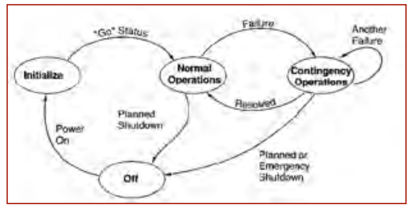
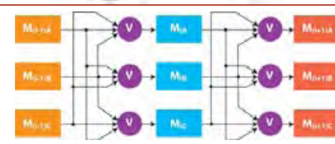
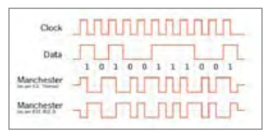
Telemetry, Command, Data Processing & Handling

Space System Design, MAE 342, Princeton University
Robert Stengel

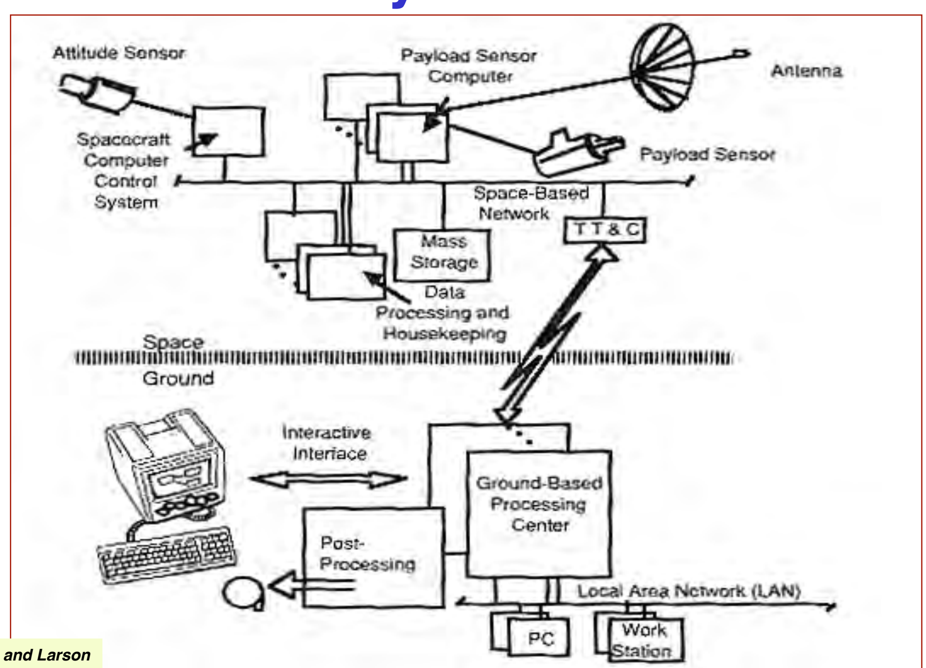
- System definition
- Computer architecture
- Components
- Data coding
- Fault tolerance and reliability
- Hardware and software testing







A Typical Space/Ground Information System



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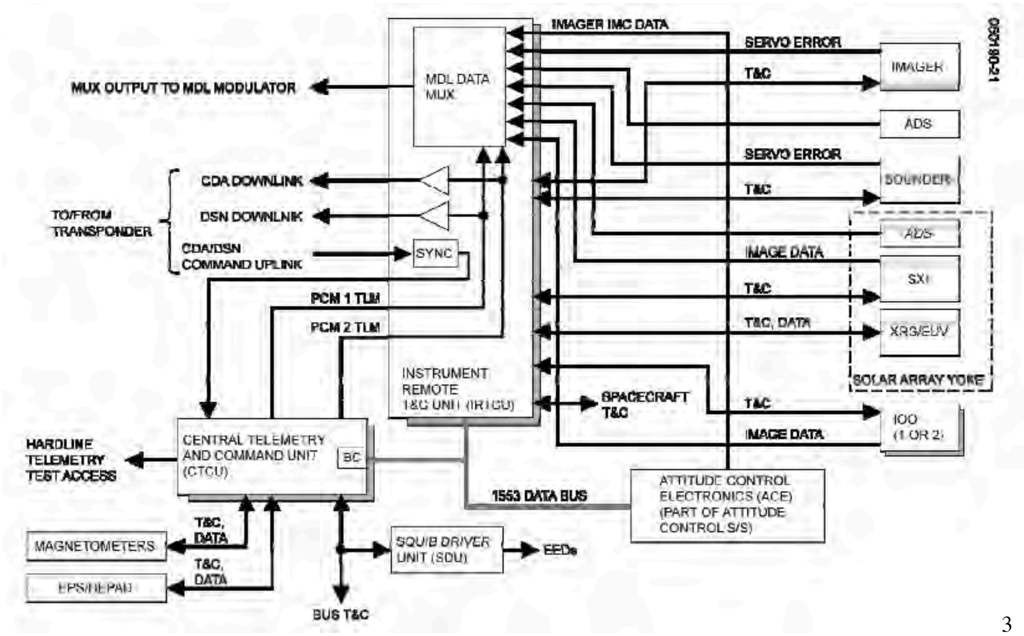
GOES Telemetry and Command Sub-System



Defining the System

- Identify the spacecraft bus and payload operational modes
- Allocate top-level requirements for the computer system
- Define sub-system interfaces
- Specify baseline computer system
  - Define computer system's operational modes and states
  - Functionally partition and allocate computational requirements to
    - spacecraft sub-systems, hardware, or software
    - ground station
  - Analyze data flow
  - Evaluate candidate architectures
  - Select basic architecture
  - Develop baseline system configuration
- Do we need a new computing system, or can we use an old system that is already certified?

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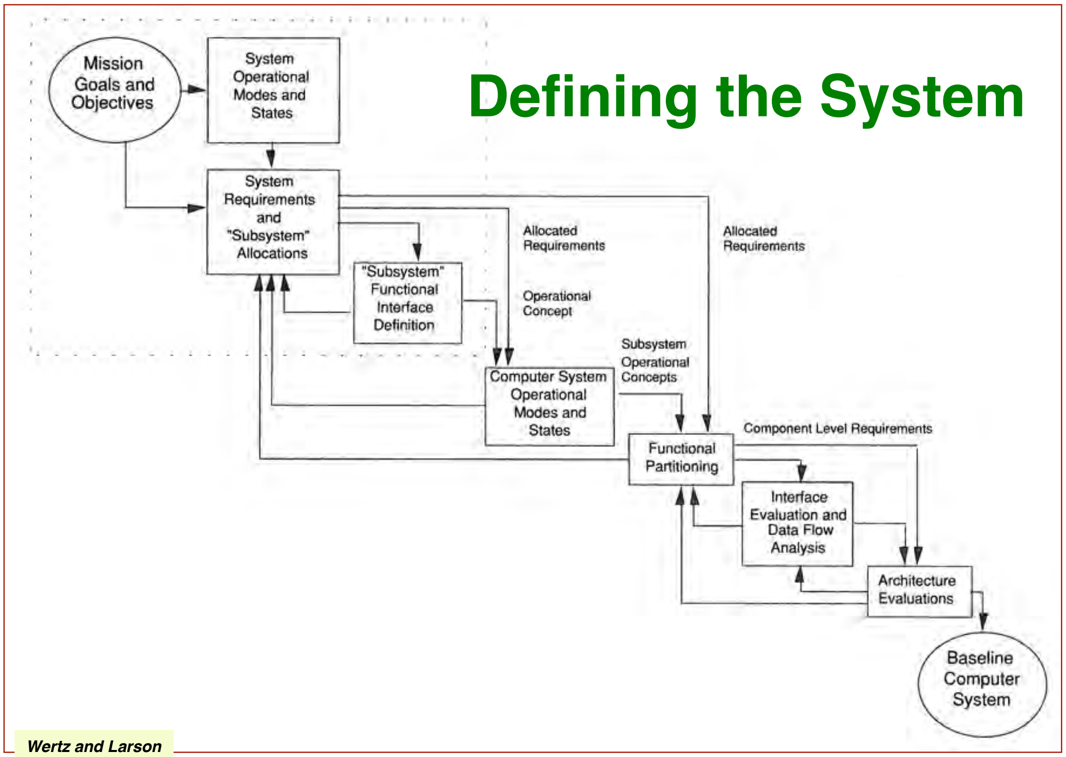

Requirements Definition

- What must the system do?
- Why must it be done?
- How do we achieve the design goal?
- What are the alternatives?
- What sub-systems perform specified functions?
- Are all functions technically feasible?
- How can the system be tested to show that it satisfies requirements?

