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Elevators

18-649 Distributed Embedded Systems
Philip Koopman
September 2, 2015

Picture source: [Strakosch98] Vertical Transportation Handbook

**Carnegie
Mellon**

Where Are We Now?

◆ **Where we've been:**
  • Real-time Embedded Control Systems

◆ **Where we're going today:**
  • You generally need to know something about the system you want to design beyond just the written specifications(!) = "domain knowledge"
  • Elevators: a distributed real-time embedded control system example
    – Gathering "domain knowledge" for course project
    – Example of factors other than digital electronics that embedded system designers need to understand to do their job

◆ **Where we're going next:**
  • Requirements; More on design process
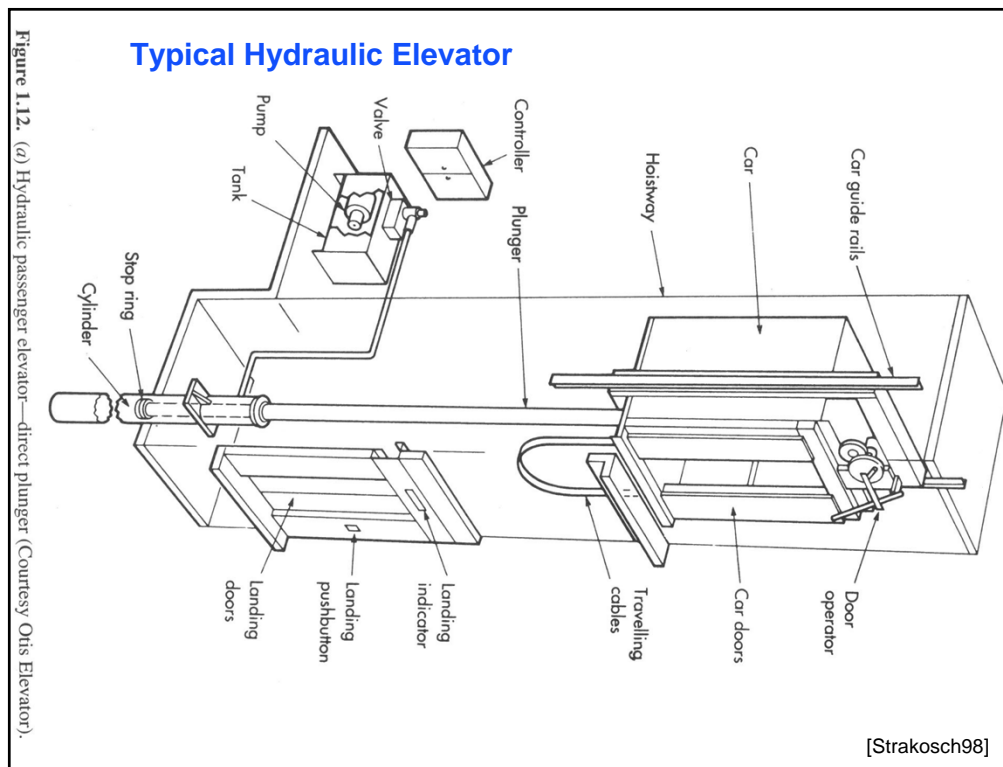 • An embedded view of distributed systems

Project Note:

◆ **This project is more open-ended than it might appear**
- Some details are unspecified
- Some behaviors are more subtle than you will see at first, and you will have to revise your understanding as you work through things
- Many problems have multiple, equally valid solutions
- Some solutions are probably better than others, but a "satisficing" solution is all that is required in many cases
- Scenarios have a lot of flexibility – make any reasonable assumptions

◆ **In most cases, the answer to "is this the right way to do it?" is some combination of the answers to:**
- Will it work?
- Is it reasonable? Did we explicitly forbid it?
- Is it exploiting a bug in the simulator or otherwise unreasonable?
- For the first weeks, if you're not sure about *elevator technical details* take a guess (confirm with real elevator). Ask for help with process questions at office hours.
- **Any reasonable technical solution that we don't forbid is OK to do. There is no single "right" answer! There are no "trick" penalties.**

Preview

◆ **Status check**
- Everyone should be tracking assignments on course schedule grid at:
  http://www.ece.cmu.edu/~ece649
- **Blackboard has announcements and grades**
- **TA office hours will be announced on blackboard**
- **Initial the attendance sheet during every class!**
  - **Attendance sheet circulation times may vary**
- **Project groups will form as soon as next pass on enrollment is settled**

◆ **Elevators are a lot more complicated than people generally think**
- Multiple computers per elevator car
- Multiple cars coordinated within a building
- Very difficult optimization problems for delivering passengers efficiently

◆ **Many different design considerations**
- Combining mechanical & electronic technology
- Performance optimization
- Human interface
- Safety
- Unconventional installations

Project Example: Elevator

- ◆ **Motor control**
  - Firm real time
  - Safety critical
  - Mechanical interlocks
  - Fail safe
- ◆ **Door control**
  - Soft real time
  - Somewhat safety critical
  - Mechanical interlocks
  - Fail safe
- ◆ **Many other subsystems**

- ◆ **Most electronics for I/O and power (replaces relays)**

(HH Elevator until 2014)

Typical Hydraulic Elevator

Pump
Valve
Controller
Tank
Plunger
Hoistway
Car
Car guide rails
Stop ring
Cylinder
Landing doors
Landing pushbutton
Landing indicator
Travelling cables
Car doors
Door operator

Figure 1.12. (a) Hydraulic passenger elevator—direct plunger (Courtesy Otis Elevator).

[Strakosch98]

High Performance Elevators

◆ **Electric motors**
- Cables instead of hydraulics
- AC or DC
- Fixed or variable speeds

◆ **Typical price-performance list:**
- 1-speed
- 2-speed
- Variable speed medium duty
- Variable speed heavy duty

The 51-story Woolworth Building still has the Otis gearless traction machinery installed in 1912.

[Strakosch98]

Basic Elevator

◆ **Counterweight at ~40% full load weight**
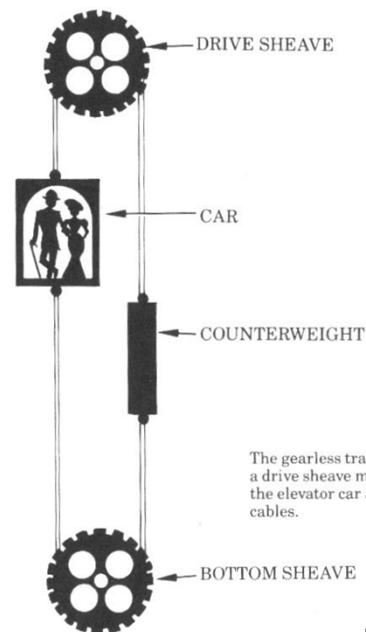- Smaller motor required than without counterweight
- Less power consumed

◆ **Bottom cables help balance load**
- 1000 feet of cable is a lot of weight!

