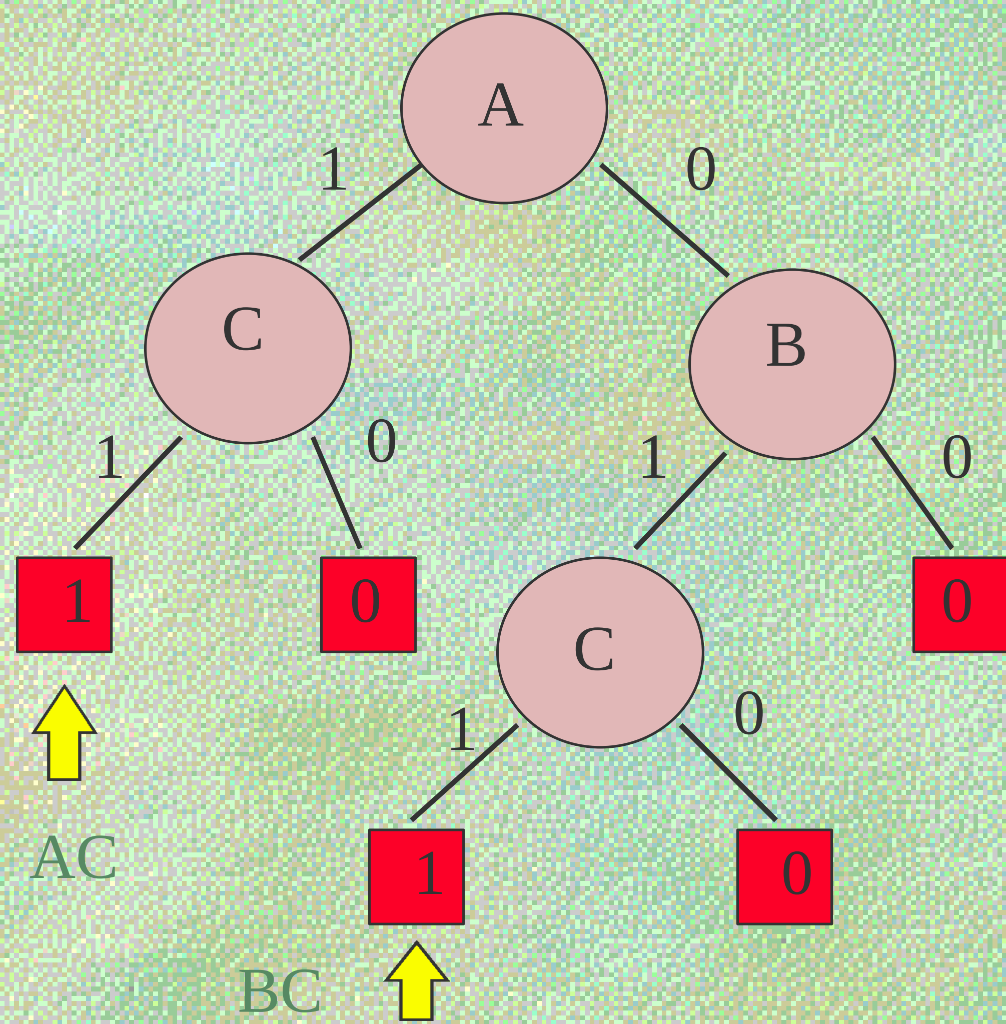
Minimal Cut Sets :-
Failure events on
path to terminal 1

Top Event Probability from B.D.D

=> Probability of the sum of disjoint paths through the bdd.

Disjoint Path - included in a path are the basic events that lie on a 0 branch on the way to a terminal 1 vertex.