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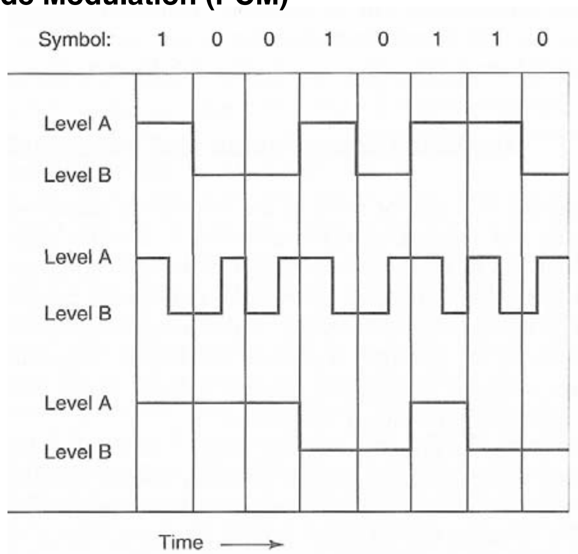
Telecommand Waveforms

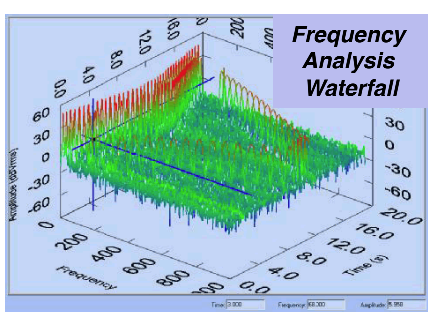
Pulse Code Modulation (PCM)

- NRZ-L *(Non-Return-to-Zero, Level)*
  - A signifies '1'
  - B signifies '0'
- SP-L *(Split-Phase, Level)*
  - '1' signified by A during 1st half, B during the 2nd half
  - '0' signified by B during 1st half , A during 2nd half
- NRZ-M *(Non-Return-to-Zero, Mark)*
  - Level change from A to B or B to A signifies '1'
  - No level change signifies '0'



Classification of Telemetry Data

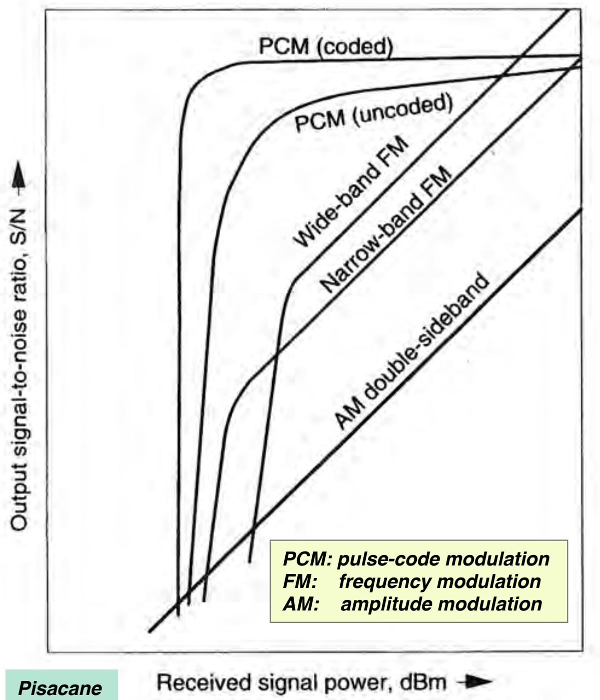
- Housekeeping data
  - Temperatures, pressures, voltages, currents, …
- Attitude and acceleration data
  - Sun sensors, star sensors, gyros, accelerometers, …
- Payload data
  - Mission dependent
  - Wide range of data rates, bandwidth, criticality, …



Frequency Analysis Waterfall

https://en.wikipedia.org/wiki/Spectrogram

Digital vs. Analog Modulation



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- **Analog**
  - **Amplitude modulation conserves bandwidth**
  - **Frequency modulation spreads information bandwidth over larger RF bandwidth**
- **Digital**
  - **Pulse-code modulation (particularly phase-shift keying) uses RF power most efficiently**

Link Budget for a Digital Data Link

$$\frac{E_b}{N_o} = \frac{S}{N}\frac{BW}{R}$$

Link budget design goal is to achieve satisfactory E_b/N_o by choice of link parameters

$$\frac{E_b}{N_o} = \frac{P_t L_l G_t L_s L_a G_r}{k T_s R}$$

... in decibels?

P_t = transmitter power
L_l = transmitter-to-antenna line loss
G_t = transmit antenna gain
L_s = space loss
L_a = transmission path loss
G_r = receiver antenna gain
k = Boltzmann's constant
T_s = system noise temperature

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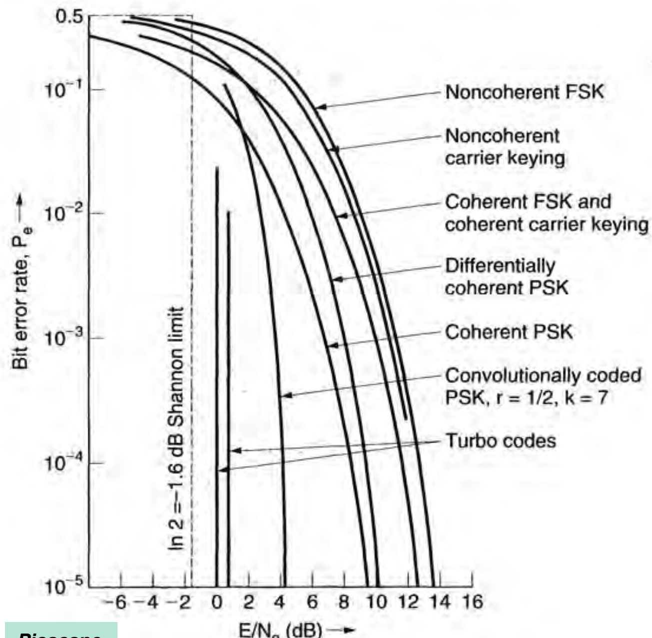
Bit Error Rate vs. E_b/N_o

- Goal is to achieve lowest bit error rate (BER) with lowest E_b/N_o
- Implementation losses increase required E_b/N_o
- Link margin is the difference between the minimum and actual E_b/N_o
- BER can be reduced by error-correcting codes
  - Number of bits transmitted is increased
  - Additional check bits allow errors to be detected and corrected



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Performance of Coding/Decoding Methods

Code	Decoding Method	Coding Gain at $P_e = 10^{-5}$	Complexity
Block	Majority—hard decision	1.5–3.5 dB	Simple
Block BCH	Algebraic	1.5–4 dB	Complex
Convolutional	Threshold—hard decision	1.5–3 dB	Fairly simple
Convolutional	Viterbi—soft decision	4.5–5.5 dB	Fairly complex
Convolutional	Sequential—soft decision	5–7 dB	Fairly complex
Concatenated block-convolutional	Viterbi + algebraic	6.7–7.5 dB	Very complex
Turbo	Maximum à posteriori	8.8–9.4 dB	Fairly complex

Note: Theoretical BPSK requires $E_b/N_0 = 9.6$ dB for $P_e = 10^{-5}$.