◆ **Late breaking news – Otis is switching from cables to belts of linked steel plates**
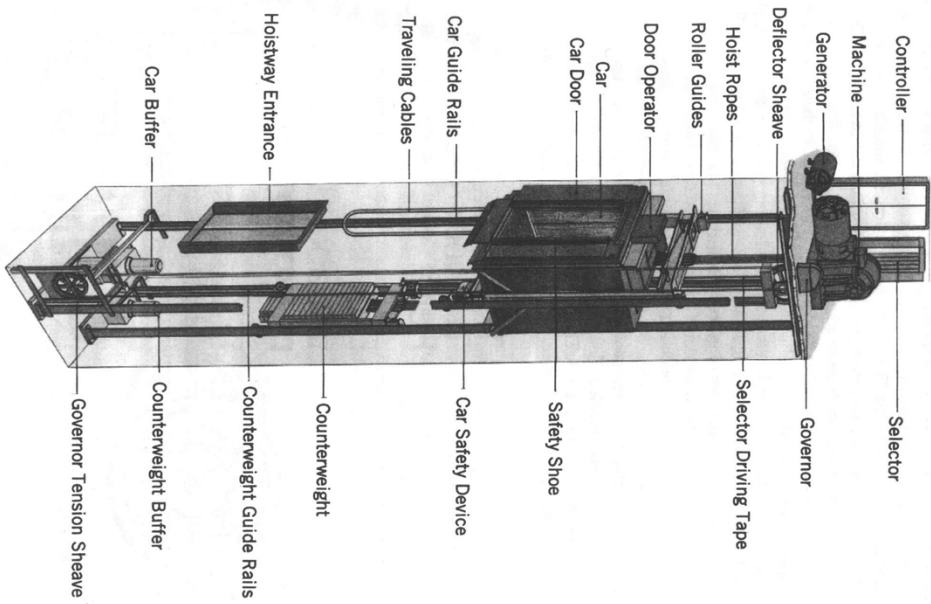- More or less a chain drive
- More flexibility means smaller motor required

DRIVE SHEAVE

CAR

COUNTERWEIGHT

The gearless traction design has a drive sheave mounted above the elevator car and a number of cables.

BOTTOM SHEAVE

[Strakosch98]

Controller
Machine
Generator
Deflector Sheave
Door Operator
Roller Guides
Hoist Ropes
Traveling Cables
Car Guide Rails
Car
Car Door
Holstway Entrance
Car Buffer

Selector
Governor
Selector Driving Tape
Safety Shoe
Car Safety Device
Counterweight
Counterweight Guide Rails
Counterweight Buffer
Governor Tension Sheave

(b)
Figure 1.5. *(Continued)*

[Strakosch98]

High Speed DC Gearless Elevator

Selector
Machine
Hoist Ropes
Roller Guides
Door Operator
Car
Travelling Cables
Car Guide Rails
Roller Guides
Compensating Cables
Car Buffer

Starter and Controller
Motor Generator Set
Secondary Sheave
Governor
Terminal Stopping Switch
Final Limit Switch
Final Limit Cam
Car Safety Device
Terminal Stopping
Switch Cam
Counterweight
Counterweight Guide Rails
Final Limit Switch
Governor Tension Frame

Figure 1.5. *(a)* Gearless elevator installation (Courtesy Otis Elevator). *(b)* Geared elevator installation (Courtesy Otis Elevator).

(a)

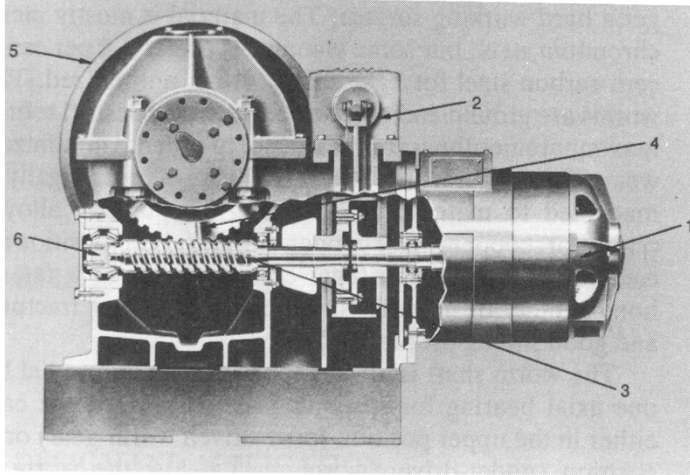[Strakosch98]

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Getting from Here to There

Fig. 4.1 — A typical under-driven worm-gear (Otis Elevator Co.).
1. a.c. driving motor
2. d.c. brake
3. Worm and worm shaft machined in one piece
4. Worm wheel
5. Traction sheave
6. Tapered roller bearings

[Strakosch98]

Acceleration/Deceleration

- **Acceleration profile:**
  - Constant jerk
  - Constant acceleration
  - Constant velocity
- **Deceleration is the reverse, but with leveling period**
  - Leveling is slow movement to get last fractions of an inch movement
  - 0.5 sec leveling period is only representative
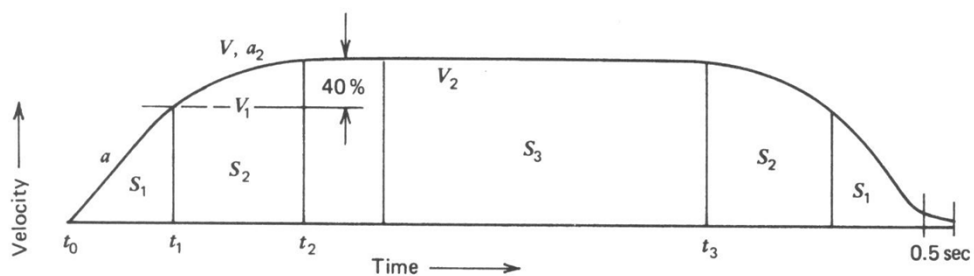
Figure 7.3. Elevator travel—velocity versus time.

[Strakosch98]

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Peak Speed Varies By Distance

◆ **Need to keep acceleration limited for fragile passengers**
- Extra-straight & smooth rails to minimize bumping at high speed
- Also, limited by air pressure change on very large buildings
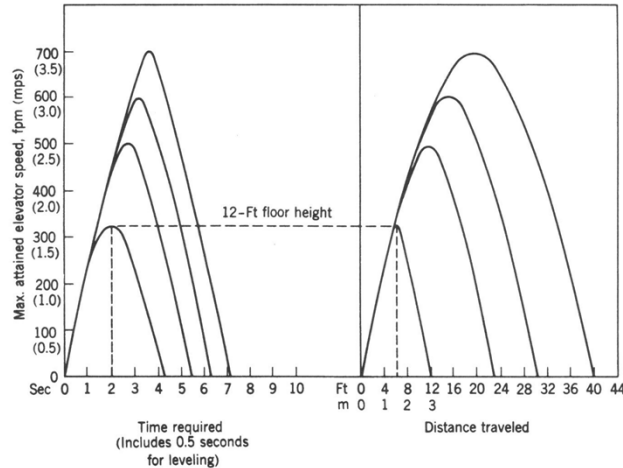- Motor size is a minor consideration – buying a bigger motor is easy

Figure 7.4. Elevator speed versus time and distance.

