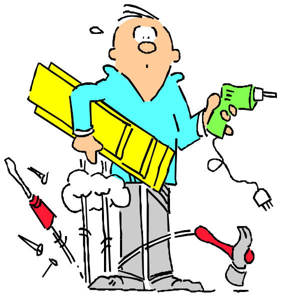


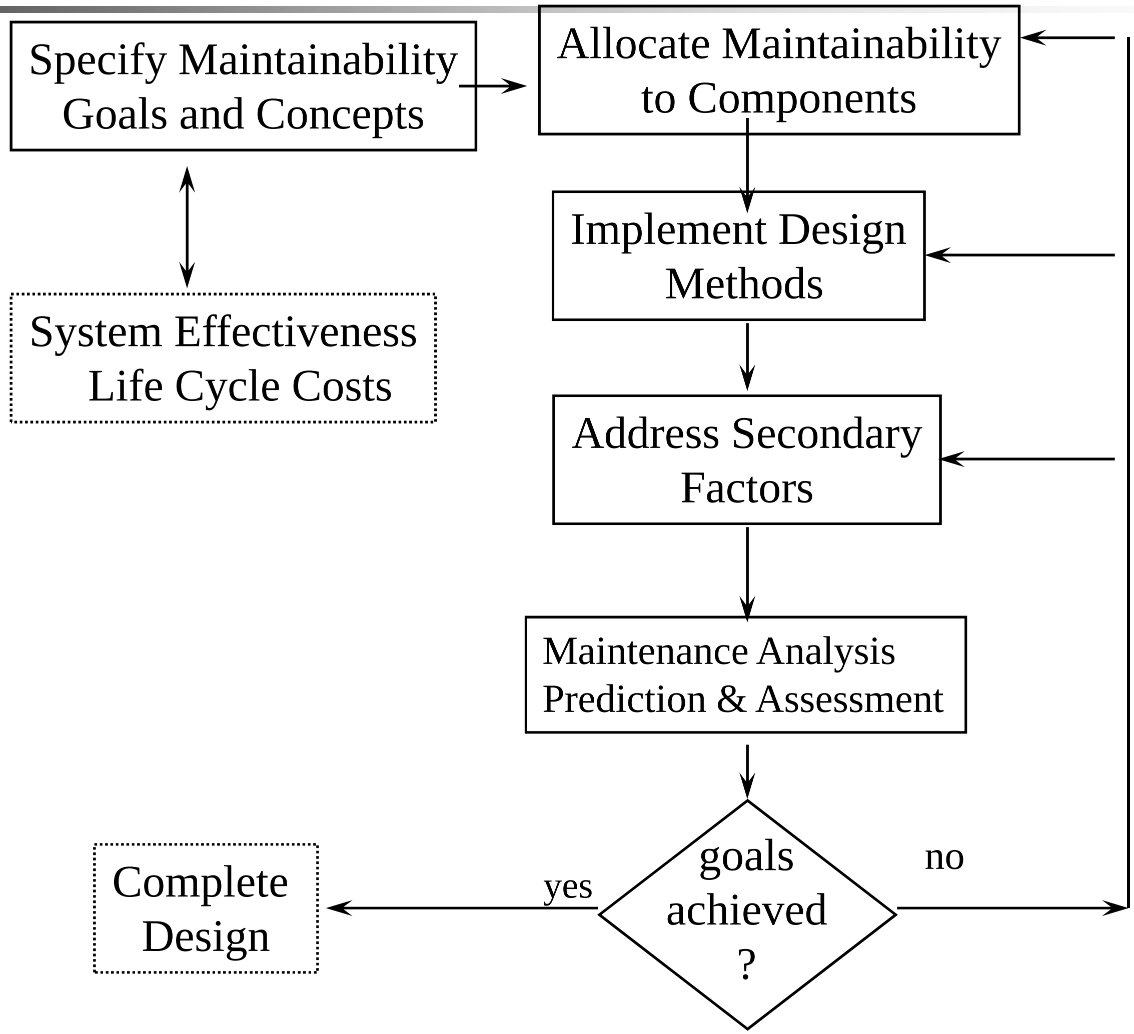
Chapter 10
Design for Maintainability

Maintenance Requirements

Design Methods

Human Factors & Ergonomics

Maintainability



Measurements and Specifications

Mean time to repair (MTTR)

Median time to repair (other quartiles)

Max time t_p where $Pr\{T <= t_p\} = H(t_p) <= p$

Mean system downtime

Mean time to restore (MTR)

Maintenance hours per operating hr (MH/OH)

Mean System Downtime

$$\overline{M} = \frac{m(t_d)\, MTTR + \dfrac{t_d}{T_p}\, MPMT}{m(t_d) + t_d / T_p}$$

T_p = the (mean) time between PM's,
t_d = the system design or (economic) life,
MPMT = the mean PM time, and
$m(t_d)$ = is the expected number of failures in the interval $(0, t_d)$

Mean Time to Restore (MTR)

$$MTR = \overline{M} + MDT + SDT$$

Maintenance Hours per Operating Hour (MH/OH)

$$MH / OH = (m(t) \times MTTR \times CREW) / t$$

Or if preventive maintenance (PM) is to be included:

$$MH / OH = [\, m(t) \times MTTR \times CREW + (t / t_p) \times MPMT \times CREW_p \,] / t$$

where $CREW_p$ is the average crew size for PM

Maintenance Concepts & Procedures

- Repair versus discard and replace
- the PM schedule and associated tasks
- For repairable units, for each failure mode, the level of repair (e.g. local, service center, or factory) ,
- For each repair task, the required skill levels, tools, test equipment, and technical manuals ,
- The number of repair channels and spare parts

Level of Repair

increased specialization
special tools and test equipment
economy of scale

Factory

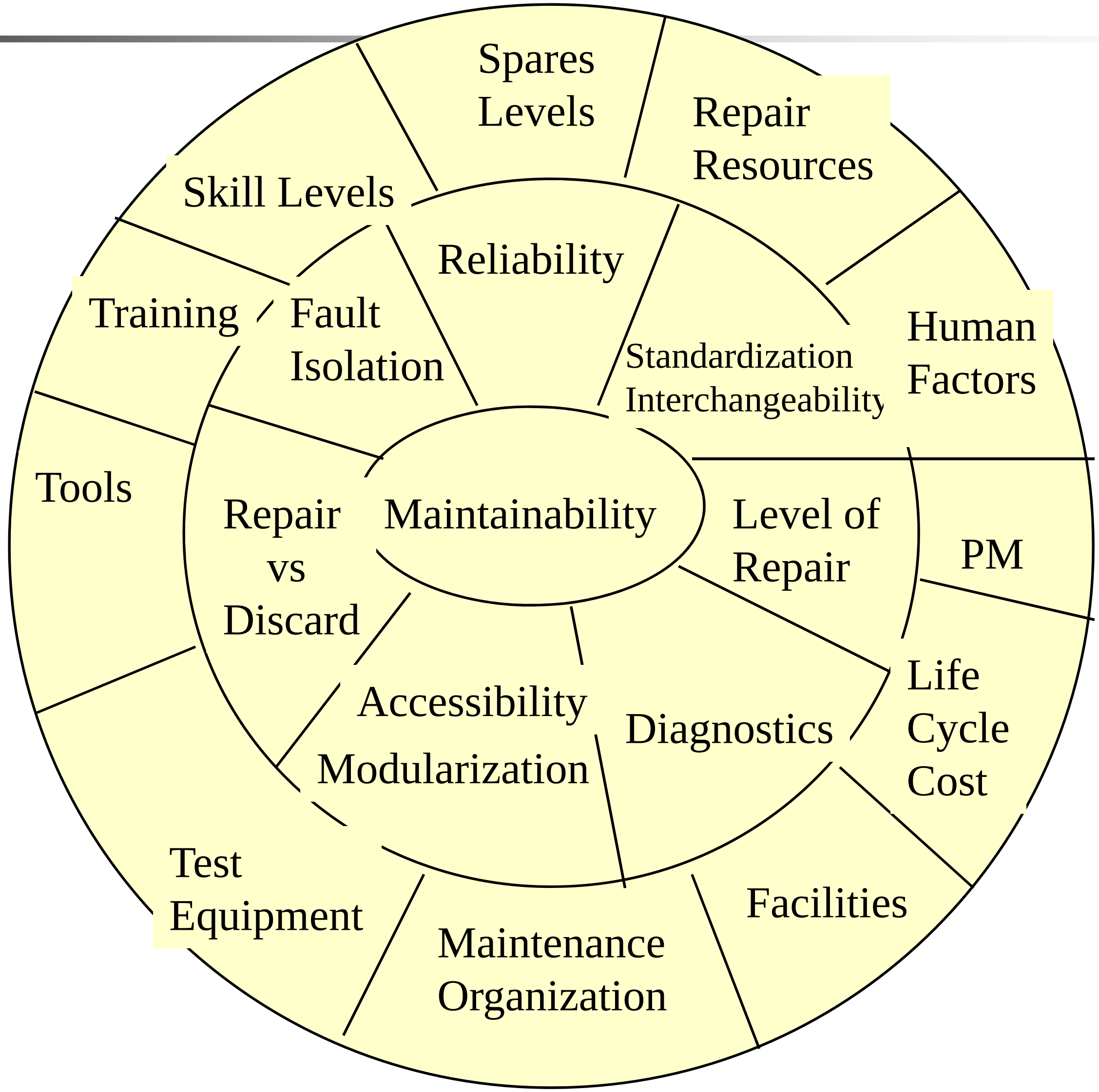
Centralized Repair Facility (Depot)