P_e = Bit Error Rate (BER)

BPSK = Binary phase-shift keying

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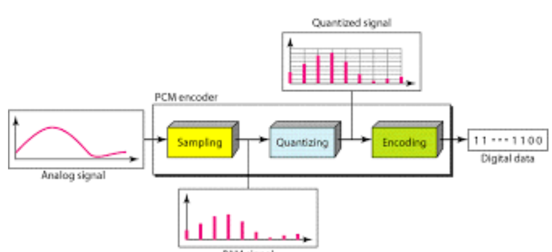
Coding gain is net *S/N* improvement provided by adding check bits

Telemetry List and Data Format

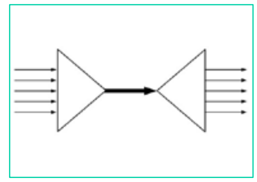
- For each item
  - Signal ID, data type, required accuracy, sampling rate
- PCM message format
  - e.g. Eight frames, each with 64 8-bit words
  - Fixed synchronization code
  - Frame ID channel
- Specification of data channels
  - Housekeeping, “prime”, commutation

Telemetry Data Encoding

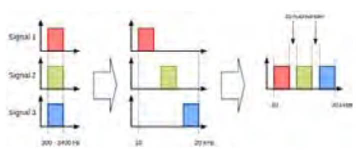
- Analog data
  - Filtering
  - A/D
  - Multiplexer, sub-multiplexer
- Digital bi-level data
  - On-off
- Digital serial data
  - Word length
  - PCM mode

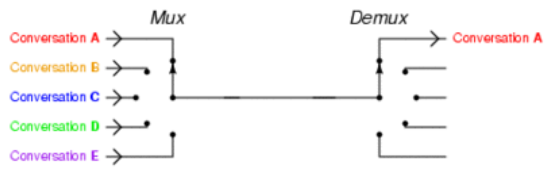


Multiplexing



- **Analog Modulation**
  - **AM, FM, PM, SSB *(single sideband)*, …**
- **Circuit Mode *(circuit mode)***
  - **TDM, FDM, Polarization, …**
- **Statistical Multiplexing *(variable bandwidth)***
  - **Packet switching, Dynamic TDMA, Spread Spectrum, …**



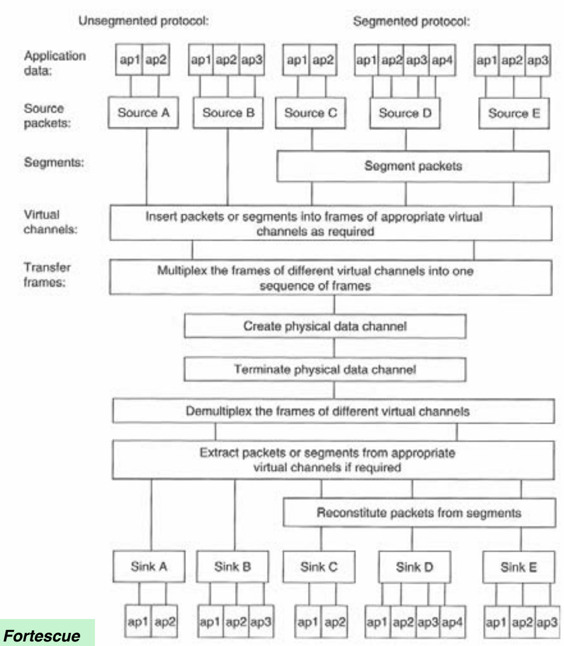


https://en.wikipedia.org/wiki/Multiplexing

Data Formatting

Packet Telemetry Data Flow

- **Application Process Layer**
- **System Management Layer**
- **Packetization Layer**
- **Segmentation Layer**
- **Transfer Layer**
- **Coding Layer**
- **Physical Layer**



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Parity and Error Detection

- *n*-bit word = (n - 1) bits of data plus a parity bit (e.g., ASCII 8-bit word for 7-bit code)
- Parity bit is computed (XOR gates) so that the number of "ones" in the word is even (or odd)
- Word is transmitted
- Error in one bit of the word is detected if the number of "ones" is not even (or odd)

Wikipedia

A wants to transmit: 1001
A computes parity bit value: 1^0^0^1 = 0
A adds parity bit and sends: 10010
B receives: 10010
B computes overall parity: 1^0^0^1^0 = 0
B reports correct transmission after observing expected even result.

- If error is detected, B requests re-transmission from A
- Error-correcting codes as in telemetry (convolution and block codes, memory refreshing, redundancy)

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Error-Control Coding

- Typical BER: 1:10^5
- Division by a polynomial
  - e.g., $x^{16} + x^{12} + x^5 + 1$
  - Send 16-bit remainder
- Ground station
  - Divide by same polynomial
  - If 16-bit remainder not the same, re-send
- Forward error correction
  - Various codes, e.g., …

http://www.ccs.neu.edu/home/rraj/Courses/6710/S10/Lectures/Coding.pdf

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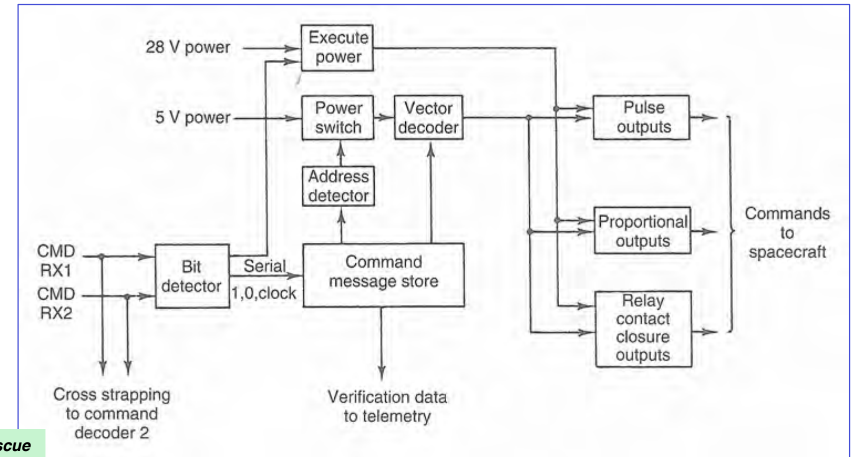
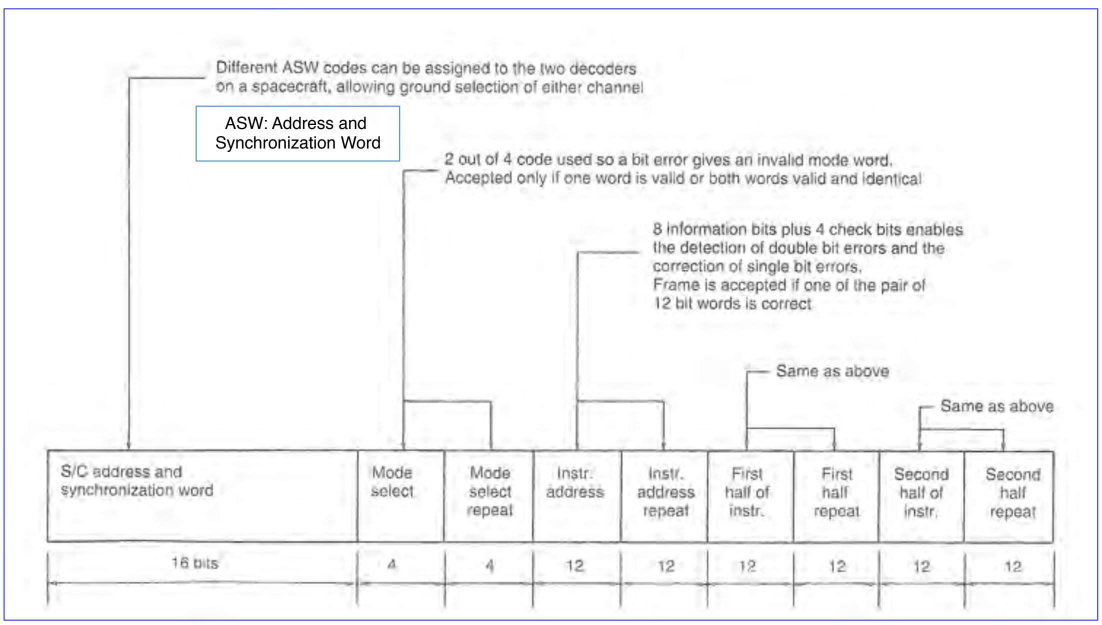
Telecommand User Interface

- Low-level on-off commands
- High-level on-off commands
- Proportional commands
- Telecommand standards