[Strakosch98]

Leveling

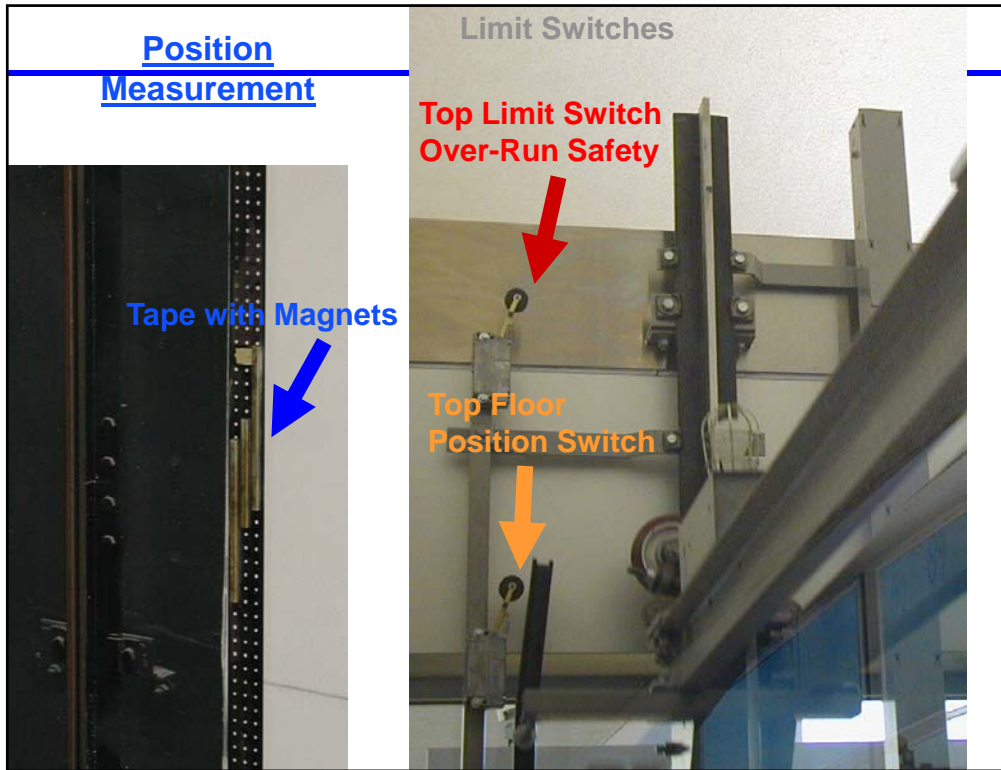◆ **"Leveling" is when elevators correct a small alignment mismatch**
- Elevator slightly below floor … need to go back up
- Elevator slightly above floor … need to go back down

◆ **Leveling is required due to following:**
- Cable slip on drive sheave when slowing down causing overshoot of floor
- Passengers enter elevator, causing cable to stretch
  - Elevator sags every time someone enters
- Passengers exit elevator, causing cable to shrink
  - Elevator springs upward every time someone leaves
- If you have 1000' of cable, it doesn't take much weight to cause noticeable stretching!

◆ **Course project elevator requires leveling**
- Passengers won't enter if elevator isn't level
- This means you might have to move even while loading passengers
  - Safety shutdown applies if you move out of the leveling zone with doors open
- (Also note: project elevator has front doors and back doors)

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Position Measurement

Limit Switches

Top Limit Switch Over-Run Safety

Tape with Magnets

Top Floor Position Switch

A Smooth Ride

◆ **Roller guides follow T-shaped railing**
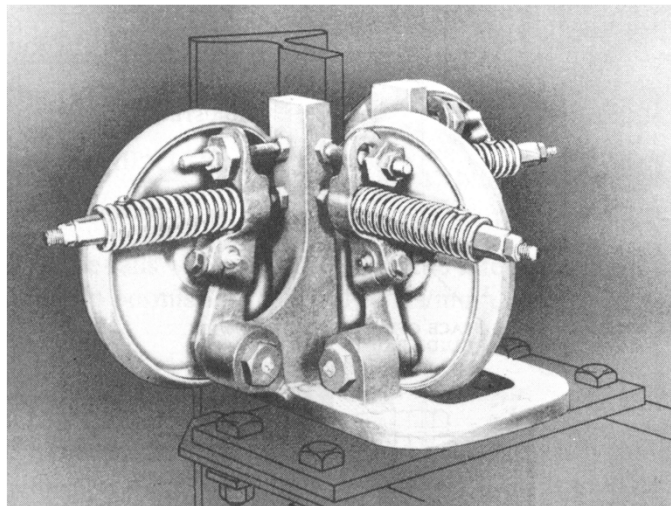 • Bumps in guides give rough ride, even with shock absorbers