Basic Events lying on a 0 branch are denoted as $\overline{Xi}$, ie. 'Not' Xi



The disjoint paths of the bdd are : AC, ABC

Top event probability : P(AC + ABC)

Disadvantages of BDD

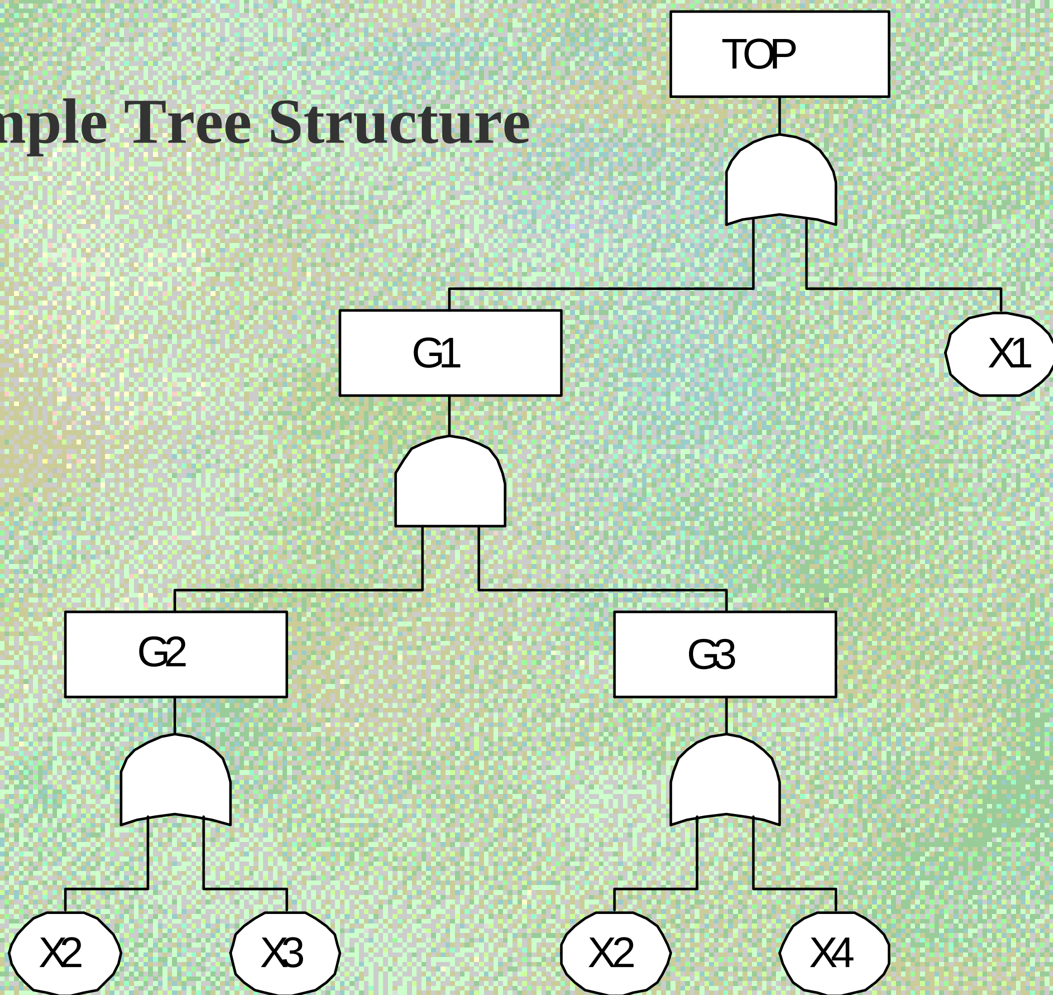
- FTA $\rightarrow$ BDD conversion
- Poor ordering can give poor efficiency