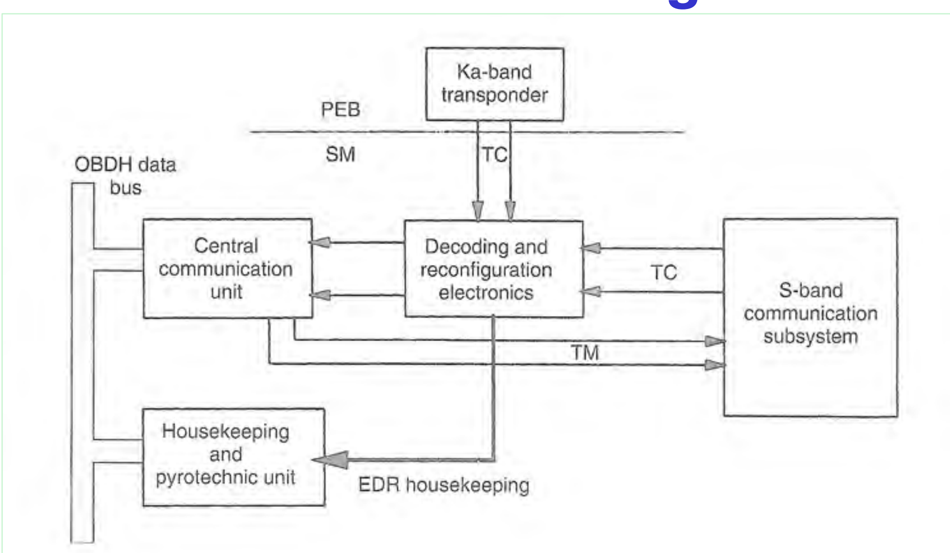
Memory Load Command Frame Structure



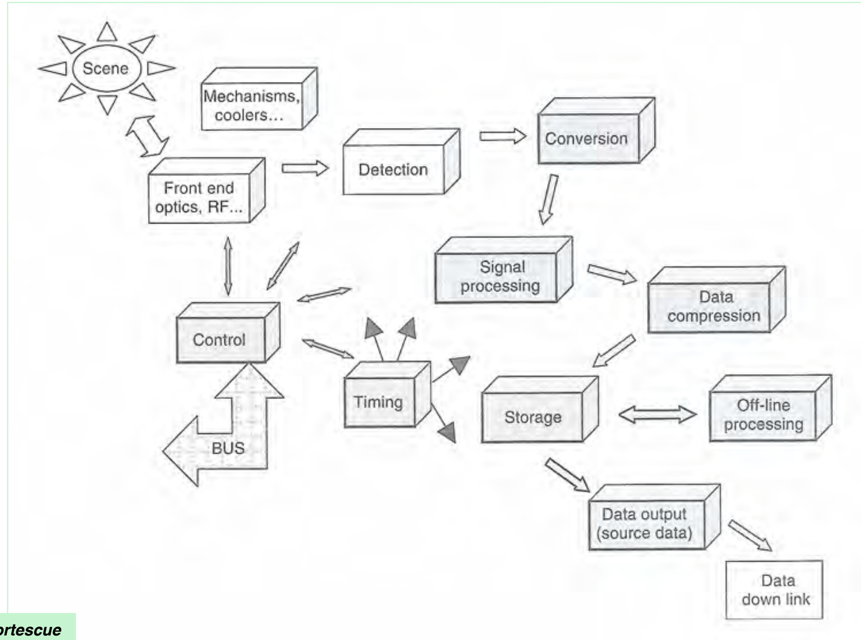
Communications Techniques & Protocols

- **Ranging**
- **Advanced Orbiting Systems**
- **Proximity Links**
- **Protocols**
  - Store-and-forward networking
  - Continuous file delivery
  - Negative automatic report queuing
  - Proxy transfer facilities
  - Graceful suspend/resume
  - Garbage clearance
  - File manipulation

On-Board Data Handling and Processing



Instruments, Experiments, and Sensors



Compression and Storage

- On-line data compression
  - Block-adaptive quantization
  - first-in/first-out buffering
- Off-line data compression
  - Lossless or lossy compression
- Data storage
  - Blocks and files

Data Downlinks

- Data-handling function RF transmit chain
  - Data routing
  - Buffering
  - Formatting
  - Carrier modulation
  - Amplification
  - Transmission
- Modulation techniques
  - QPSK
  - Amplification
  - Link layer
  - Link availability

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Electronics Technology

- Radiation hardness
- Single-event upsets
- CMOS latch-up
- Parity
- Error detection and correction
- Triple modular redundancy
- Multiple execution
- Fault roll-back
  - repeat the function if error is sensed
- Fault roll-forward
  - correct the error and move on
- Watchdog timers
  - detect unusual execution time for program function
  - force a restart if faul is detected
- Improper sequence detection
- Hardware vs. software errors

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Radiation Hardness and Single-Event Upsets

- Radiation degrades semiconductor devices
- Ionization due to Gamma rays may trap charges in devices, altering their function
  - Can produce a single-event upset
- Random and age-related failures must be anticipated
  - Shielding
  - Radiation-hardened dielectrics
- Single-event upset (SEU)
  - Radiation flips a bit in data or instruction
- CMOS latch-up
  - Large transient current flow may destroy the device
  - Build in a circuit breaker that shuts off current before damage is done

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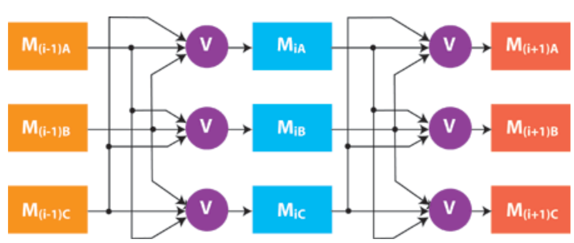
Triple Modular Redundancy: Hardware

- Parallel hardware implementation for fault tolerance
  - Each sensor, computer, or actuator is replicated three times
  - Multiple execution
  - Voting logic compares the three versions of each output and chooses the version
    - transmitted by two (or all three),
    - middle value, or
    - average value
  - Cost and maintenance implications



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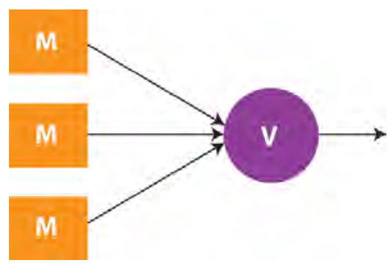
Triple Modular Redundancy: Software

- **Software implementation for serial data transmission**
  - Each word is transmitted three times
  - Voting logic compares the three versions and chooses the version transmitted by two (or all three)
  - Serial data transfer rate is slowed by a factor of three



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Reliability

Probability of Success during Period of Operation

$$R(t): \textit{Probability of success}$$

$$P(t): \textit{Probability of failure}$$

$$\boxed{R(t) = 1 - P(t)}$$

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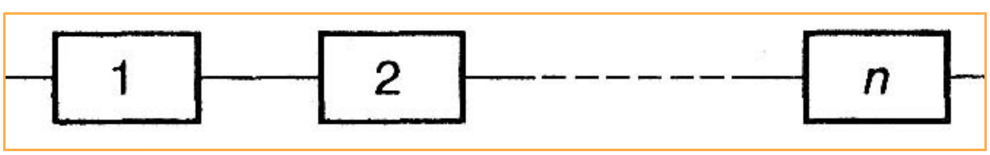
Reliability Assessment

- **Tools for reliability assessment: Testing**
  - Levels of test: development, qualification, acceptance, function
  - Destructive physical analysis
- **Tools for reliability assessment: Analysis**
  - Statistical distributions
  - Statistics, regression, and inference
  - Fault trees and reliability prediction
  - Confidence level or interval

Reliability of a Single String

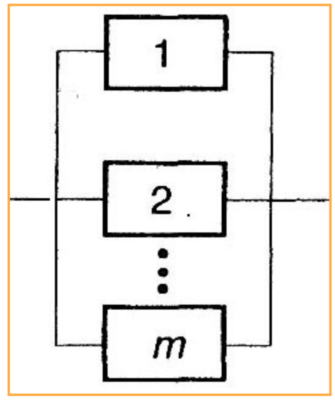


Reliability of a string of components = product of individual reliabilities

$$\boxed{R_{1-n}(t) = R_1 R_2 \ldots R_n}$$

Reliability of Parallel (Redundant) Components

Probability of failure of parallel components = product of individual probabilities



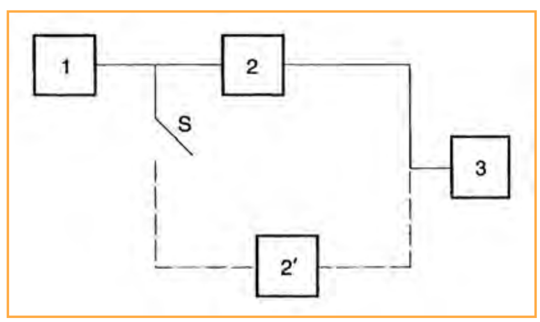
$$P_{13}(t) = P_1(t)P_2(t)P_3(t)$$

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

$$R_{13}(t) = 1 - P_{13}(t) = 1 - P_1(t)P_2(t)P_3(t)$$

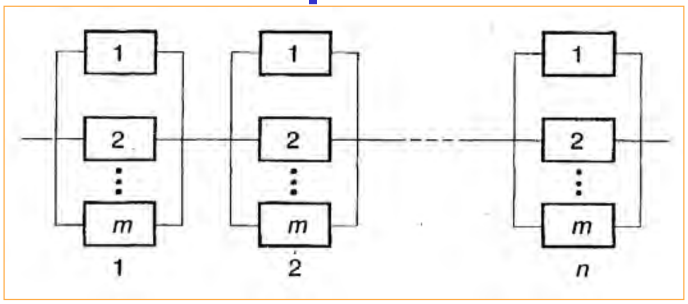
Reliability of a Switched Redundant System