Local Repair

On-site Repair

decreased response time
routine maintenance
reduced skill levels

Maintainability Design Features



A Simple Cost Model

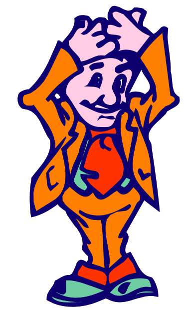
t_d = design or economic life in operating hours,
C_a = acquisition cost
C_f = fixed cost of a failure (e.g. spare parts)
C_v = variable cost per hour of downtime
(e.g. labor rate x crew size, loss of production, etc.)

Then Cost = $C_a + (t_d / \text{MTBF})(C_f + C_v\,\text{MTTR})$

assumes a renewal process

Exercise

Vendor A



Vendor B

A voltage regulator may be obtained from two vendors. Vendor A's regulator costs $150 and Vendor B's regulator costs $200. Vendor A's is less reliable with a MTTF of 1800 days while Vendor B's MTTF is 2600 days. Vendor A's regulator has a more modular design and is therefore easier to replace with a MTTR of 4 hr while Vendor B's regulator takes 6 hr. to replace. If a failed regulator must be replaced at its unit cost, which product should be used? The labor rate is $45 per hour and the design life of the regulator is considered to be 10 yr.

Exercise - solution

Vendor A: 150 + (10 x 365 / 1800) [150 + 45 (4)] = $ 819

Vendor B: 200 + (10 x 365 / 2600) [200 + 45 (6)] = $ 860

Component Maintainability

Set $MTTR_s$ and use trial and error and iteration to find $MTTR_i$

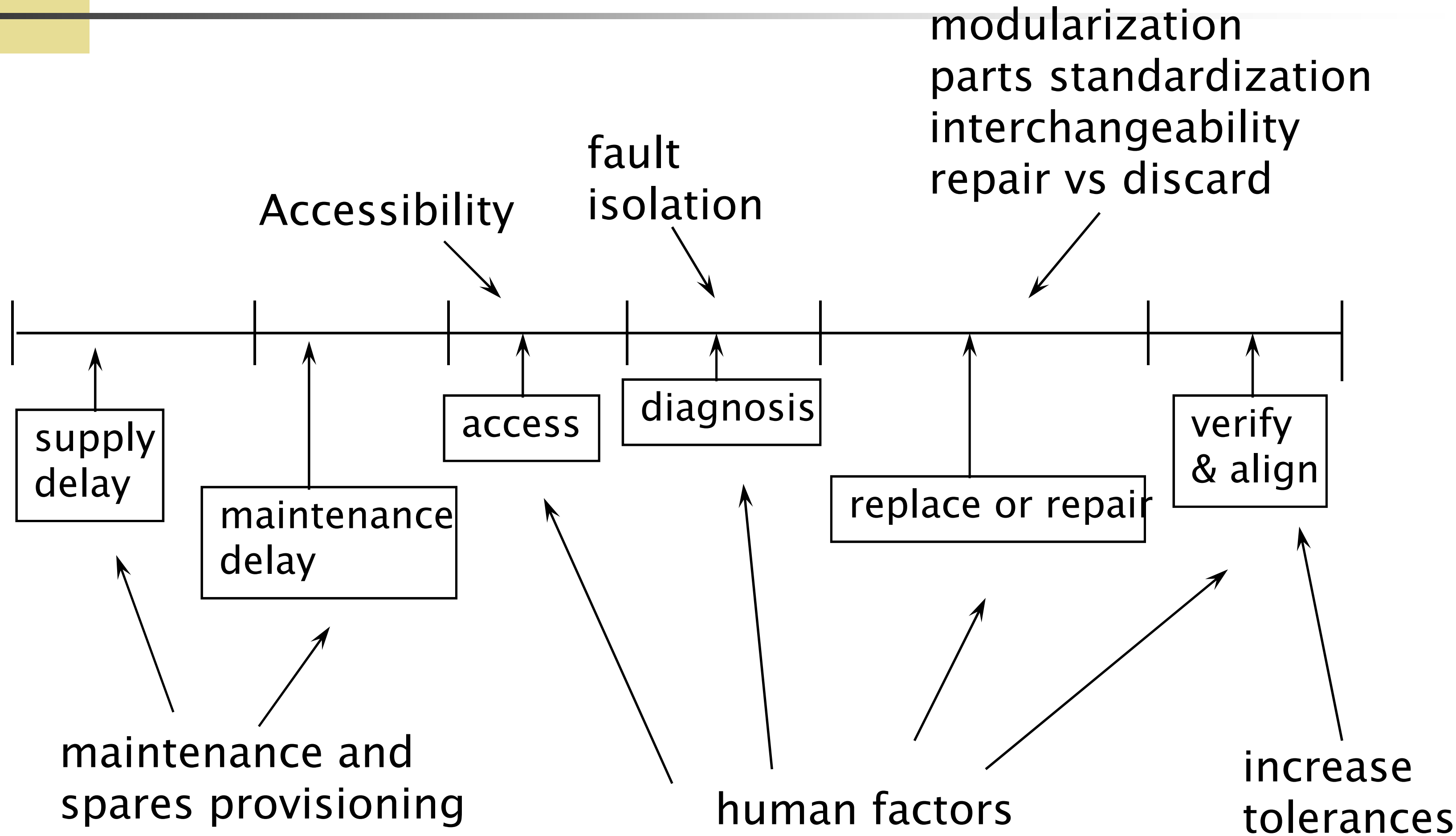
$$MTTR_s = \frac{\sum_{i=1}^{n} q_i f_i \quad MTTR_i}{\sum_{i=1}^{n} q_i f_i} \qquad f_i = \begin{cases} \dfrac{t_{oi}}{MTTF_i} & \text{for renewal process} \\ \int_0^{t_{oi}} \rho(t)dt & \text{for minimal repair} \end{cases}$$

$MTTR_s$ = system maintainability goal
f_i = expected number of failures of ith component
q_i = number of identical units of component I
n = number of components

Design methods

- Fault Isolation and self-diagnostics
- Parts Standardization and Interchangeability
- Modularization and Accessibility
- Repair vs. Replace
- Proactive Maintenance

Design Methods



Fault Isolation

high skill

low skill

Manual

- trial and error process
- may use test equipment such as oscilloscopes, gauges, meters, etc.
- process of elimination