Advantage of BDD

- improved efficiency
- improved accuracy

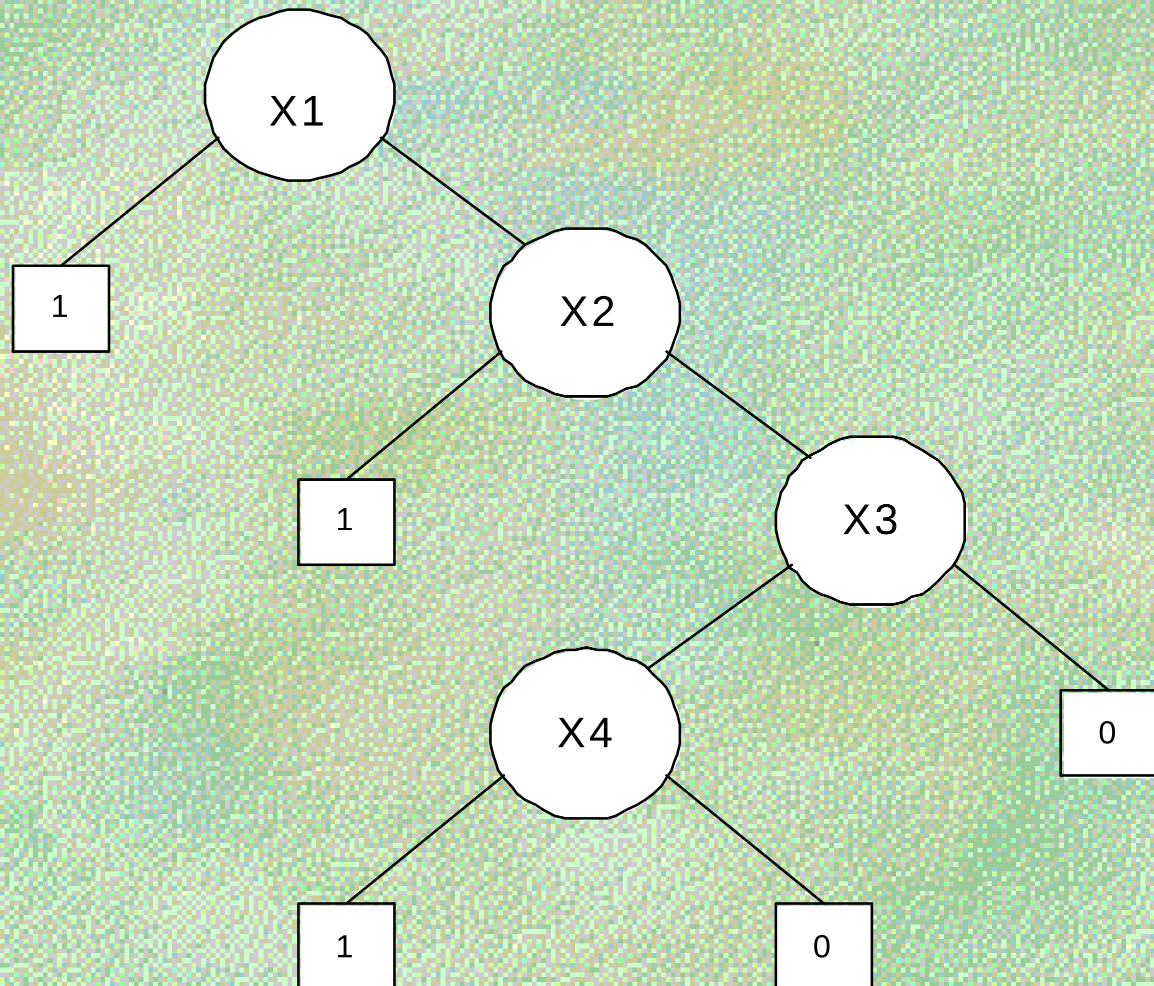
Result of Different Ordering Permutations