Reliability of the switch must be considered



$$R_{system}(t) = R_1(t)\left\{1 - \left[1 - R_2(t)\right]\left[1 - R_S(t)R_{2'}(t)\right]\right\}R_3(t)$$
$$= R_1(t)\left\{1 - P_2(t)P_{S2'}(t)\right\}R_3(t)$$

Reliability of a String of Parallel Components

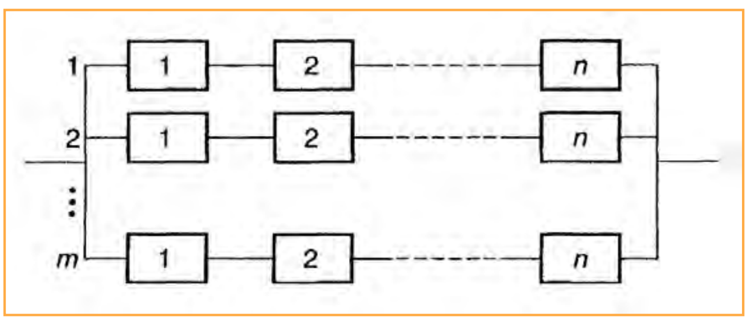


$$R_{system}(t) = \sum_{x=r}^{n} \binom{n}{x} R^x (1-R)^{n-x}$$

Binomial coefficient $$\binom{n}{x} = \frac{n!}{x!(n-x)!}$$

r = # of elements in a parallel component that must survive for operation

Reliability of Parallel Strings

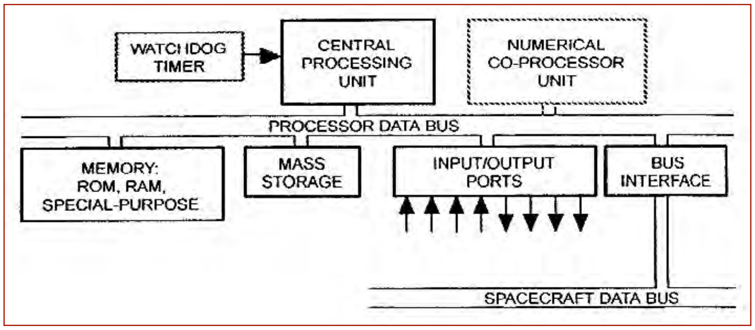


$$P_{1n}(t) = P_1(t)P_2(t)\ldots P_n(t)$$

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

$$R_{1n}(t) = 1 - P_{1n}(t) = 1 - P_1(t)P_2(t)\ldots P_n(t)$$

Spacecraft Computers



- **Spacecraft computing hardware; analogous to Macs and PCs, but**
  - **Must be ultra-reliable**
  - **A few generations behind the state-of-the-art**
- **Memory**
- **Input/output**
- **Fault tolerance**
- **Special-purpose peripherals**

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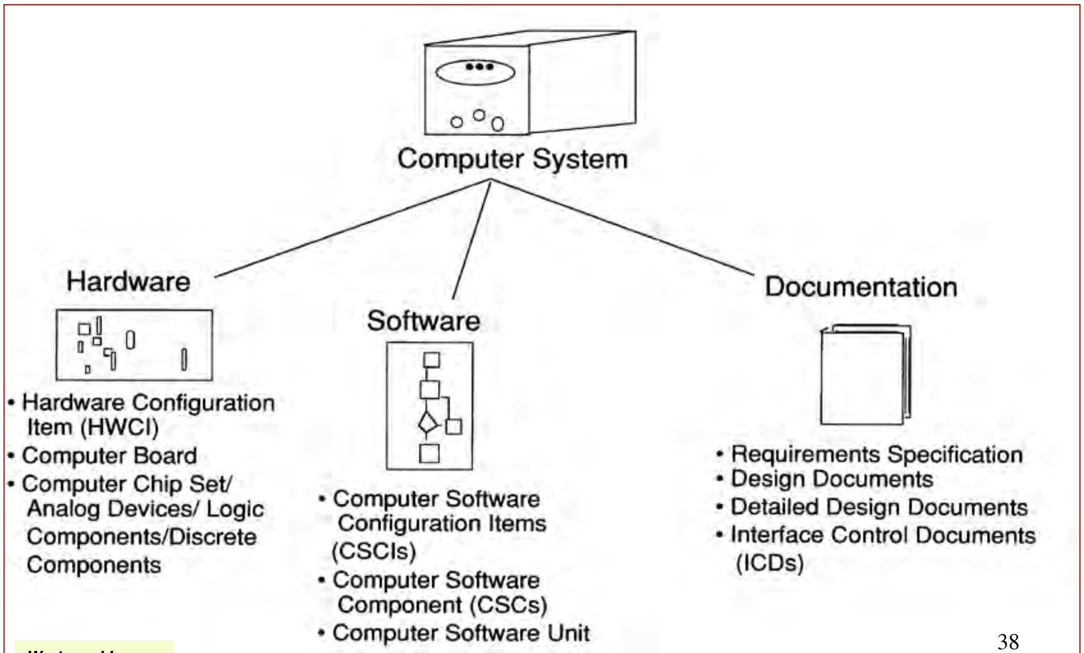
Hardware, Software, and Documentation



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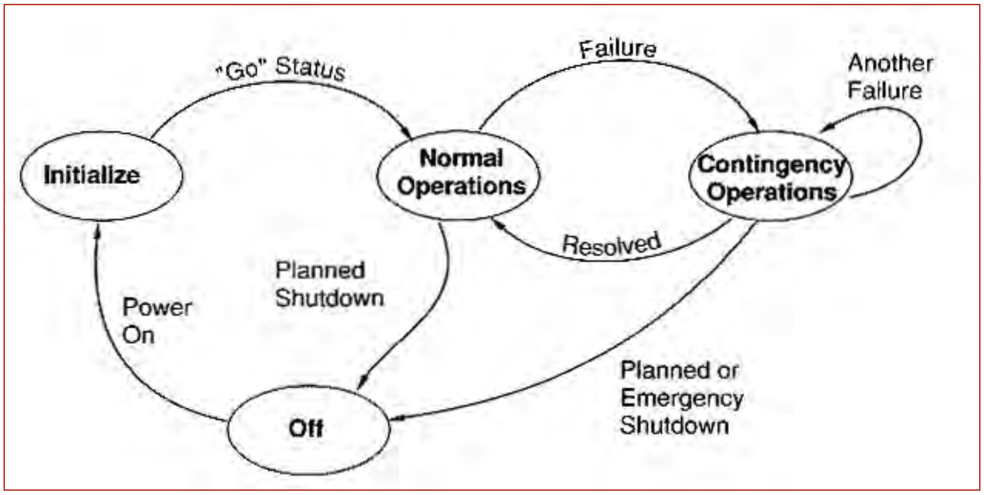
Computer System State Diagram



System states must be consistent with allocated requirements and with spacecraft's and ground station's concepts of operation ("conops")

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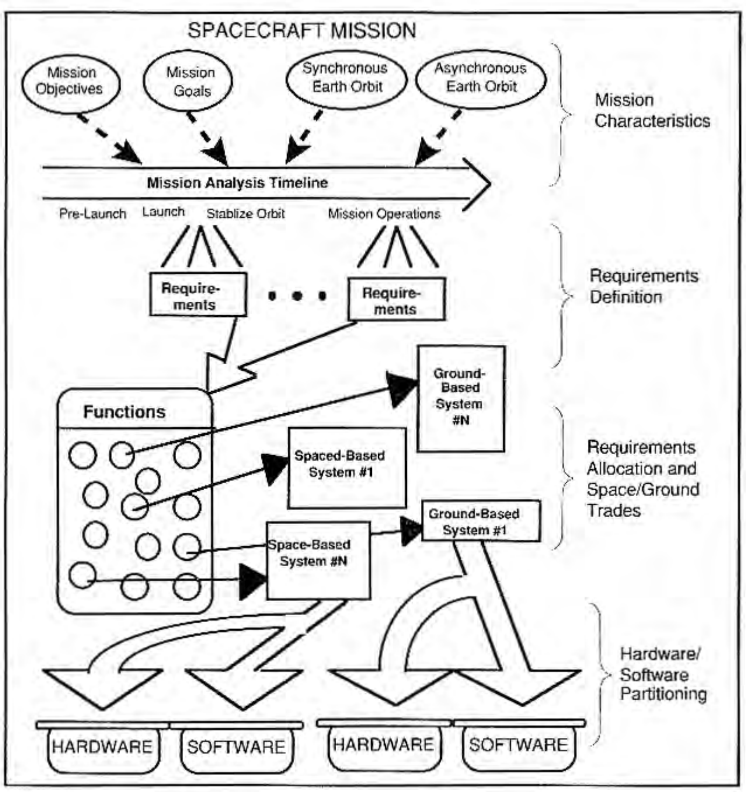