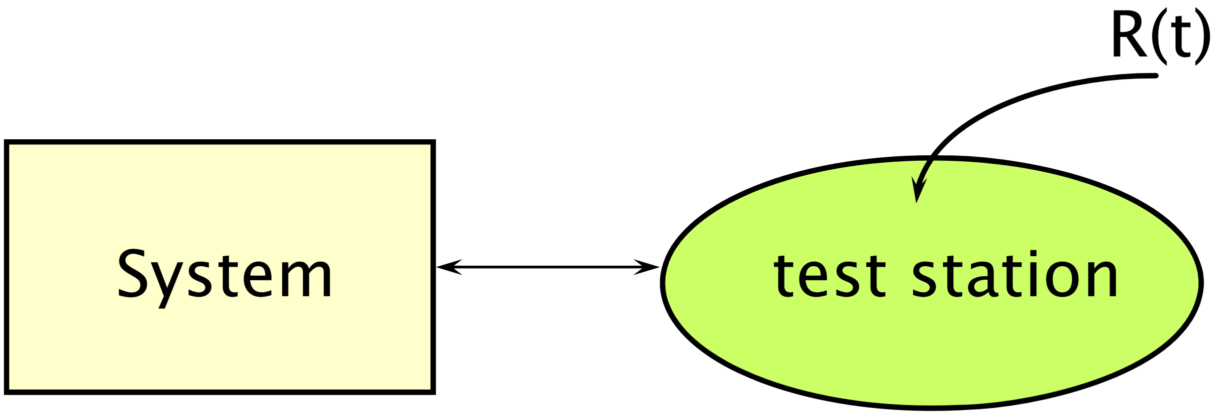
Automatic

- failed unit is removed and connected to computerized test station or test set is transported to system and connected
- computer executes one or more diagnostic programs

Self-diagnostic

- built-in test equipment (BITE)
- upon failure, system switches to diagnostic mode
- must detect and then isolate the fault

Fault Isolation - test equipment



$MTTR_{sys}$ $\quad$ $MTTR_{test\ sta}$

included

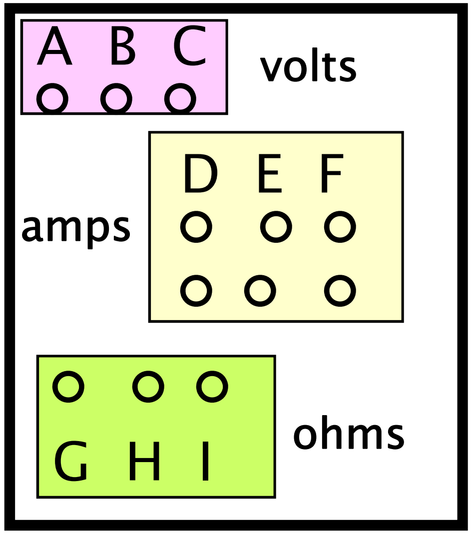
Let T = avg time on test station

$$MTR = MTTR_{sys} + [1 - R(T)]\, MTTR_{test\ sta}$$

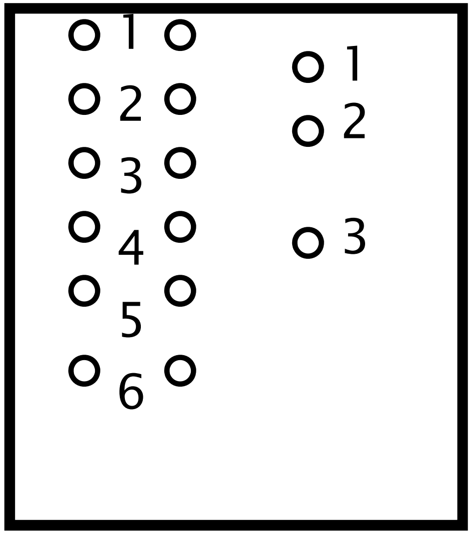
Animated

Fault Isolation

- Provide easy access to failed units
- Clearly identify and group test points

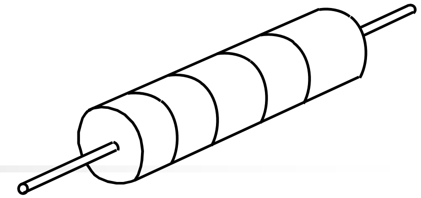


Good design

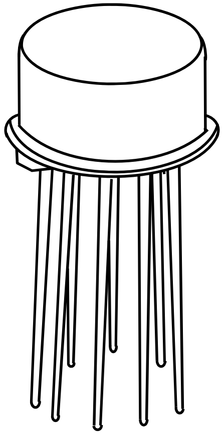


Poor design

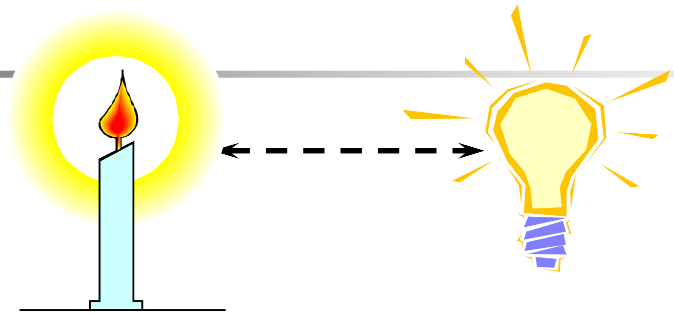
Parts Standardization



- Reduce to a minimum the range (breadth) of parts which must be maintained and stocked.
- Reduces training and skill requirements.
- Simplifies coding and labeling.
- Allows for fewer tools, test equipment, and tech manuals.
- Improved part reliability will have an effect wherever the part is used.



Interchangeability



A design policy that allows specified parts to be substituted within an assembly for any like part.

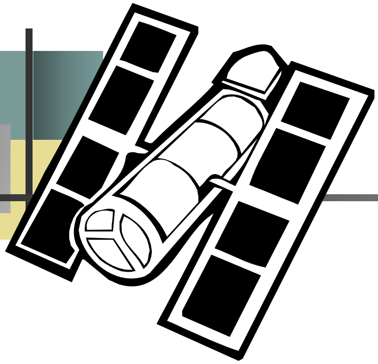
Requires both functional and physical substitution.

Physical substitution requires standardization in mountings, pins, connectors, etc. as well as compatibility in size and required space.

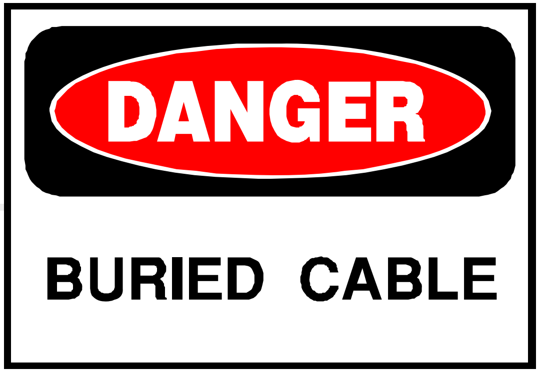
Converse to interchangeability: If two components are not intended to be functionally interchangeable, they should *not* be physically interchangeable.

Modularization

- Isolates problem to a physical unit (module)
- Supports remove and replace maintenance concept
- Permits packaging against environment
  - increases reliability
- Minimize number of connectors
- Reliability of all components in a module should be equal



Accessibility



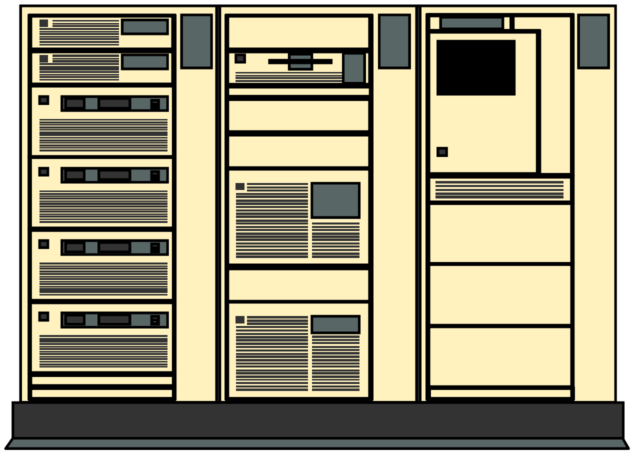
- Design accessibility down to the discard level.
- High failure components should be more accessible than those that seldom or never fail.
- Size, weight, and clearances must be considered in designing removal modules.
- Ideally removing a failed unit should not require removal of a unit that has not failed.