An Example Tree Structure



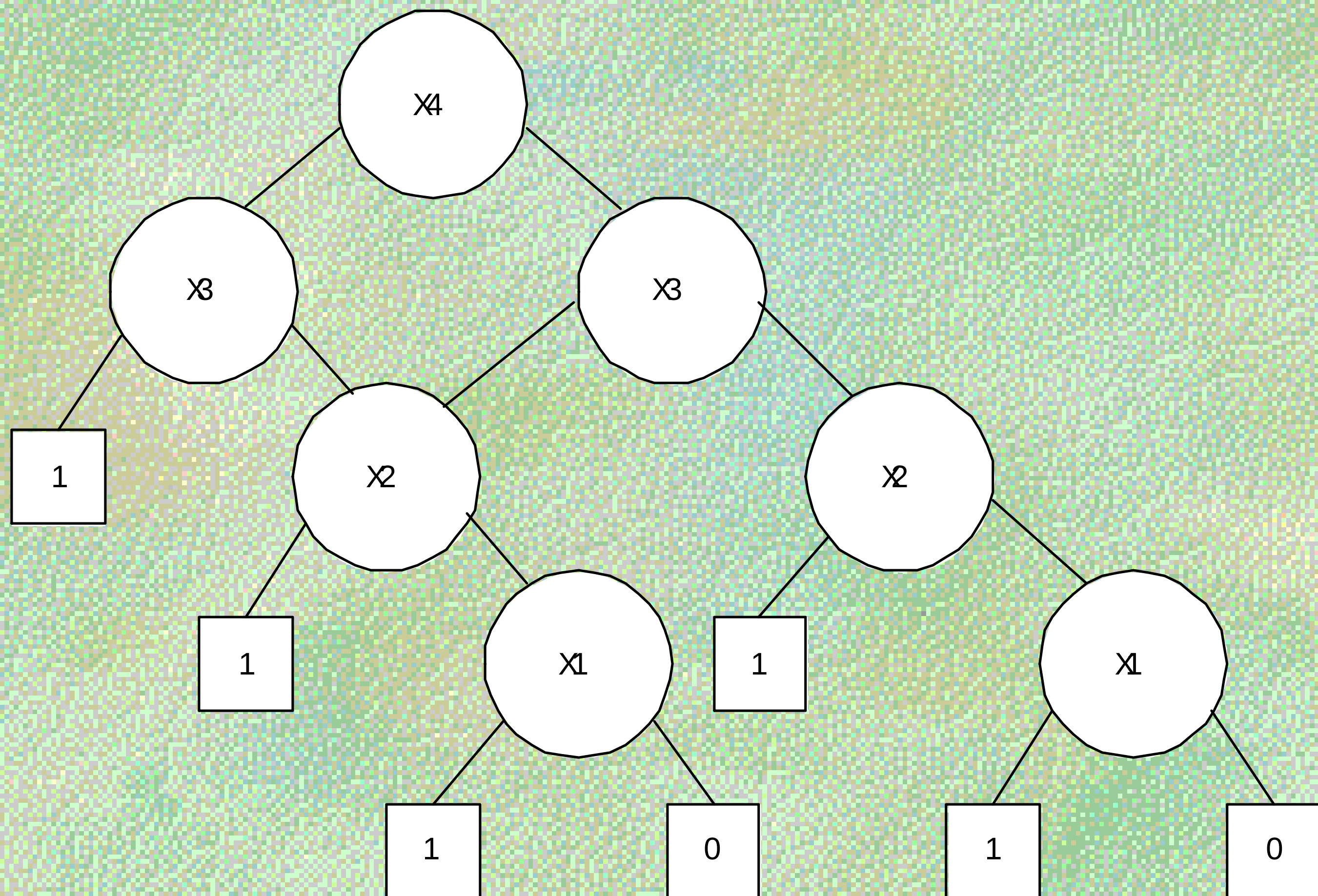
Result of Ordering :

X1 < X2 < X3 < X4



Result of Ordering :

X4 < X3 < X2 < X1



FAULT TREE CHARACTERISTICS

? ? ? ?