Computer System Functional Partitioning

- **Group functions**
  - Similarity
  - Complexity
  - Processing type
  - Urgency
  - Timing and throughput
  - External interface
  - Data storage req't
  - Human participation
  - Flight safety
- **Space/ground tradeoffs**
  - Autonomy
  - Time criticality
  - Downlink bandwidth
  - Uplink bandwidth
- **Hardware/software tradeoffs**
  - Special-purpose h/w
  - Algorithmic complexity

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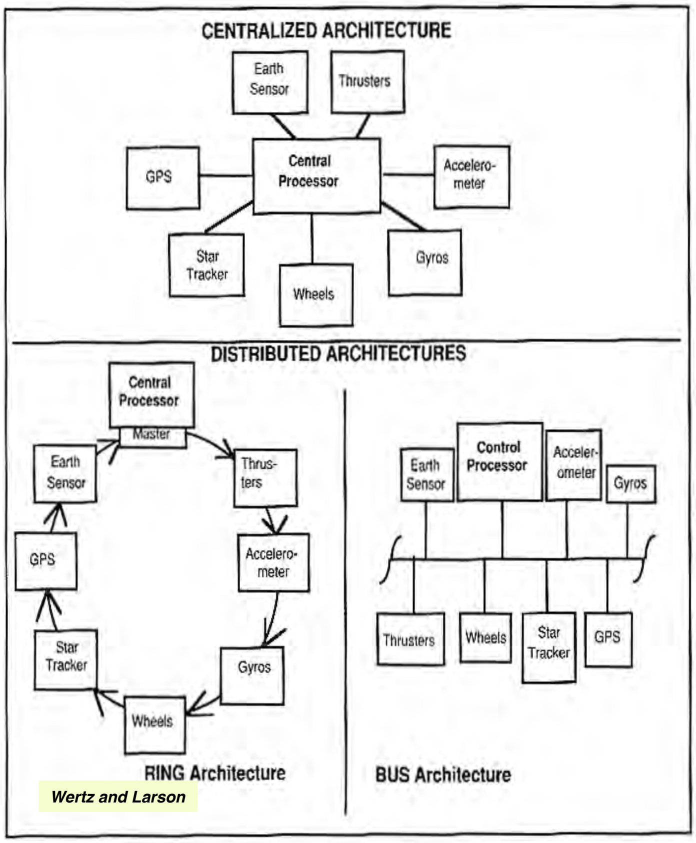

Computer Architecture

- Central processor
  - Point-to-point interfaces, central processor and devices
  - Dedicated wiring and software
- Bus
  - Processors and devices communicate via a bus
  - Protocol software for transmission control
  - Standard interfaces
- Ring
  - Established arbitration (e.g., token-passing) for bus control
- Instruction set
  - Assembly language
  - Higher-order language

Computer Resource Estimation

- Defining processing tasks
  - Software requirements specification
  - Interface requirements specification
  - Principal classes
    - Control systems
    - System management
    - Mission data management
    - Operating system
      - Utilities
      - Built-in test
- Estimating software size and throughput
  - Processor instruction sets
  - Processor clock speeds
  - Historical data for similar processing tasks
  - Preliminary coding of example tasks

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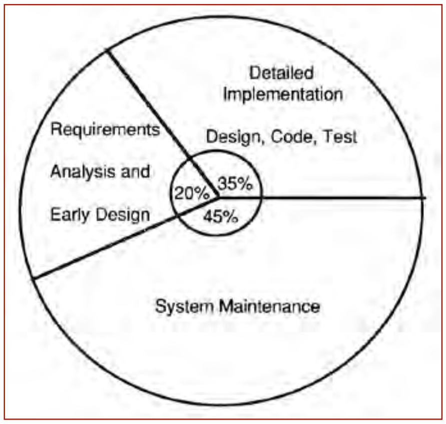
Development Phase Issues

- **Hardware selection**
  - Performance, cost, availability, vendor competition
- **Developmental environment**
  - Software languages, tools for coding, compiling, and testing
  - Host/target machines
- **Development costs**
  - Mission life cycle
- **Development tools and methodologies**
  - Specification and analysis aids
  - Design aids
  - Traceability analysis
  - Documentation aids

Typical Life-Cycle Cost Distribution



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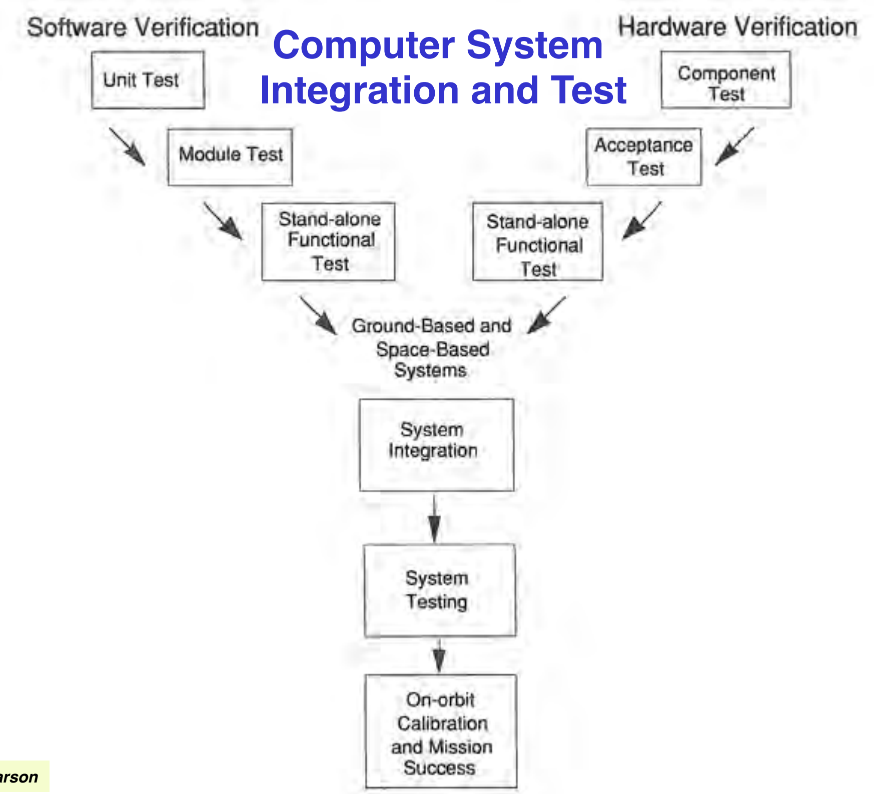
Computer System Integration and Test



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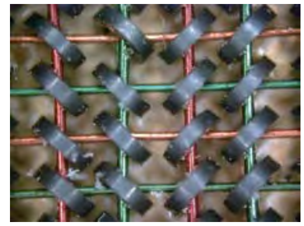
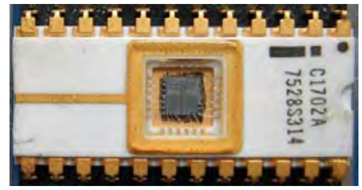
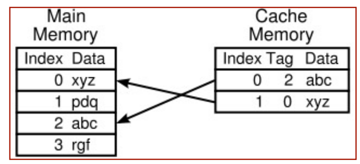
Computer Memory





- Read-only memory (ROM)
  - Non-volatile
  - Non-alterable
  - Store critical programs
  - EAROM, EEROM, EEPROM
- Flash memory (special EEPROM)
- Random-access memory
  - Volatile
- Special-purpose memory
  - Multi-port
  - Cache
  - Multiply-accumulate $a \leftarrow a + (b \times c)$
- Disk
  - Magnetic
  - CD, DVD