Accessibility

most preferred

- Direct access
- Opening with no cover
- Pull out drawers
- Hinged door access
- Removable panels
    - quick open captive fasteners
    - non-captive fasteners
    - screws or bolts
    - rivets
- Remove other components

least preferred



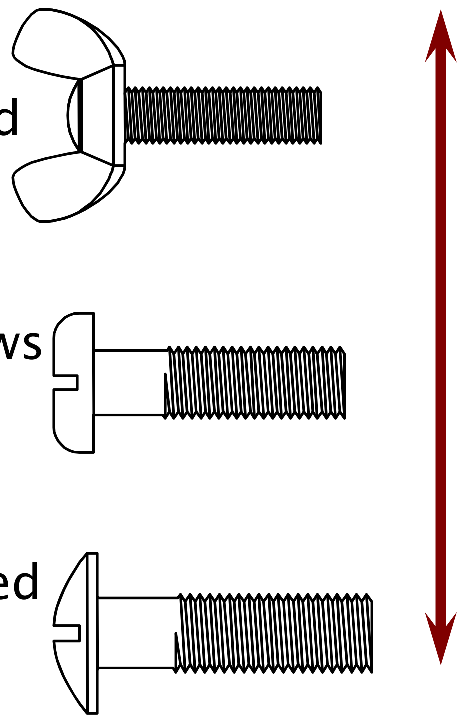
Accessibility

most preferred

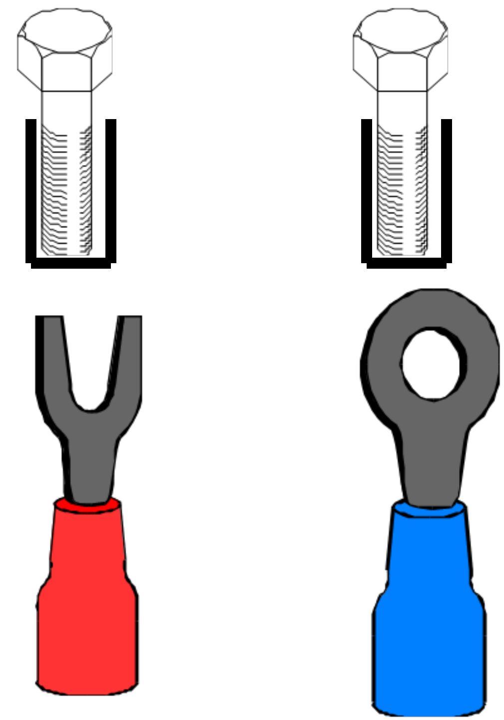
No tools needed

Grip head allows use of wrench

must be drilled out if slot is damaged



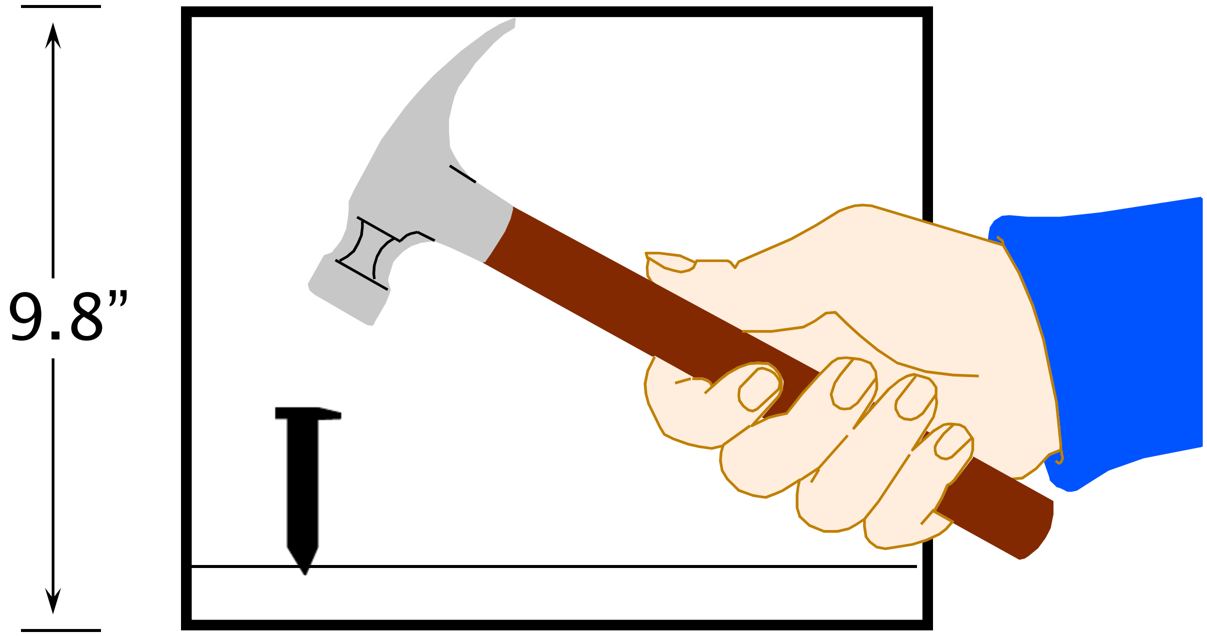
least preferred



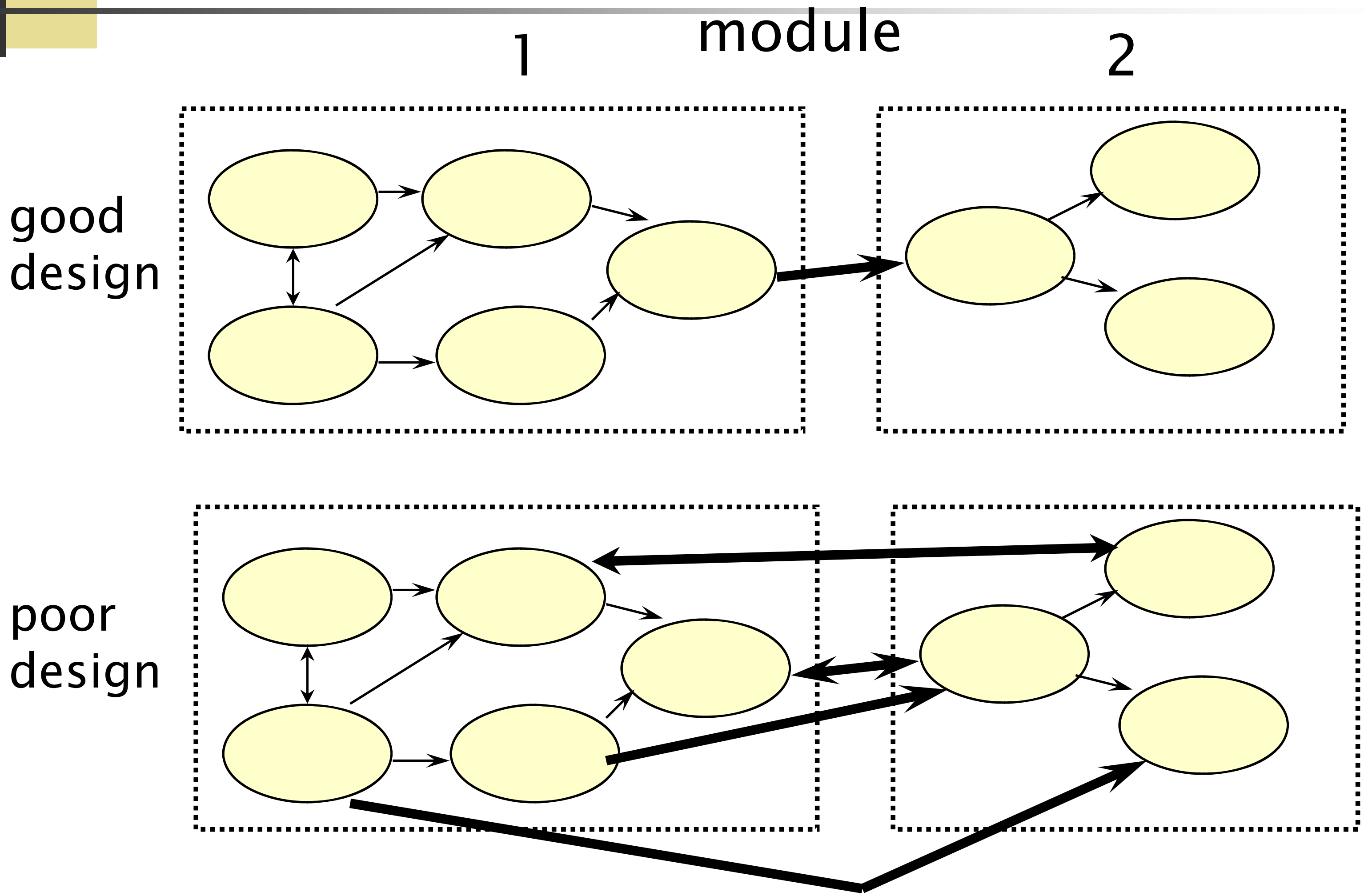
good

bad

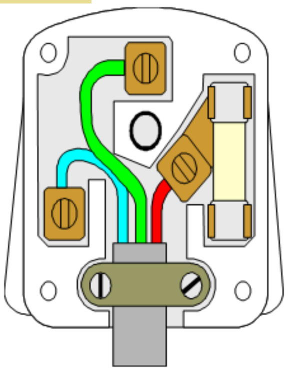