EFFICIENT B.D.D VARIABLE ORDERING

Training Methods

- Classifier System
- Neural Networks

Direct evaluation of Fault Tree Structure

Safety System Design Considerations

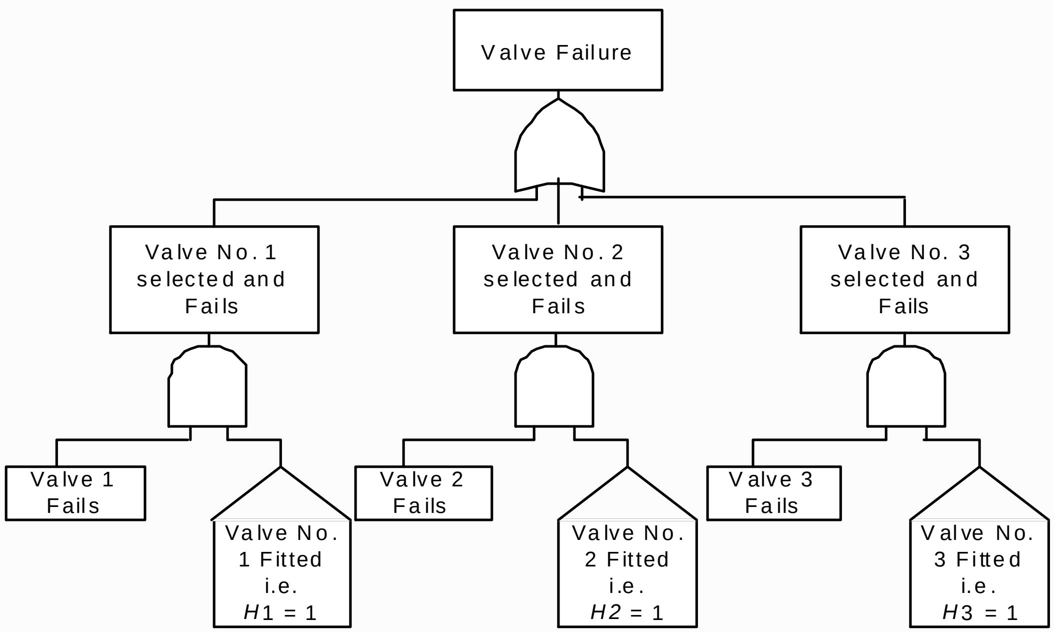
- Redundancy and diversity levels
- Component selection
- Time interval between testing the system

*Choice of design not unrestricted

System Analysis

- **Fault Trees** represent and quantify the system unavailability of each potential design
- **House events** used to construct a single fault tree representing the failure mode of EACH design

Fault tree representing selection of valve type 1,2 or 3



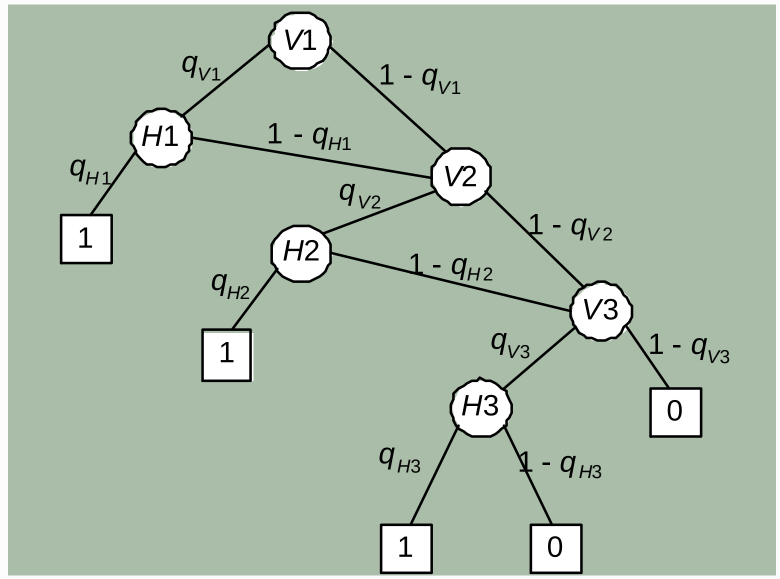
System Analysis, contd.

Binary Decision Diagrams improve efficiency of system analysis

BDD

- Connecting branches
- Non-terminal vertices
  - correspond to basic events
- Terminal vertices
  - 0, i.e. system works
  - 1, i.e. system fails