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Computer Input/Output

- Ports
  - Data transfer between processor and bus
    - Serial I/O ports
    - Parallel I/O ports
    - I/O-mapped ports
    - Memory-mapped ports
- Direct memory access
  - Sub-systems access memory without going through the processor for large blocks of data or high data rate
- Multi-port memory
  - Simultaneous data access by two or more devices
- Interrupts
  - May be generated by a timer or an event, changing processor function
  - Synchronize activity of multiple processors
  - Context switching and storage
- Timers
- Bus interface

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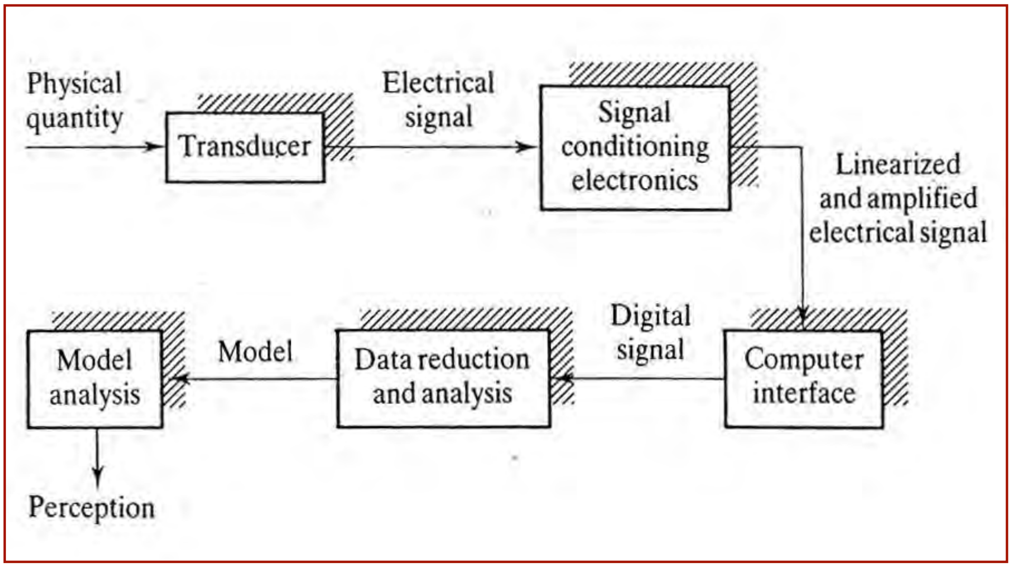
Special-Purpose Peripherals (Signal-Processing Hardware)

Data acquisition



Special-Purpose Peripherals (Signal-Processing Hardware)

- Logarithmic and data compression
  – Rounding, filtering, coding, channel capacity, probability, incremental values, ...
- Frequency domain transformation
  – Time domain -> frequency domain
  – Fourier transform, inverse transform , wavelets
- Power/energy spectrum accumulation
- Image processing
- Digital/analog conversion

Apollo GNC Software Testing and Verification

- Major areas of testing
  - Computational accuracy
  - Proper logical sequences
- Testing program
  - Comprehensive test plans
  - Specific initial conditions and operating sequences
  - Performance of tests
  - Comparison with prior simulations, evaluation, and re-testing
- Levels of testing
  - 1: Specifications coded in higher-order language for non-flight hardware (e.g., PCs)
  - 2: Digital simulation of flight code
  - 3: Verification of complete programs or routines on laboratory flight hardware
  - 4: Verification of program compatibility in mission scenarios
  - 5: Repeat 3 and 4 with flight hardware to be used for actual mission
  - 6: Prediction of mission performance using non-flight computers and laboratory flight hardware

Apollo GNC Software Specification Control

- Guidance System Operations Plan (GSOP)
  - NASA-approved specifications document for mission software
  - Changes must be approved by NASA Software Control Board
- Change control procedures
  - Program Change Request (NASA) or Notice (MIT)
  - Anomaly reports
  - Program and operational notes
- Software control meetings
  - Biweekly internal meetings
  - Joint development plan meetings
  - First Article Configuration Inspection
  - Customer Acceptance Readiness Review
  - Flight Software Readiness Review

Apollo GNC Software Documentation and Mission Support

- **Documentation generation and review**
  - **GSOP: 1: Prelaunch 2: Data links 3: Digital autopilots 4: Operational modes 5: Guidance equations 6: Control data**
  - **Functional description document: H/W-S/W interfaces, flowcharts of procedures**
  - **Computer listing of flight code**
  - **Independently generated program flowchart**
  - **Users' Guide to AGC**
  - **NASA program documents: Apollo Operations Handbook, Flight Plans and Mission Rules, various procedural documents**
- **Mission support**
  - **Pre-flight briefings to the crew**
  - **Personnel in Mission Control and at MIT during mission**

Apollo Guidance Computer

- **Parallel processor**
- **16-bit word length (14 bits + sign + parity)**
- **Memory cycle time: 11.7 μ*sec***
- **Add time: 23.4 μ*sec***
- **Multiply time: 46.8 μ*sec***
- **Divide time: 81.9 μ*sec***

- **Memory (ceramic magnetic cores)**
  - **36,864 words (ROM)**
  - **2,048 words (RAM)**
- **34 normal instructions**
- **Identical computers in CSM and LM**
- **Different software (with many identical subroutines)**
- **70 lb, 55 w**

- **There were NO computer hardware failures during Apollo flights**

Some Flight Computer Variations

Integrated Spacecraft Computer (ISC) Family

Technical Specifications

					
	On-Board Computer	**VME Compatible On-Board Computer**	**Single-String Controller**	**C&DH Payload Controller**	**Mechanism Controller**
Instruction Set	PowerPC	PowerPC	PowerPC	PowerPC	PowerPC
Peak Throughout	480 MIPS	480 MIPS	480 MIPS	480 MIPS	960 MIPS
Processor RAM	256 MB	64 MB	256 MB	256 MB	256 MB
Non-Volatile Program Storage	144 MB	16 MB	144 MB	144 MB	144 MB
DMA Channels	5	5	10	10	20
System Bus	2-1553	1-1553	2-1553	3-1553	2-1553
Other Interfaces	3 High-Speed Serial, VME Bus	3 High-Speed Serial, VME Bus	Analog and Digital Interfaces	Telecommand and Telemetry, Analog and Digital Interfaces	Position Inputs Torque Outputs Stepper Motor DC Brushless Motor
Typical Size (inches)*	9 x 6.6 x 3.3 (3 Modules)	Single-Width 6U IEEE 1101.2	9 x 6.6 x 4.8 (5 Modules)	9 x 6.6 x 9.3 (10 Modules)	9 x 6.6 x 9.3 (10 Modules)
Typical Power (Watts)	15 - 30	10 - 25	10 - 35	Application dependent	Application dependent
Weight*	3.5 Kg	1.2 Kg	5 Kg	9 Kg	9 Kg

*Exclusive of mounting flange

Processor Mean Time to System Upset (LEO Orbit)	>1000 Years
Total Dose Tolerance (LEO Orbit to 1400 Km)	>10 Years
Total Dose Tolerance (GEO Orbit)	>15 Years

Pervasive use of VMEbus in spacecraft computers

RAD750 Single Board Computer

- **Mars Curiosity Rover, Mars/Lunar Reconnaissance Orbiters, Deep Impact, …**

Produced	From 2001 to Present
Designed by	IBM
Manufacturer	BAE
Max. CPU clock rate	110 MHz to 200 MHz
Min. feature size	250 nm to 150 nm
Instruction set	PowerPC v.1.1
Microarchitecture	PowerPC 750
Cores	1
Application	Radiation hardened

RAD5545 Single Board Computer

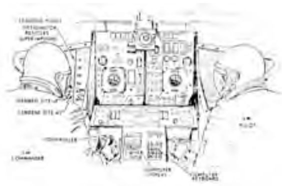
Designed by	IBM, Freescale
Manufacturer	BAE
Speeds	5200 MIPS, 3700MFLOPS
Min. feature size	45 nm
Instruction set	Power ISA, v 2.06
Microarchitecture	PowerPC e5500, VPX backplane
Cores	4
Application	Radiation hardened

Fault Tolerance Requirements for Overall System

- **Failure at a single point should not cause failure of entire system**
- **It should be possible to isolate the effects of a single component failure**
- **It should be possible to contain individual failures to prevent failure propagation**
- **Reversionary modes should be available ("fail-safe" design)**
  - **backup software**
  - **backup hardware**