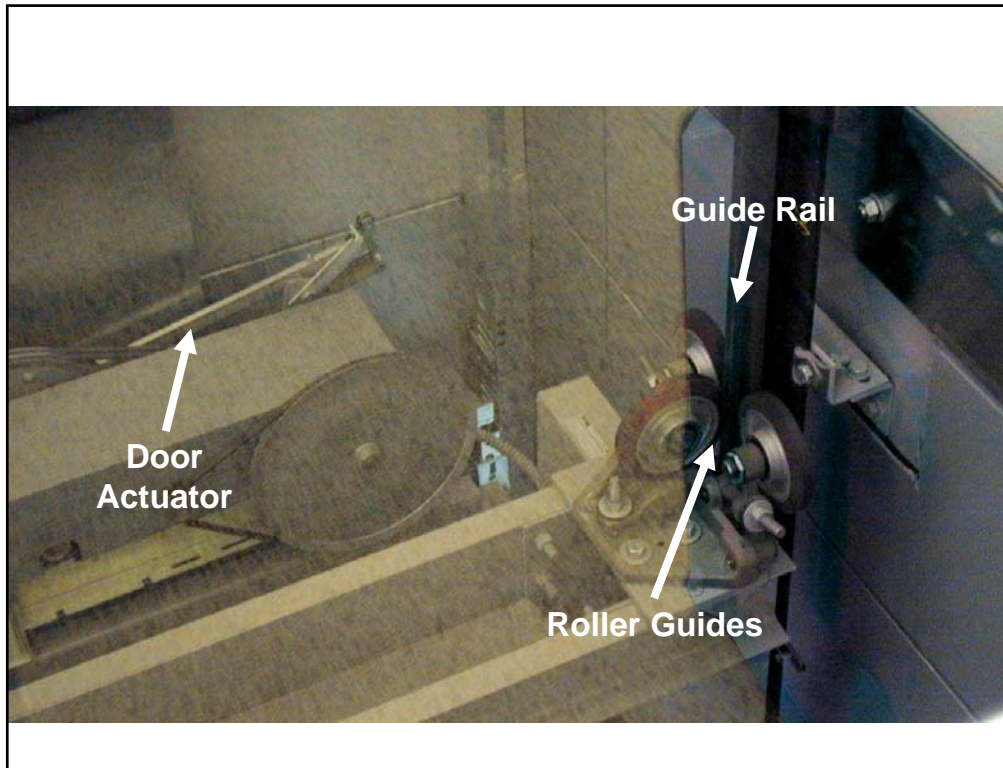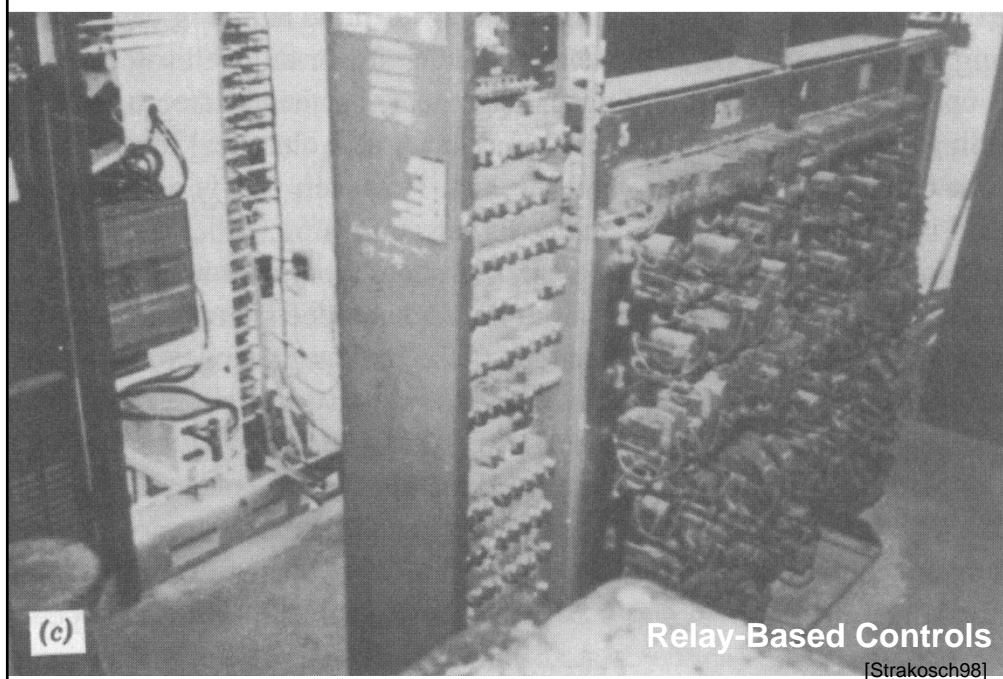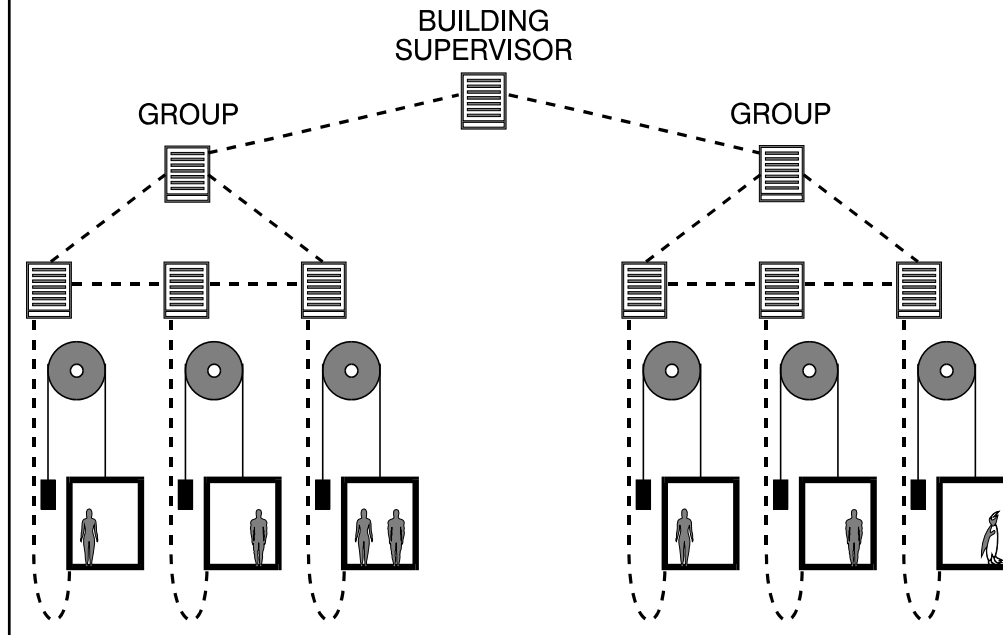Fig. 7.8 — Roller guide shoes (Otis Elevator Co.).

[Strakosch98]

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Guide Rail

Door Actuator

Roller Guides

Control Electronics

(c)

Relay-Based Controls

[Strakosch98]

Hierarchical Control Architecture

◆ **Typically up to 8 cars per group; 8 groups per building**

BUILDING
SUPERVISOR

GROUP

GROUP

Old Days: Relay Control

◆ **Remember that relay computers used to exist**
- Big relays used to control power
- Little relays used to implement switching logic
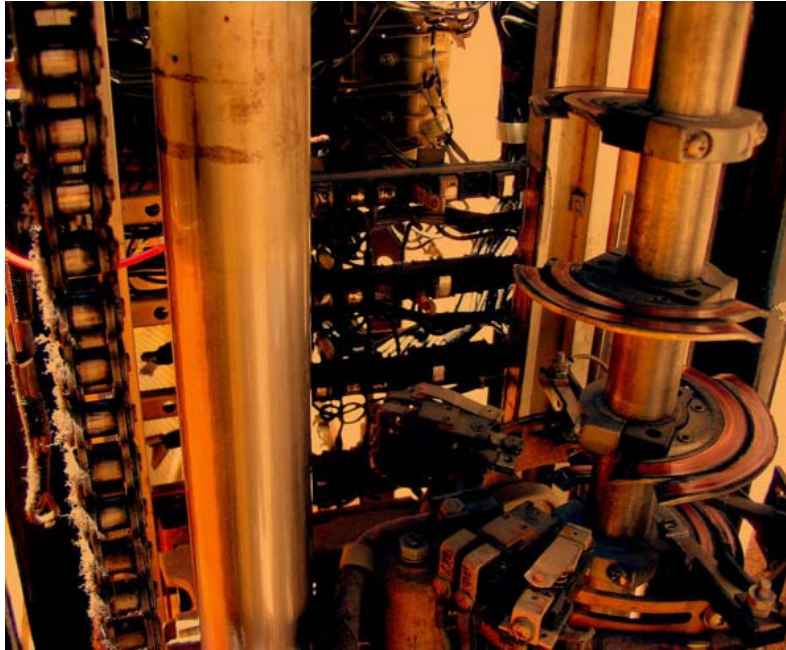- Many elevators are hybrid computer + relay

http://www.wadeinstruments.com/relays/control_relay_tutorial.htm

A modern controller high atop Detroit's Plaza Hotel. [Strakosch98]

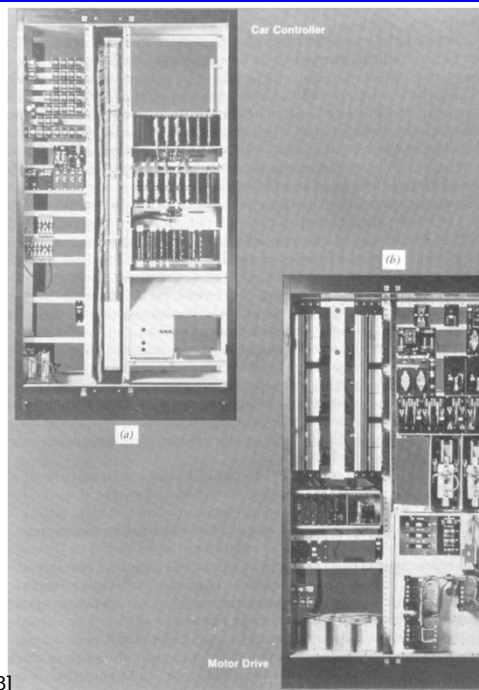http://www.elevatorbobs-elevator-pics.com/elec_sel.html

Modern: Electronic Control

◆ **High-end CPUs for control algorithms**
  - e.g., Pentium-class CPU

◆ **Most of area is for power switching**
  - Still some relays
  - Power electronics

[Strakosch98]

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Embedded Distributed Architecture

◆ **Separate Control Systems for many functions**
- (Real elevators have more than are shown here.)