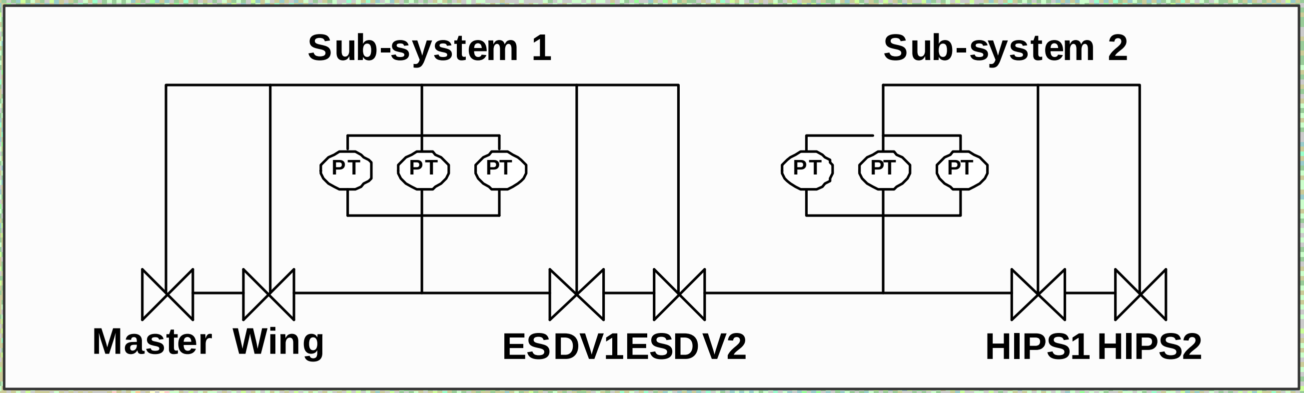
BDD - Valve selection



The Optimisation Problem

- System performance CANNOT be expressed as an explicit objective function
- Most design variables are integer or Boolean
- Constraints are of both implicit and explicit type

High Integrity Protection System



Designer Options	**Variable**
❖No. ESD valves (0,1,2)?	E
v No. HIPS valves (0,1,2)?	H
v No. PT's each subsystem (0 to 4)?	N_1, N_2
v No. PT's to trip?	K_1, K_2
v Type of valve?	V_1, V_2
v Type of PT?	P_1, P_2
v MTI each subsystem (1 to 104 weeks)?	θ_1, θ_2

Limitations on Design

- Cost < 1000 units
- Maintenance Dwn Time (MDT) < 130 hours
- Spurious trip occurrences < 1 per year

Genetic Algorithms

Structure of the GA

Set up **initial population** of strings

Loop

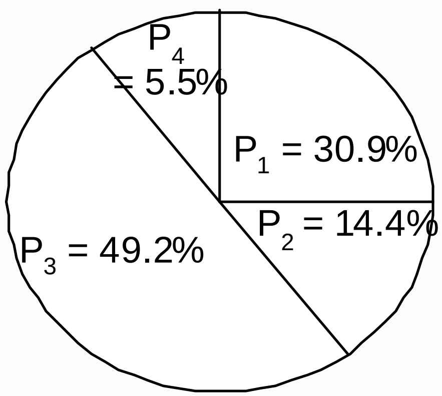
- Evaluate **fitness** of each string
- **Selection** - biased roulette wheel
- **Crossover/Mutation** on selected offspring