Accessibility

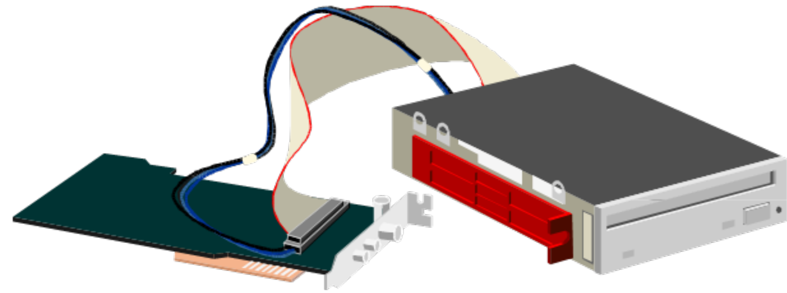


Modularization & Connectors

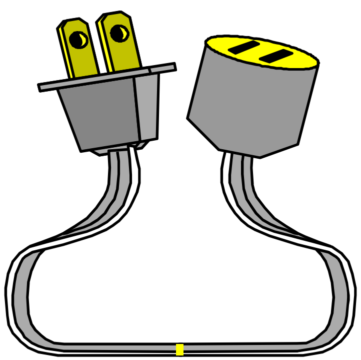


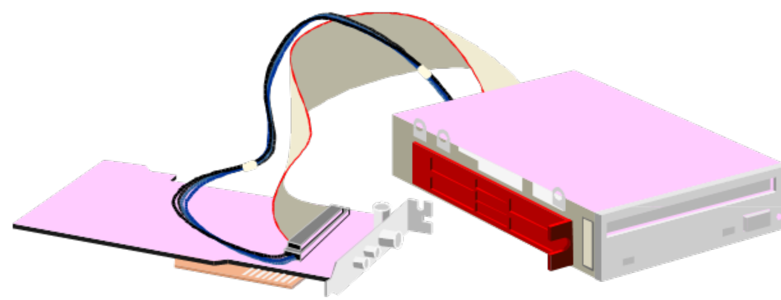
Modularization & Connectors





(color) code connector and receptacles





Remember, however, that 5% of population is color blind!

Modularization & Packaging

plug-in

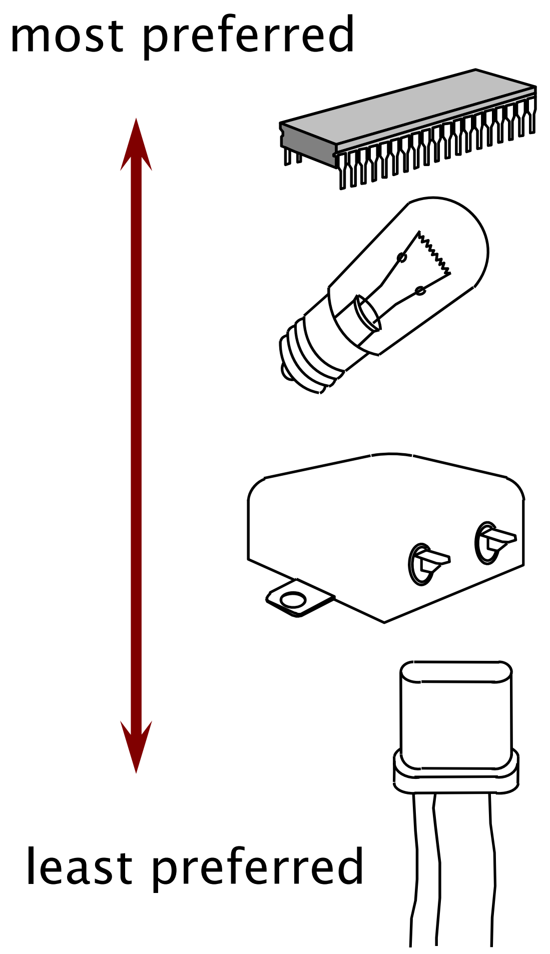
plug in + connectors

fastening (screws, bolts, etc.)

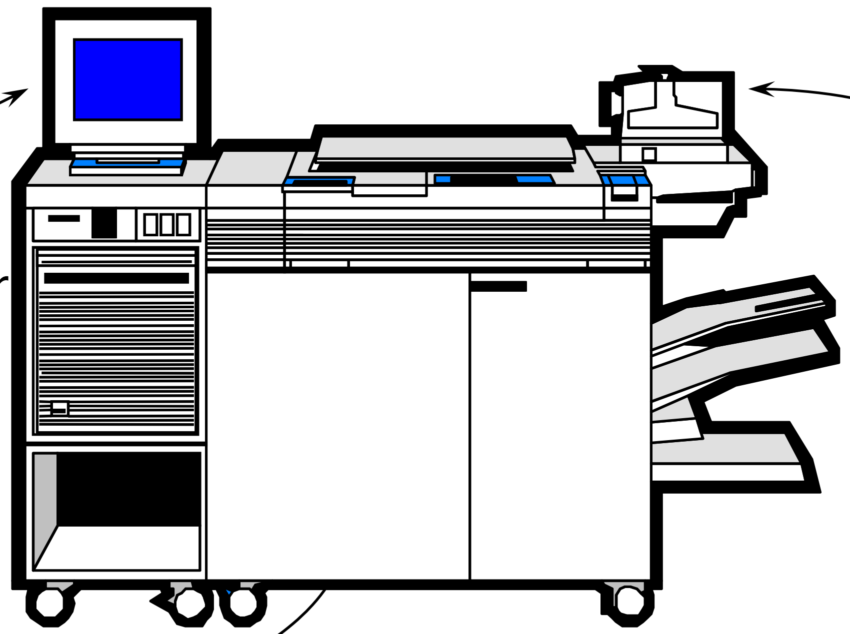
fastening + attaching leads

plug-in + soldering contacts

fastening + soldering contacts



Good Maintenance Design Methods?