CAR 1 CAR 2 CAR 3 CAR 4 CAR 5 CAR 6 CAR 7

GROUP 0

BRIDGE

BUS

BRIDGE

CAR 0

BUS

OPERATION

MOTION

DRIVE

DOOR

DISPATCH

GROUP 1
GROUP 2
GROUP 3
GROUP 4
GROUP 5
GROUP 6
GROUP 7

BUILDING BUS

REMOTE MONITORING

BUILDING CONTROL
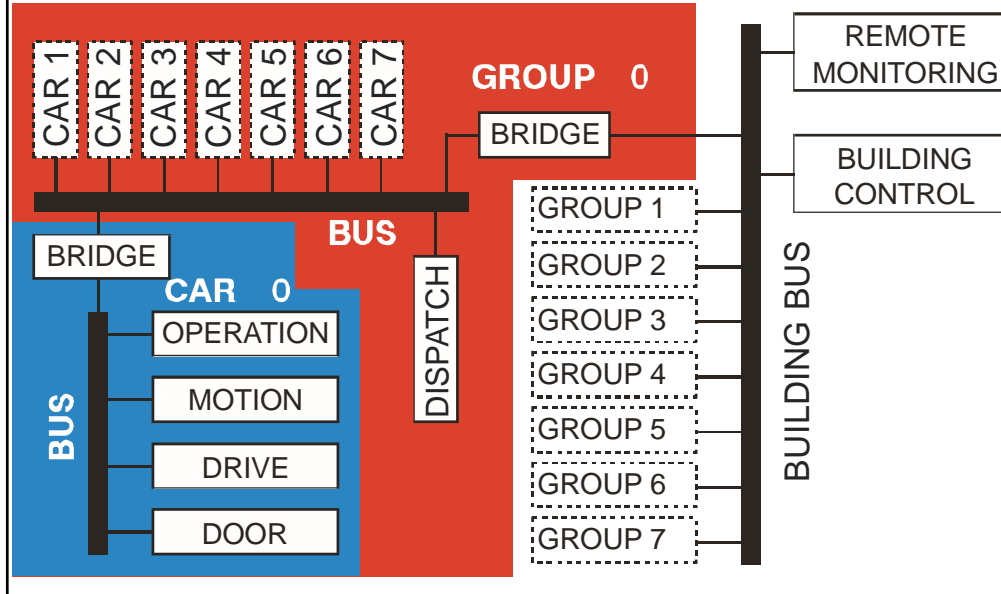
The Otis Safety Brake

Figure 1.2. (*a*) Otis's demonstration, Crystal Palace, New York, 1853. (*b*) Otis's patent sketch for a safety device (Courtesy Otis Elevator).

[Strakosch98]

Emergency Braking
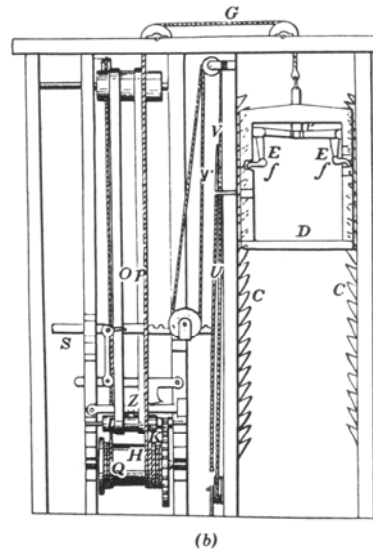
◆ **Speed governor trips safety gear**

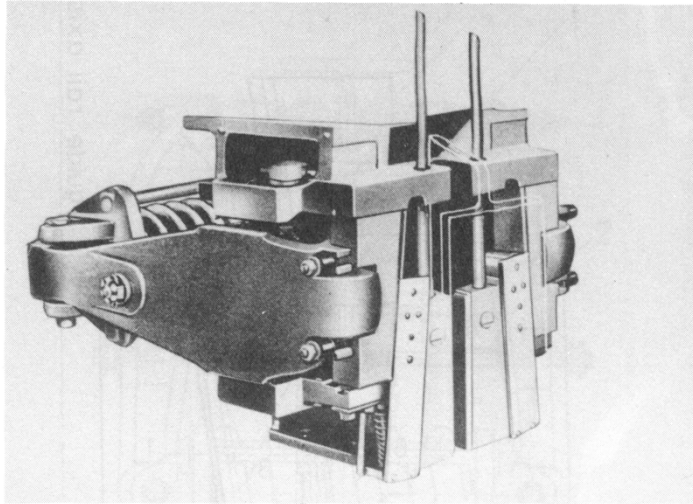 • Note that falling "up" is more likely than falling down

Fig. 8.7 — Flexible guide clamp safety gear for heavy duty elevators (Otis Elevator Co.)

[Strakosch98]

Safety Features

Pit Stop Switch Light Switch & Ladder

Car Safety & Structural Steel Car Frame

Door Operator & Door Protection
Top of car operating device & light

Deflector Sheave (Under Machine Room Floor)

Governor

Rope Brake

Figure 2.8. Safety features of elevators: mechanical and electrical (Courtesy G.A.L. Manufacturing Corp. and Hollister-Whitney Corp. (photos), and Leibowitz Communications).