*One iteration of each loop

= **generation**

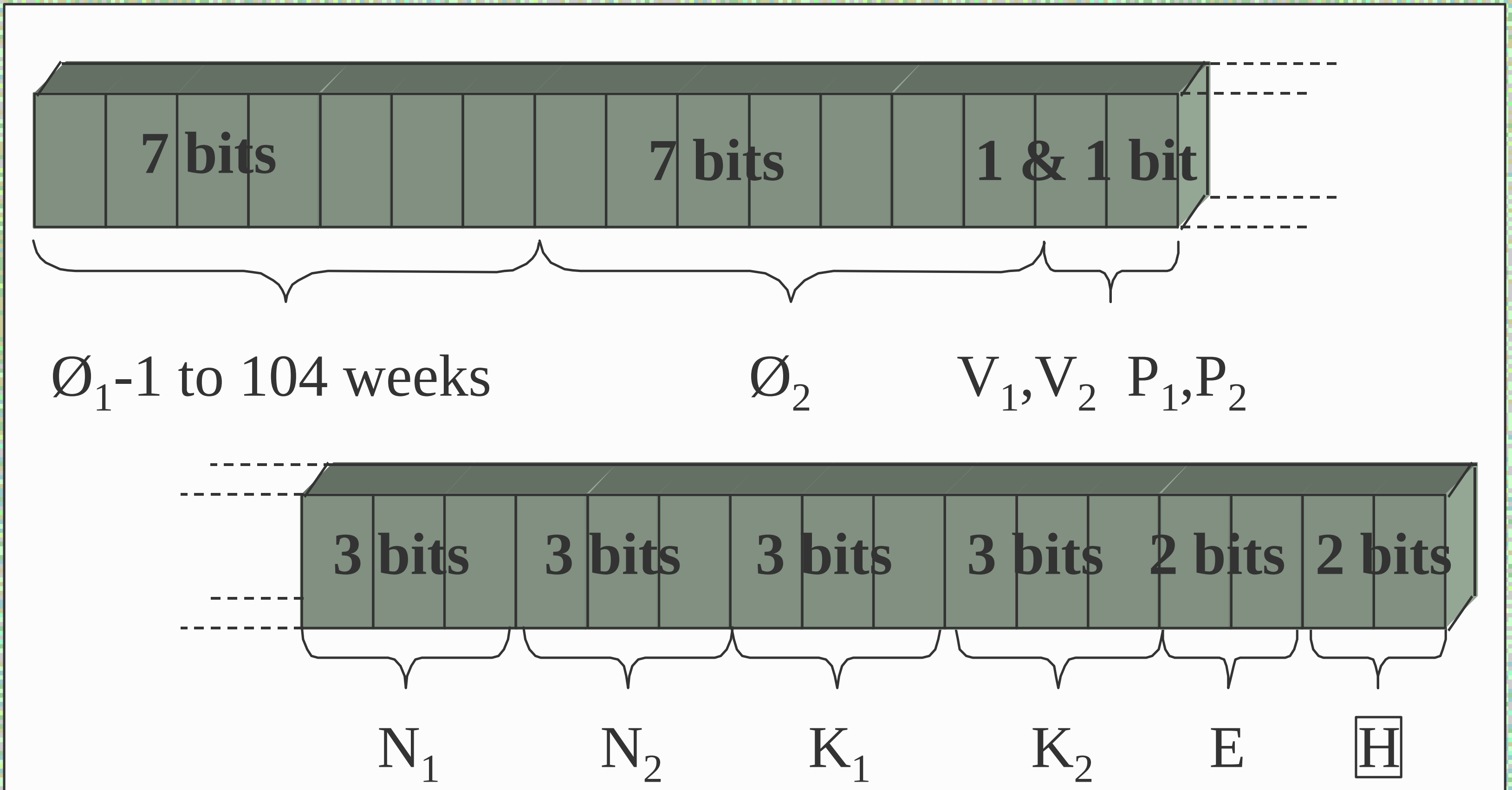
Selection

Biased roulette wheel



$$P_i = \frac{\text{individual fitness of chromosome}}{\text{total fitness of gene pool}}$$

Initialising a System Design



Total = 32 bits

Evaluating Design Fitness

The fitness of each string comprises of four parts;

- ❖ Probability of system unavailability
- v Penalty due to excess cost
- v Penalty due to excess MDT
- v Penalty due to excess spurious trip frequency

As a sole fitness value;