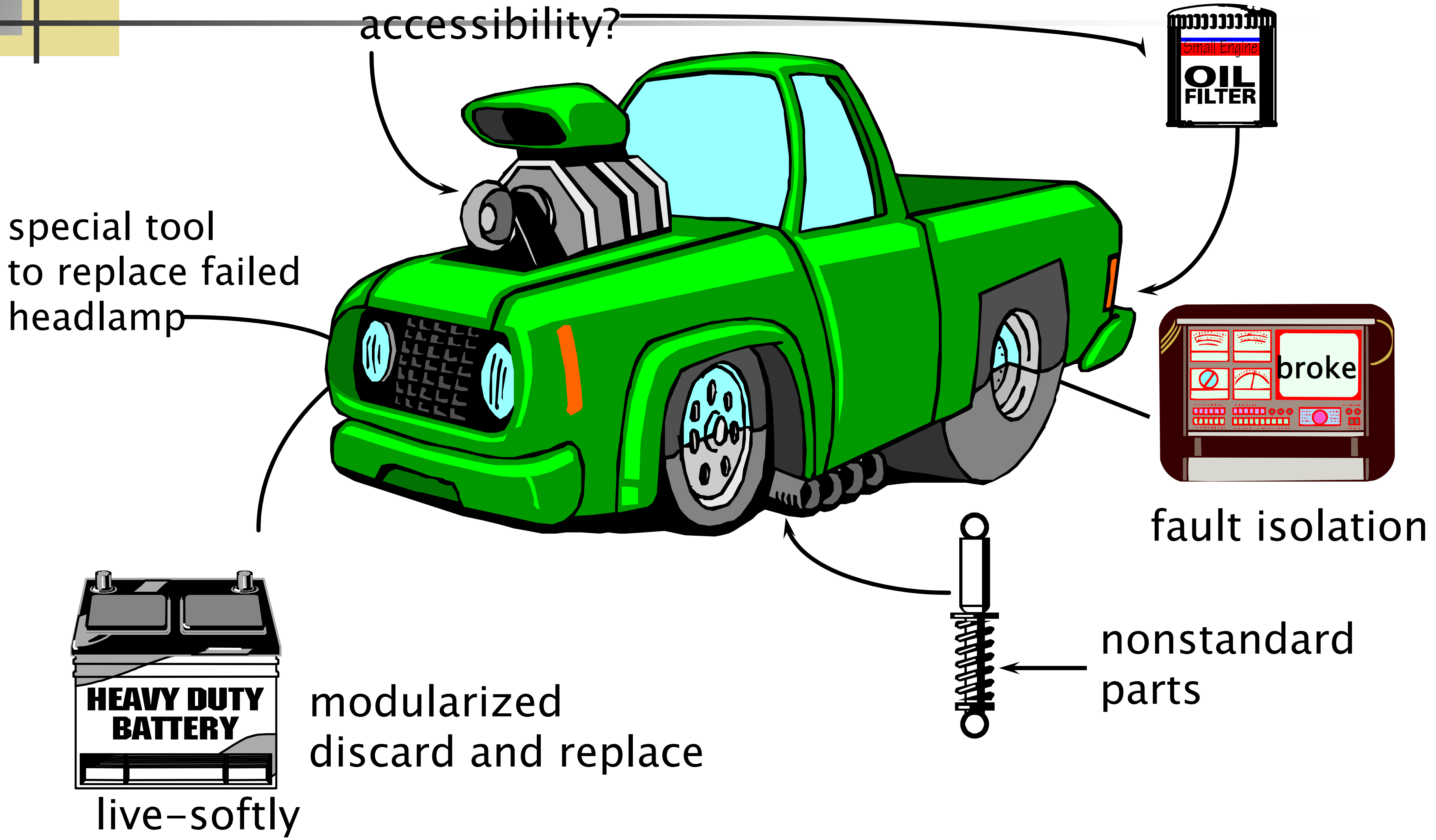
Fault Isolation
(failure mode codes
and location indicator

modularization

Accessibility
(pull out drawers)

supports operator maintenance

Poor Maintenance Design Methods?



Repair vs. Replacement

A Cost Trade-off Model

f = the number of part failures over the life of the system,
c = unit cost of the part,
a_r = fixed cost of repair
a_d = fixed cost of discarding where $a_d < a_r$
b_r = cost to repair a failure (e.g. labor rate x crew size x MTTR),
b_d = cost to remove and replace a part where $b_d < b_r$,
k = condemnation fraction

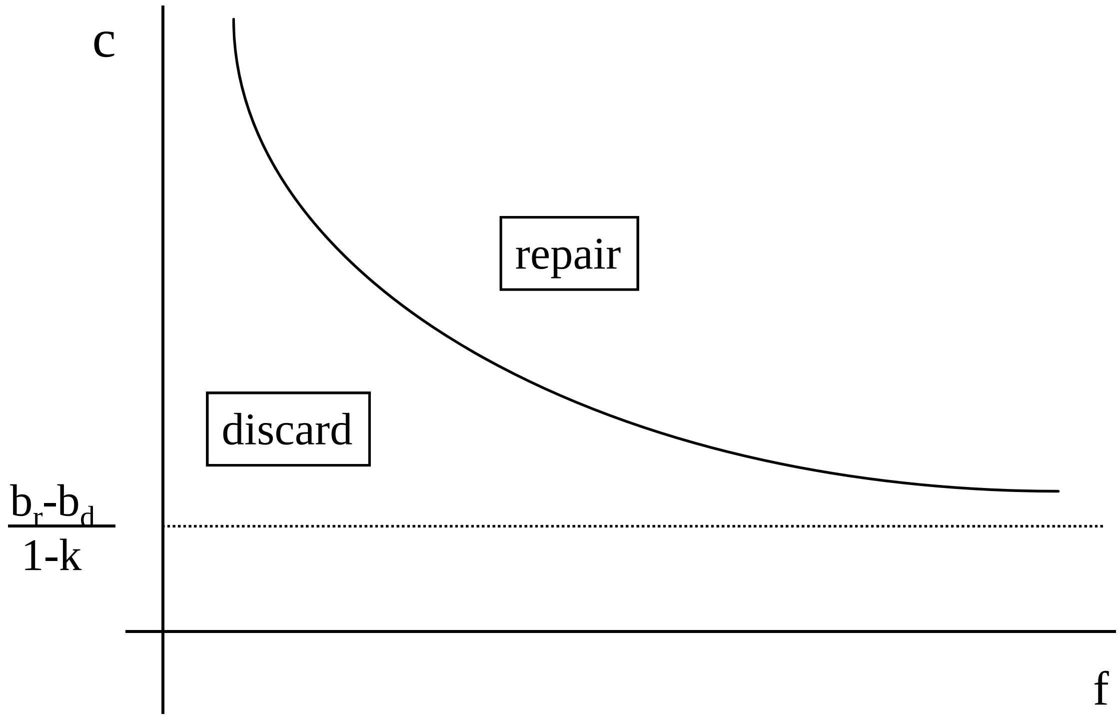
$$\boxed{\begin{array}{l} \text{repair cost} = a_r + b_r f + c k f \\ \text{discard cost} = a_d + (c + b_d) f \end{array}}$$