Interlock

Car & Counterweight Buffers

Lower Stopping & Reversal Limits

Counterweight

Floor Selecting Device

Upper Stopping & Reversal Limits

Controller

Machine Motor Brake

[Strakosch98]

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Human Interface

Modern Elevators Are Robots

◆ **Operator inputs are guidance to the robot, not necessarily commands**
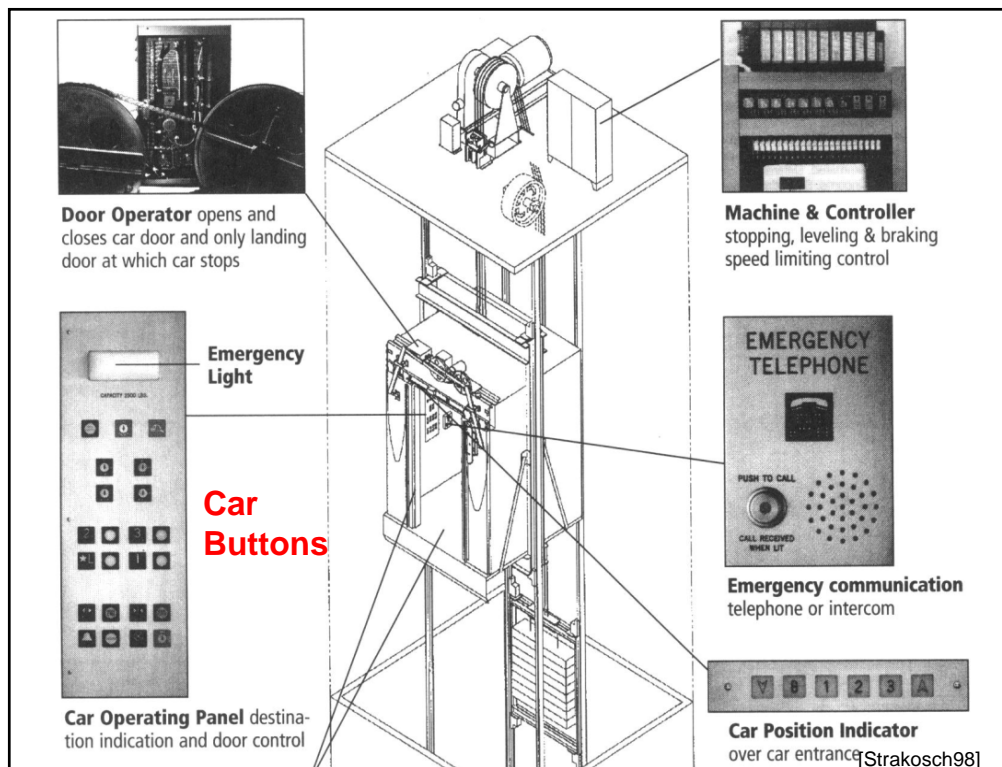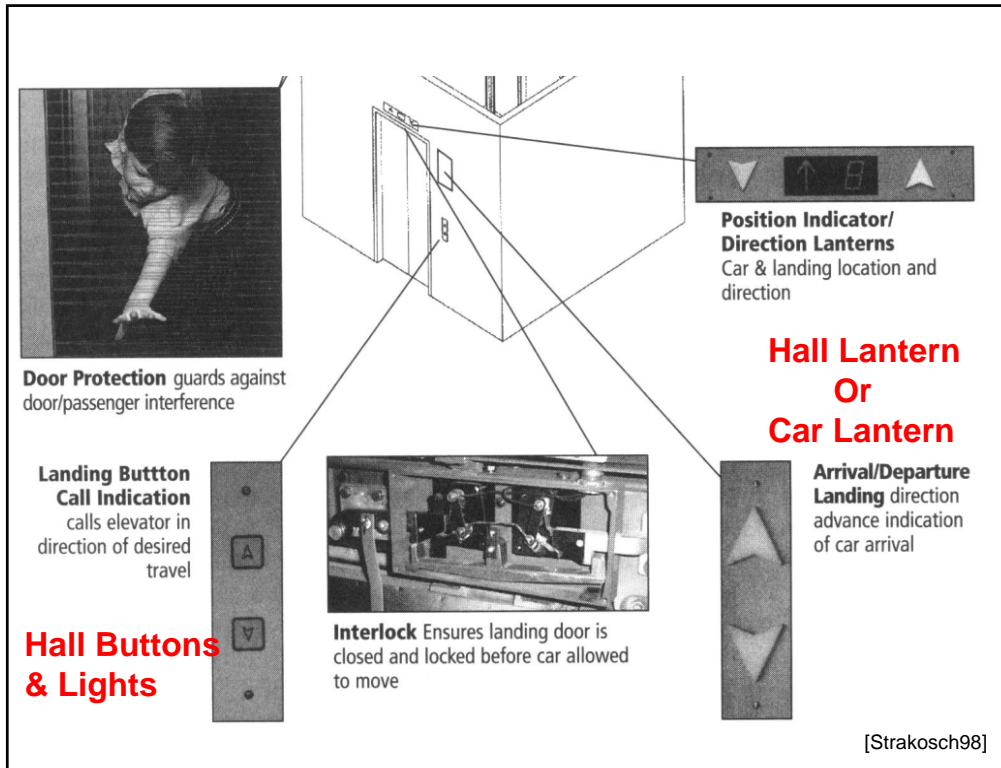

Fig. 12.1. Elevators being modernized while one car (center) continues in operation. [Strakosch98]

Door Operator opens and closes car door and only landing door at which car stops

Machine & Controller stopping, leveling & braking speed limiting control

Emergency Light

Car Buttons

EMERGENCY TELEPHONE

Emergency communication telephone or intercom

Car Operating Panel destination indication and door control

Car Position Indicator over car entrance [Strakosch98]

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Position Indicator/
Direction Lanterns
Car & landing location and direction

Hall Lantern
Or
Car Lantern

Door Protection guards against door/passenger interference

Landing Buttton Call Indication calls elevator in direction of desired travel

Hall Buttons & Lights

Interlock Ensures landing door is closed and locked before car allowed to move

Arrival/Departure Landing direction advance indication of car arrival

[Strakosch98]

Manual Doors

◆ **Culzean Castle, Scotland**

PLEASE CLOSE
BOTH DOORS
FIRMLY WHEN
ENTERING AND
LEAVING THE LIFT

Excerpt from "50 Fun Things to Do in an Elevator"

◆ **When arriving at your floor, grunt and strain to yank the doors open, then act embarrassed when they open by themselves.**

◆ **Greet everyone getting on the elevator with a warm handshake and ask them to call you, "Admiral".**

◆ **Meow occasionally.**

◆ **Say, "Ding!" at each floor.**

◆ **Stare, grinning, at another passenger for a while, and then announce, "I've got new socks on!"**

◆ **Bring a chair along.**

http://quest.nasa.gov/space/teachers/liftoff/micro.html

◆ **[bonus] Say: "I've done a design review of the software in this elevator" and then hold onto the side railings for dear life.**
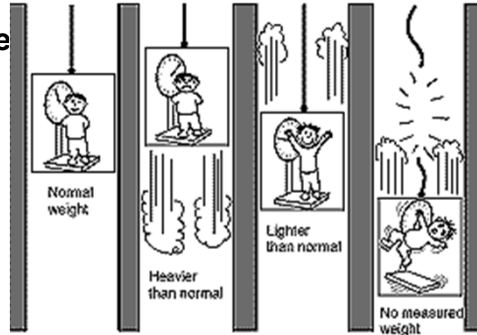
Disclaimer: The 18649 course staff do not advocate or recommend any of these practices. Jumping in an elevator can trigger the safety brake.