$$\boxed{Q'_{SYS} = Q_{SYS} + CP + MDTP + STFP}$$

* = penalised probability of system unavailability

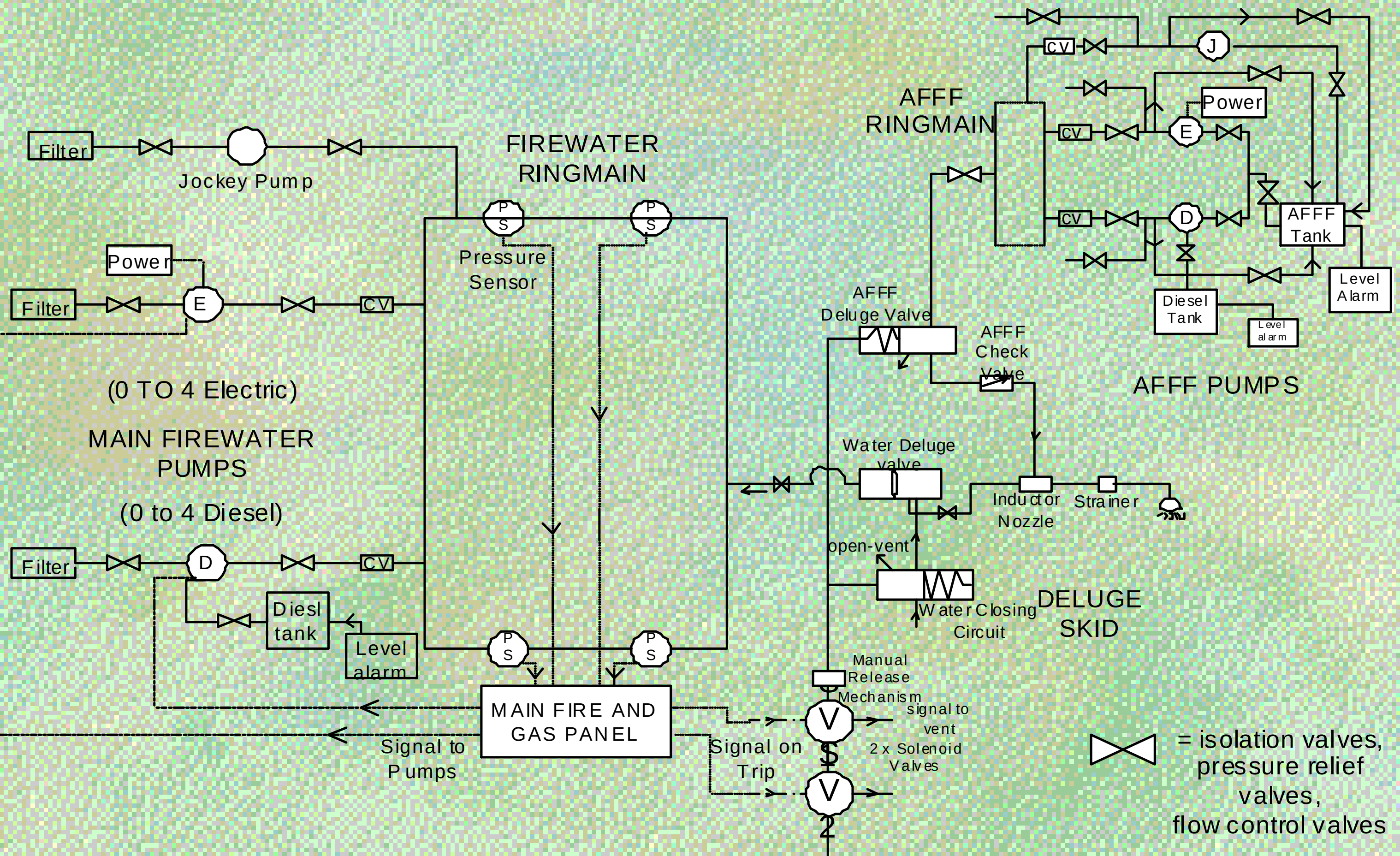
Best Design's Characteristics

		Subsys 1 & 2		Type
❖	No. ESD/HIPS valves	0	2	2
v	No. PT's	3	3	1
v	No. PT's to trip system	2	2	
v	M.T.I.	23	57	

❖	MDT	123 hours
v	Cost	842 units
v	Spurious trip	0.455

System Unavailability **0.0011**

Diagram of The Deluge System



Design Variables of Deluge System

- ❖ No. of electric pumps firewater system (1 to 4) – type E1 to E5
- v No. of electric pumps AFFF system (1,2) – type E6, E7
- v No. of diesel pumps firewater system (1 to 4) – type D1 to D5
- v No. of diesel pumps AFFF system (1,2) – type 6, D7
- v No. of pressure sensors firewater ringmain (1 to 4)
- v No. of sensors to trip
- v Type of pressure sensor
- v Type of water deluge valve
- v Type of afff deluge valve
- v Type of pipework
- v Maintenance interval for pump tests
- v Maintenance interval for pump and ringmain tests
- v Maintenance interval for full tests

Deluge system

- Fault tree in excess of 450 gates and 420 basic events
- Fault tree converted to 17 BDD’s
- In excess of 44000000000 design variations!!