Repair vs. Replacement

If $\boxed{a_d + (c + b_d)\, f \;<=\; a_r + b_r\, f + c\, k\, f}$

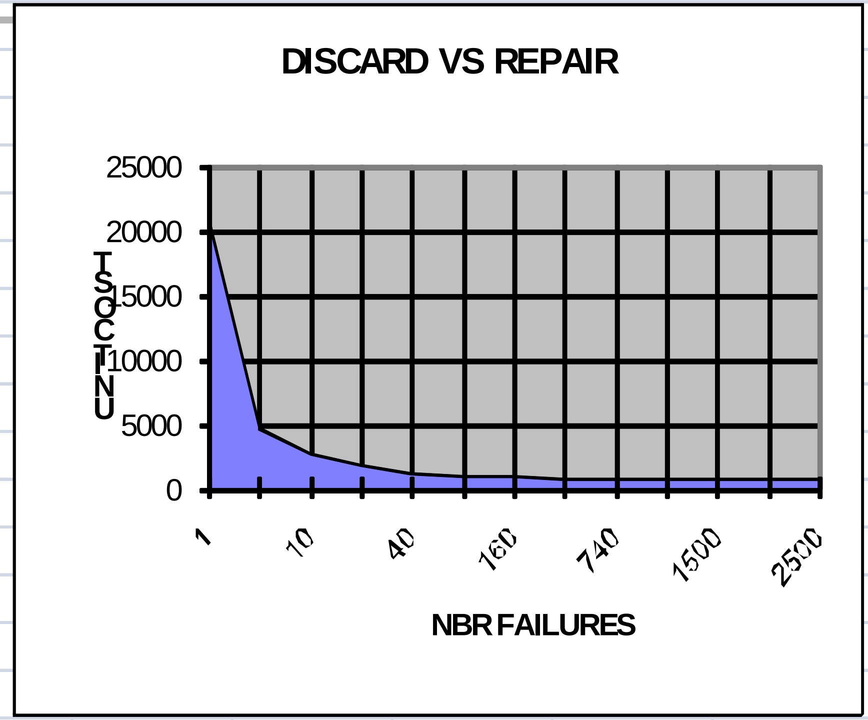
Then discard

$$c = \frac{a_r - a_d}{f\,(1-k)} + \frac{b_r - b_d}{1-k}$$



Example - circuit board

$c = 783.2 + 19789.5 / f$.



a_r = \$ 20,000 (primarily test equipment and facilities) ,

a_d = \$ 1200 (warehouse overhead for the spares),

b_r = \$ 768 / failure (\$48 / hr labor x 8 hr MTTR x 2 crew members),

b_d = \$ 24 / failure (\$48 / hr labor x .5 hr R&R x 1 crew member),

$k = .05$

Replacement Model

C_u = unit cost,
C_o = operating cost per unit of time,
C_f = cost of a failure
t = replacement time

$$C(t) = C_u + C_0 t + C_f \int_0^t \rho(t)dt$$

$$C = \frac{C_u}{t} + C_0 + \frac{C_f}{t} \int_0^t \rho(t)dt$$

Replacement Model

For the power law process:

$$C = \frac{C_u}{t} + C_0 + C_f a t^{b-1}$$

$$\frac{dC}{dt} = \frac{-C_u}{t^2} + (b-1)C_f a t^{b-2} = 0$$

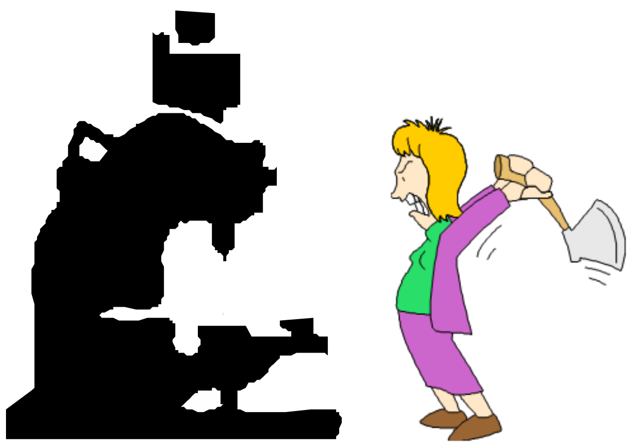
$$t^* = \left[\frac{C_u}{C_f a(b-1)}\right]^{1/b}$$

what if b <= 1?

Example 10.6

A repairable machine has a NHPP with an intensity function of $\rho(t) = 2 \times 10^{-6}\, t$ with t measured in operating hours. If the cost of a failure (repair) is \$500 and the unit cost is \$21000,

then $t^* = (21000/[(500)(10^{-6})])^{.5} = 6481$ operating hours.



Replace at 6481 hr

Replacement Model

For the log-linear intensity function:

$$C = \frac{C_u}{t} + \frac{C_f}{t}\int_0^t \rho(t)\,dt = \frac{C_u}{t} + \frac{C_f}{t}\frac{e^a}{b}\left(e^{bt} - 1\right)$$

$$\underset{t>0}{Min}\ \frac{C_u}{t} + \frac{C_f}{t}\frac{e^a}{b}\left(e^{bt} - 1\right)$$

Example 10.6 Revisited

$$\rho(t) = e^{-10+0.001t}$$

$$\underset{t>0}{Min}\ \frac{C_u}{t} + \frac{C_f}{t}\frac{e^a}{b}\left(e^{bt} - 1\right)$$

$$= \underset{t>0}{Min}\frac{21,000}{t} + \frac{500}{t}\frac{e^{-10}}{0.001}\left(e^{0.001t} - 1\right)$$

$$= \underset{t>0}{Min}\frac{21,000}{t} + \frac{22.7}{t}\left(e^{0.001t} - 1\right)$$

The Solution

t	cost per hour
100	210.02
200	105.03
500	42.03
1000	21.04
1500	14.05
2500	8.50
3000	7.14
3500	6.21
4000	5.55
4500	5.12
5000	4.87
5500	4.82
6000	5.02
6500	5.55
7000	6.55
7500	8.27
8000	11.08

The Solver way

t	cost per hour
5357.039	4.81

Some more of the Replacement Model

For the bounded intensity function:

$$\rho(t) = a\left(1 - e^{-bt}\right)$$

$$\underset{t>0}{Min}\,\frac{C_u}{t} + \frac{C_f}{t}\int_0^t \rho(t)\,dt$$

$$= \underset{t>0}{Min}\,\frac{C_u}{t} + \frac{C_f}{t}\left(at + \frac{e^{-bt}}{b} - \frac{1}{b}\right)$$

$$= \underset{t>0}{Min}\,\frac{C_u}{t} + C_f a + \frac{C_f}{bte^{bt}} - \frac{C_f}{b}$$

Preventive Maintenance

C_r = cost of a repair or replacement action,
C_s = cost of a preventive maintenance activity, where $C_r > C_s$,
T = time in hours between preventive maintenance activities, and
$\rho(t)$ = intensity function of a NHPP

$$E\left[N(T)\right] = \int_0^T \rho(t)dt$$

Expected hourly cost of unscheduled maintenance:

$$\frac{C_r}{T}\int_0^T \rho(t)dt$$

Preventive Maintenance

Total expected hourly cost: $TC = \frac{C_r}{T}\int_0^T \rho(t)dt + \frac{C_s}{T}$

For power law process:

$$TC = \frac{C_r}{T}\int_0^T ab\,t^{(b-1)}dt + \frac{C_s}{T} = C_r\,a\,T^{b-1} + \frac{C_s}{T}$$

$$\frac{dTC}{dT} = (b-1)C_r\,a\,T^{b-2} - \frac{C_s}{T^2} = 0$$

$$T^* = \left[\frac{C_s}{C_r\,a(b-1)}\right]^{1/b}$$

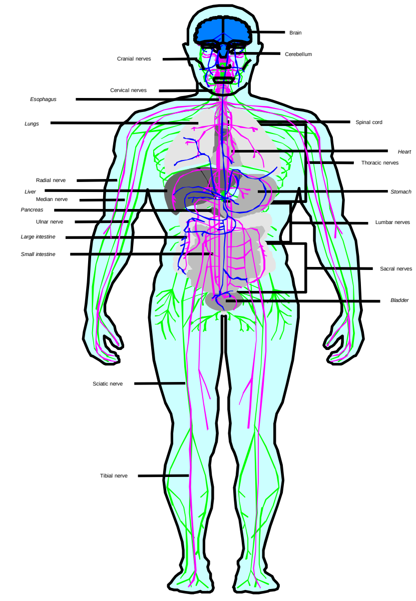
PM - Example

A grinding machine has a power law process (NHPP) with b = 2.4 and a = 2.55×10^{-5} hours. The cost of scheduled maintenance is \$20, and the cost of an unscheduled repair is \$80. Find the least cost preventive maintenance interval.