Elevators "Controlling" People

◆ **Elevators make people move via lights & other behaviors**
  - People get in when correct hall lantern direction is illuminated
    - Special case: neither lantern illuminated means everyone gets in
  - People get out when correct floor shown on car floor indicator
  - People press buttons until they see button light illuminate as confirmation

◆ **Special door & alarm behavior**
  - Alarm sounds when car is over-weight
    - If doors open, people will get out when they hear the alarm
  - Door "nudge" is there to shove people out of the way
    - Slow speed door operation with low torque
    - Door reversal is inactive during nudge – it nudges people out of the way

Elevatoring

◆ **Performance analysis and optimization**

◆ **How many hoistways per building?**
  - Elevator hoistways are *expensive* (area multiplies for every story)
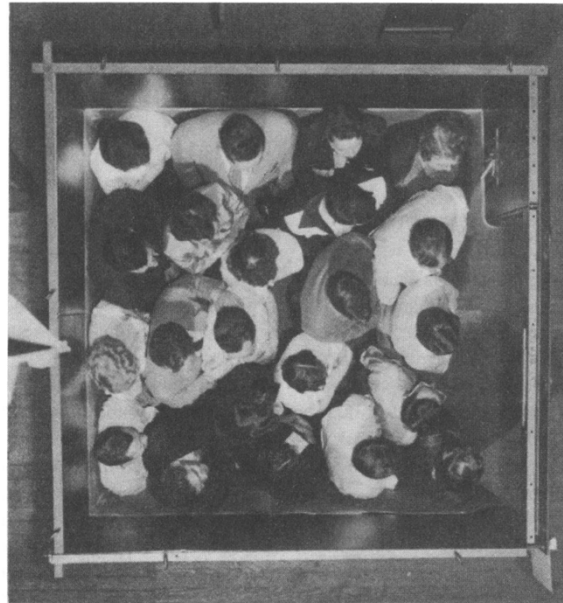 - Limit to building size is elevator capacity

Figure 6.1. Heavy elevator car loading. [Strakosch98]

Daily Usage Profiles

◆ **"Up-peak" during morning rush hour**
  - Send cars to lobby
◆ **"Down-Peak" in evening**
  - Optimize for people heading to lobby
◆ **Profiles differ by building type, hour, day-of-week, and building design**
  - Some buildings even have lobbies on the 5th floor...


(a) Professional building
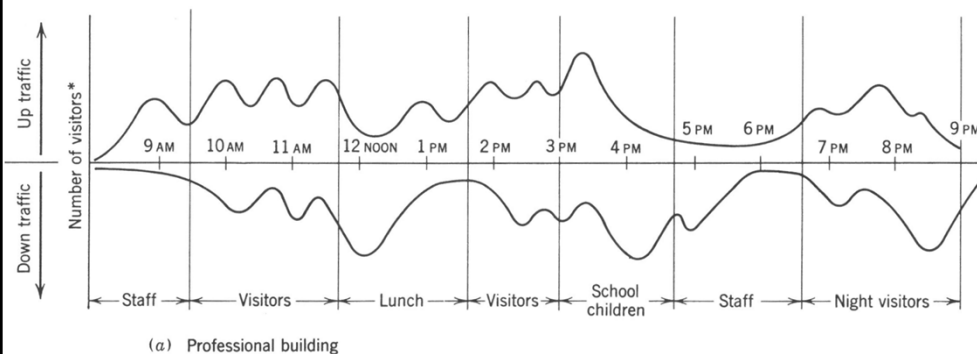
[Strakosch98]

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Key Concepts For Dispatching

◆ **Dispatching: assigning a particular car to stop at a particular floor**
  - Group dispatching (multiple cars) is really difficult to do well
  - We're doing one car to make it easier

◆ **Key concept: Desired Floor**
  - The floor the dispatcher wants to stop at next (usually due to button press)
  - Might be different than current floor elevator is on
  - Can vary with time as new button presses arrive

◆ **Key concept: Commit Point**
  - Point after which it becomes too late to stop at a floor
  - Might be multiple floors away due to acceleration profile
  - Varies depending on current elevator speed

◆ **Key concept: Desired Direction**
  - Direction elevator will travel *after* the next stop
  - Will be different than direction of motion at end of a run
    – Example: Elevator is currently at floor 5 (current floor) moving up (current direction); dispatcher wants to stop at floor 7 (desired floor) and after that go down (desired direction);
    dispatcher decelerates starting 6 m before floor 7 (commit point); stops at floor 7;
    doors open and the Down Hall Lantern is illuminated when doors open on floor 7.

Commit Point Calculation

◆ **Stopping distance:**
  The distance between where you are now and where you can stop
  - Assumes following normal (non-emergency) acceleration profile
  - At high speeds, this might be multiple floors away

◆ **Commit Point:**
  The elevator position at which you must decide whether to stop at particular floor
  - Occurs when elevator reaches the stopping distance from that floor location
  - This is a function of elevator speed!

◆ **When you pass the commit point, you lose the option of stopping**
  - Even if you still haven't reached the floor yet
  - Think of the "point of no return" for that floor

Elevator Motion Profiles
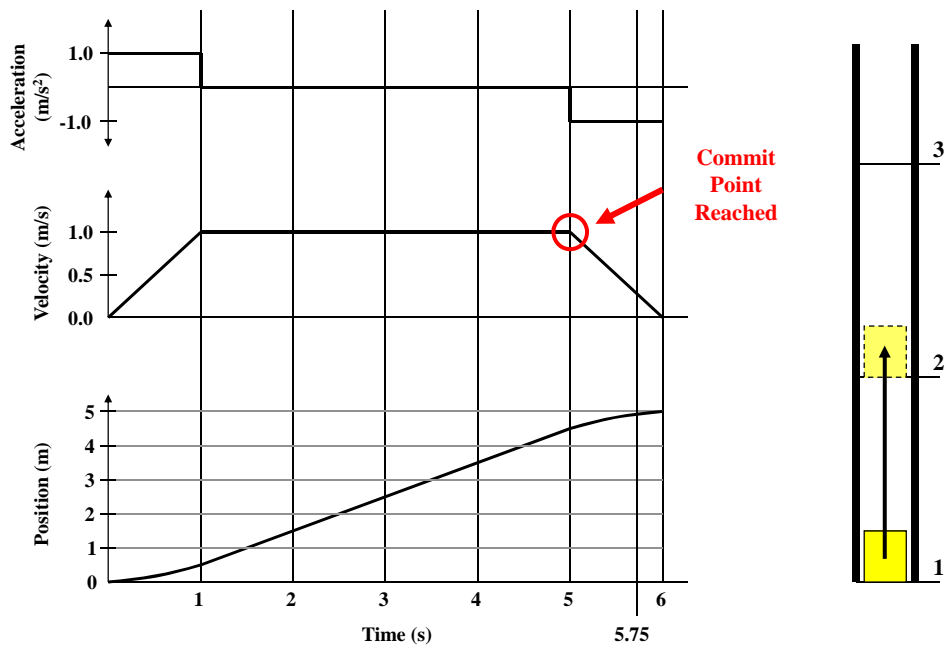
Using The Commit Point

◆ **The commit point gets further away as speed increases**
   • When stopped, the commit point is exactly at the floor
     (stopping distance = 0)
   • At high speeds, commit point is several floors away from elevator position

◆ **The course project elevator can stop "instantly" from slow speed**
   • But, from fast speed you need to ramp down

◆ **Computation must be conservative, take into account**
   • Granularity of sensor inputs
   • Worst case network delays

◆ **Controllers need to have a consistent notion of commit point**
   • Not too difficult in the fault-free case, or with dropped message faults

◆ **In real elevators, how does commit point usually affect car floor indicator?**
   • Why?

A *Few* Elevator Operating Modes

◆ **Parking / shutdown**
◆ **Maintenance / inspection modes**
◆ **Independent service**
   • Someone can control elevator with controls in the car
   • Ignore hall calls
   • Useful for movers, operators in fancy hotels or stores
◆ **Building security**
   • Restrict access to some floors
   • Card key or key code access only
   • Homing to lobby for visual inspection of the car
◆ **Maternity ward mode**
   • Babies are tagged with RFID bracelets
   • Elevator automatically returns to maternity ward if bracelet is detected
◆ **Sabbath / Streetcar mode**
   • Sabbath observance prohibits doing work, including pressing buttons
   • Behavior similar to the baseline dispatcher from course project

[Photo credit: http://commons.wikimedia.org/wiki/File:Sabbath_on-off.j

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A *Few* Emergency Operating Modes

◆ **Generally initiated by key switches, sensors, or special panels**

◆ **Fire Modes – two stages**
   • Stage 1 – return to lobby and clear the elevators
   • Stage 2 – rescue workers control the car
   • Different state and municipal elevator codes require different behaviors for car buttons

◆ **Hospital operations – "Code blue"**
   • Stage 1 – Override current calls and bring the elevator to a certain floor
   • Stage 2 – Independent service (controlled from car by hospital staff)

Fire Stage 1   **Fire Stage 2**

◆ **Earthquake mode**
   • Move the car in a direction that avoids passing counterweigh

◆ **Riot mode**
   • Exclude the lobby or lower floors to prohibit access to the rest of the building

https://secure.flickr.com/photos/doctorow/8451112794/sizes/m/in/photostr

Elevators & the Course Project

◆ **Discrete event simulation of multi-CPU elevator**
  - Fine grain distributed system – every button, light, motor has its own CPU on an embedded real time control network
  - No actual hardware – we provide simulation infrastructure in Java

◆ **Emphasis on complete flow of design process**
  - Requirements => Design => Implementation => Test
  - Simple elevator first half of course
  - Redesign formore complex elevator second half of course
  - High quality design process is more important than amazing elevator algorithms
    - (But, there is a small bonus for best performing elevator)

To: koopman@cmu.edu
Subject: Re: Request for Professional Reference
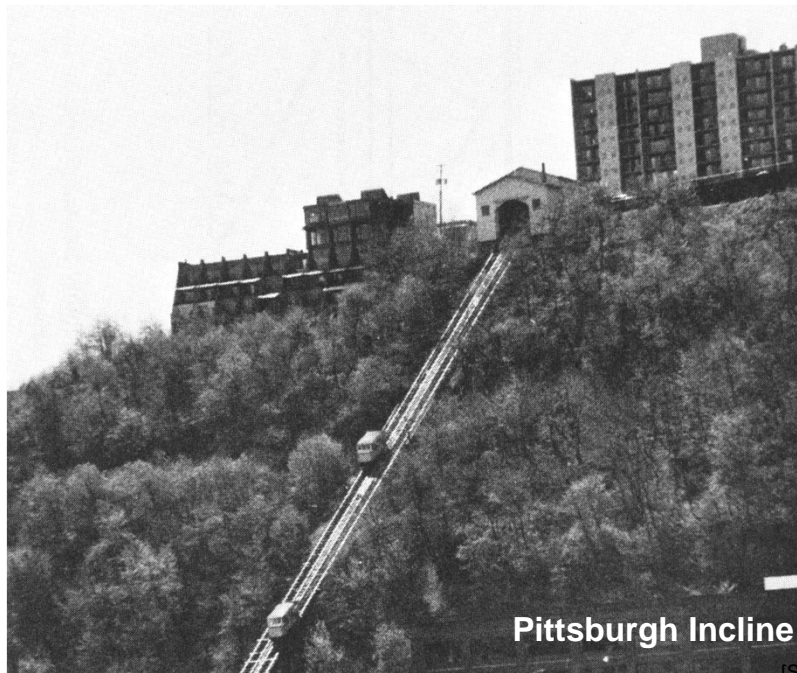**From: <student@andrew.cmu.edu>**
Date: Mon, 26 Mar 2012 17:43:36 -0400

Hi Dr. Koopman,

Thank you for your support with the process. I will most probably be accepting the offer from Qualcomm. The position is of embedded Linux kernel development. I also wanted to mention that during the course of my interviews I spoke to a lot of people about the elevator project and a lot of the employers were quite impressed with the process that the project tries to teach. Some of the questions I was asked in addition to the process were things like, Why use a time triggered design as opposed to event triggered? Why use Java instead of C or C++? How did you ensure robustness of each of the controllers in the presence of stale messages? What would happen if one of the controllers went down? Overall the project was very valuable in terms of my interviews. I wanted to thank you for that as well.

Regards,
<student>

Unconventional Elevators

Pittsburgh Incline

[Strakosch98]

How Do You Maximize Capacity?

◆ **Old idea: conveyor belt approach / paternoster**
◆ **New idea: "free cars" that attach and detach from central cable**
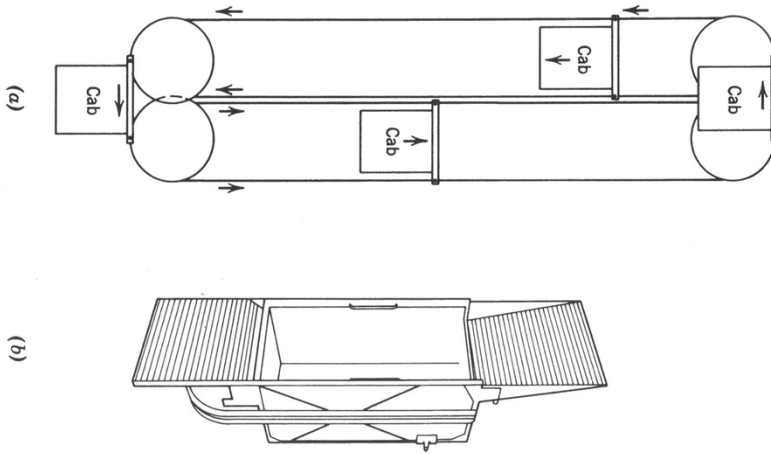

Paternoster

Figure 5.1. *(Continued)* *(c)* Actual installation.

[Strakosch98]

Paternoster Elevator

Figure 5.1. "Paternoster elevator" (Courtesy Elevator World Magazine). (a) Schematic; (b) paternoster car.

[Strakosch98]

Elevator Videos

◆ **Paternoster, a Cyclic Elevator:**
  • http://www.youtube.com/watch?v=OXSnNzGJDdg

◆ **Paternoster: Eastern Europe's Elevator of Death**
  • http://www.youtube.com/watch?v=Ro3Fc_yG3p0

Review

- **Elevators span a large price-performance range**
  - 2-story hydraulic elevators
  - 100+ story high-end systems

- **Tricky blend of technologies**
  - Mechanical/motion
  - HW/SW/mechanical safety
  - Dispatching heuristics
  - Human interface

- **Dispatching fundamentals**
  - Workload varies by time of day
  - Dispatcher thinks about where it is going next before it even stops at a floor