$$T^* = \left(\frac{20}{80(2.55x10^{-5})(2.4-1)} \right)^{\frac{1}{2.4}} = 40\ hrs$$

Human Factors

- Anthropometry - study of human body dimensions
- Biomechanics - how movements are performed
- Physiology - study of human processes such as muscle movements and joint system
- Psychophysics- study of human perceptual capability
- Perception - how information is received, stored, and interpreted
- Human Performance - how humans interface in the workplace



Design for Maintainability

Human Factors Considerations:

Controls

Displays

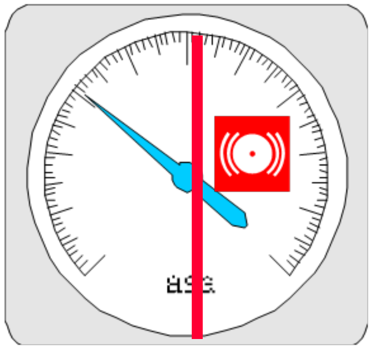
Tool and equipment design

the workplace

the environment

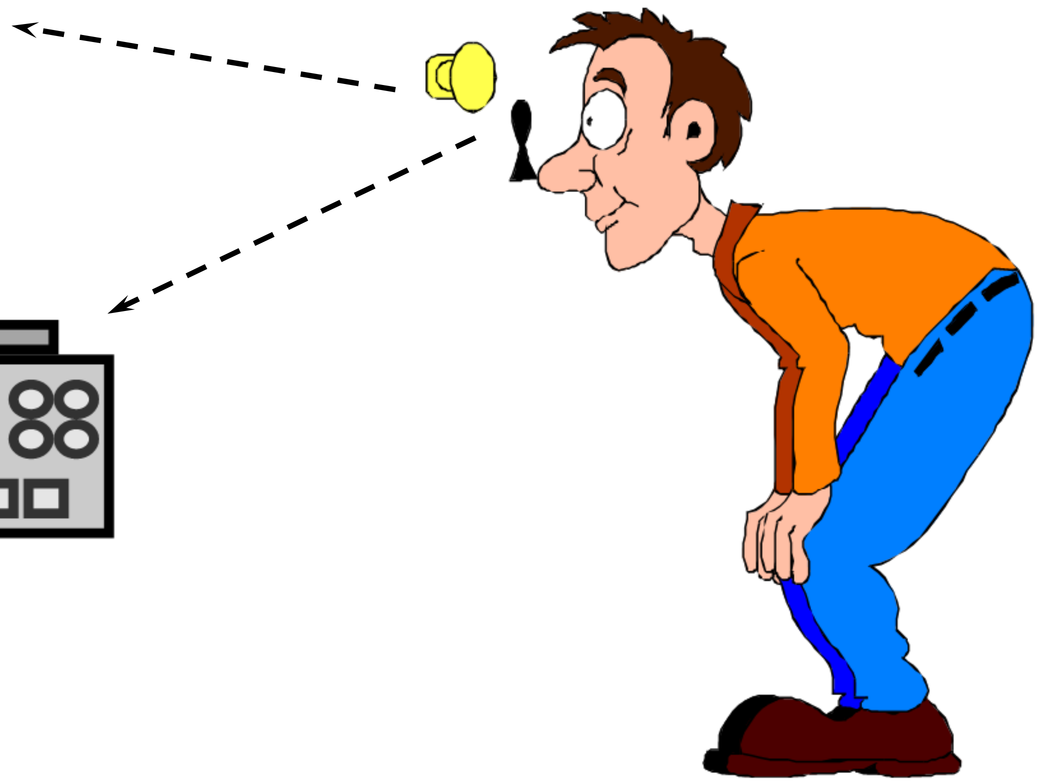
The Coffee is terrible.
I can't work here!

Controls and Displays



analog

Displays should be placed at eye level!



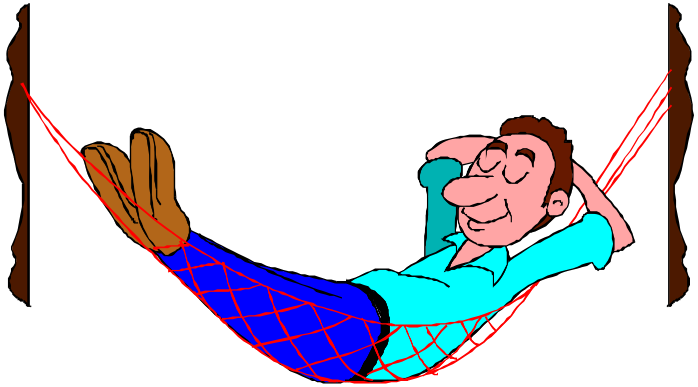
digital

Selected Human Factors Data

Measurement	5th percentile	50th percentile	95th percentile
Eye height - males	60.8 in	64.7 in	68.7 in
Eye height - females	57.3	60.3	65.3
Forward reach - males	31.9	34.6	37.3
Forward reach - females	29.7	31.8	34.1
Standing height - males	63.6	68.3	72.8
Standing height -females	59.0	62.9	67.1
Weight - males	124 lbs.	168 lbs.	224 lbs.
Weight - females	104	139	208

The Working Environment

- Noise
  - pain at 130 db
- Illumination
  - 50 foot-candles for dials, gauges, and meters
- Vibration
  - exposure limits depends on frequency and amplitude
- Ambient Air
  - temperature (55^0 to 75^0 F.)
  - humidity



Human Reliability

human reliability: $R_h = 1 - e/n$
n = number of tasks
e = number of unsuccessful completions

Task	error rate (per task)
read 5 letter word incorrectly	.0003
read digital display wrongly	.001
leave light on	.003
select wrong switch among similar	.005
read 10 digit number incorrectly	.006
mate a connector wrongly	.01
wrong selection –vending machine	.02
dial 10 digits incorrectly	.06
fail to check hardware unless specified	.1
fail to notice wrong position of valves	.5

Human Errors

- random - unbiased
  - stress level too high -panic, time constraints
  - stress level too low - boredom
- systematic
  - biased, casual effect
  - improper tools
  - incorrect procedures
- sporadic
  - carelessness
  - forgetfulness

Causes of Human Error

- Poor training and low skill levels
- Inadequate maintenance or operating procedures
- Inadequate supervision
- Poor working environment
- Improper or lack of motivation

Skill Levels

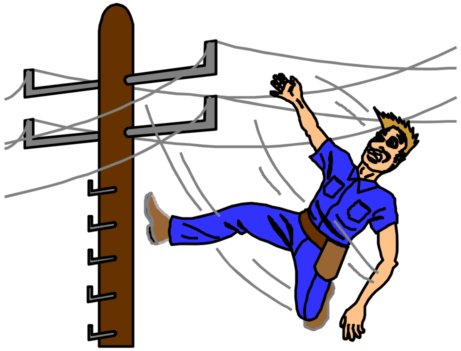
Effective maintainability is dependent upon the designer's being fully aware of the limitations of maintenance personnel.

The average technician performing maintenance should **not** be expected to:

- read at higher than ninth grade level,
- perform any mathematical calculations including simple addition and subtraction,
- consolidate or integrate any information from several different sources,
- collect, process, or report any unusual or complex data,
- and post data from one form to another or keep any records.

Maintainability Engineering, US Army Materiel Command, 1965

Human Factors Considerations



- minimize skill requirements
- minimize tools and test equipment
- minimize adjustments and calibrations
- allow for visual inspection if possible
- put handles on heavy equipment
- use bad-good or redline meters - avoid numerical readouts

In Conclusion
Ideal Design Criteria for Maintainability

- Maintenance is available on site with no waiting
- Fault isolate is immediate and accurate
- Access is direct
- Necessary spare parts are on-hand
- Maintenance is remove and replace with no tools required
- No requirement to recalibrate, adjust, align or otherwise verify