Next Time:
Ground Segment

Supplemental Material

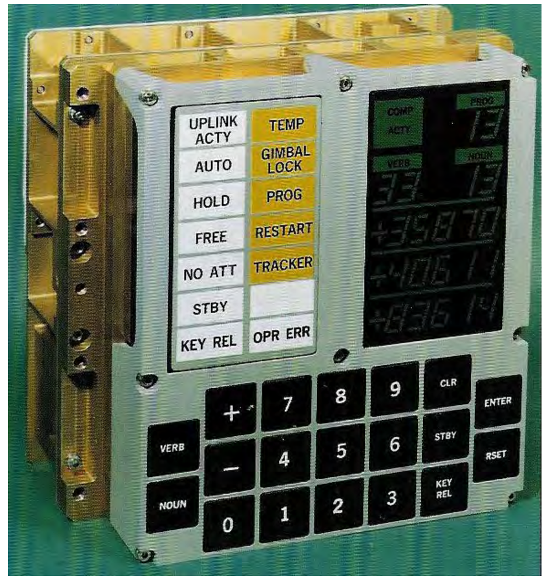


Astronaut Interface With the AGC

- Computer Display Unit or Display/Keyboard
- Sentence
  - Subject and predicate
  - Subject is implied
    - Astronaut, or
    - GNC system
  - Sentence describes action to be taken employing or involving the object
- Predicate
  - Verb = Action
  - Noun = Variable or Program

See http://apollo.spaceborn.dk/dsky-sim.html

And http://www.ibiblio.org/apollo/ for simulation



Verbs and Nouns in Apollo Guidance Computer Program

- Verbs *(Actions)*
  - Display
  - Enter
  - Monitor
  - Write
  - Terminate
  - Start
  - Change
  - Align
  - Lock
  - Set
  - Return
  - Test
  - Calculate
  - Update
- Selected Nouns *(Variables)*
  - Checklist
  - Self-test ON/OFF
  - Star number
  - Failure register code
  - Event time
  - Inertial velocity
  - Altitude
  - Latitude
  - Miss distance
  - Delta time of burn
  - Velocity to be gained
- Selected Programs (CM)
  - AGC Idling
  - Gyro Compassing
  - LET Abort
  - Landmark Tracking
  - Ground Track Determination
  - Return to Earth
  - SPS Minimum Impulse
  - CSM/IMU Align
  - Final Phase
  - First Abort Burn

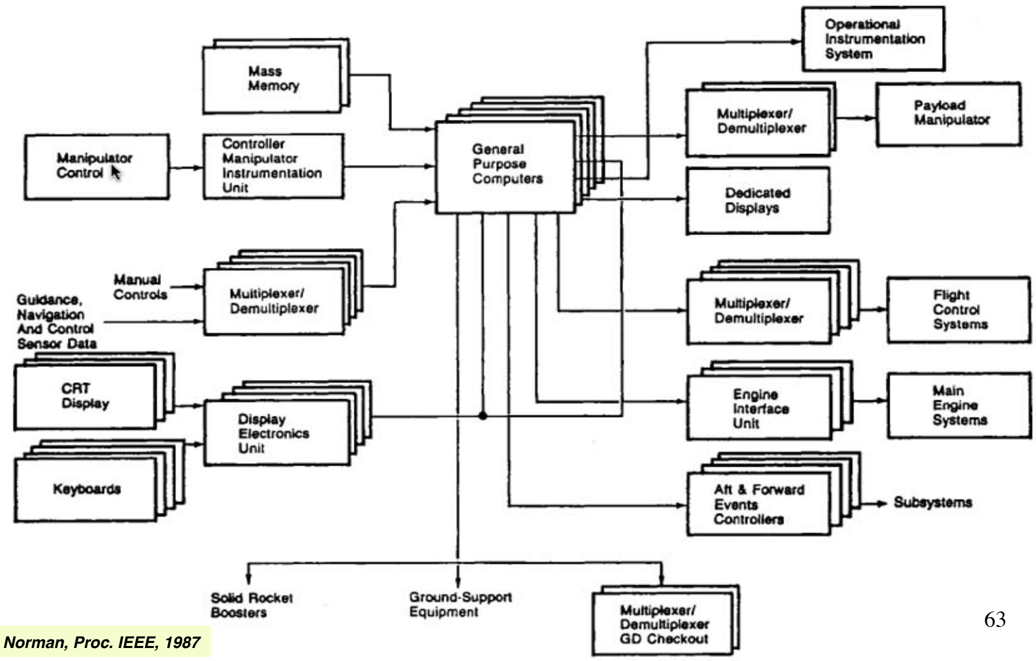
A Little AGC Digital Autopilot Code

```
GAP:  ASSEMBLE REVISION 131 OF AGC PROGRAM LUMINARY BY NASA 2021112-091      17:53 DEC. 19,1969  LMDAP   .025  PAGE 1427

L        P-AXIS RCS AUTOPILOT                                                     USER'S PAGE NO.  15      E6 S4

05931                         16,3255  0 0003 1          RELINT
0594   REF   5  LAST 1426     16,3256  4 1454 1          CS      PLAST
0595   REF  15  LAST 1417     16,3257  6 1421 1          AD      OMEGAP
0596   REF   1                16,3260  55'427 0          TS      EDOTP
0597   REF  28  LAST 1426     16,3261  11'734 0          CCS     DAPTEMP1        IF P COMMAND CHANGE EXCEEDS BREAKOUT
0598                          16,3262  1 3265 1          TCF     +3              LEVEL, GO TO DIRECT RATE CONTROL. IF NOT
0599                          16,3263  1 3273 0          TCF     +8              CHECK FOR DIRECT RATE CONTROL LAST TIME.
0600                          16,3264  1 3265 1          TCF     +1
0601   REF   5  LAST  296     16,3265  6 1476 0          AD      -RATEDB
0602                          16,3266  0 0006 1          EXTEND
0603                          16,3267  6 3273 1          BZMF    +4
0604   REF   1                16,3270  3 4771 1          CA      40CYC
0605   REF   2  LAST 1414     16,3271  55'445 1          TS      TCP
0606   REF   1                16,3272  0 3304 0          TC      PEGI
0607   REF  38  LAST 1426     16,3273  3 1262 0          CA      RCSFLAGS        CHECK FOR DIRECT RATE COMMAND LAST TIME.
0608   REF   2  LAST 1424     16,3274  7 4742 0          MASK    PBIT
0609                          16,3275  0 0006 1          EXTEND
0610                          16,3276  1 3300 0          BZF     +2
0611   REF   2  LAST 1427     16,3277  0 3304 0          TC      PEGI            TO PURE RATE COMMAND
0612   REF   7  LAST 1425     16,3300  3 1446 0          CA      DXERROR         PSEUDO-AUTO CONTROL.
0613   REF   1                16,3301  55'751 1          TS      E               X-ATTITUDE ERROR (SP)
0614   REF   6  LAST 1425     16,3302  55'464 1          TS      PERROR          LOAD P-AXIS ERROR FOR MODE1 FDAI DISPLAY
0615   REF   4  LAST 1425     16,3303  0 3473 1          TC      PURGENCY +4
0616   REF  28  LAST 1426     16,3304  3 0032 0  PEGI    CA      CDUX            DIRECT RATE CONTROL.
0617   REF  23  LAST 1426     16,3305  55'634 0          TS      CDUXD
0618   REF 286  LAST 1426     16,3306  3 4755 1          CA      ZERO
0619   REF   8  LAST 1427     16,3307  55'446 1          TS      DXERROR
0620   REF   9  LAST 1427     16,3310  55'447 0          TS      DXERROR +1
0621   REF   7  LAST 1427     16,3311  55'464 1          TS      PERROR          ZERO P-AXIS ERROR FOR MODE1 FDAI DISPLAY
0622   REF   2  LAST 1427     16,3312  11'427 0          CCS     EDOTP
0623                          16,3313  0 3316 0          TC      +3
0624                          16,3314  0 3316 0          TC      +2
0625                          16,3315  0 3316 0          TC      +1
0626   REF   1                16,3316  55'736 0          TS      ABSEDOTP
0627   REF   1                16,3317  6 1476 0          AD      TARGETDB
0628                          16,3320  0 0006 1          EXTEND                  IF RATE ERROR IS LESS THAN DEADBAND,
0629   REF   1                16,3321  6 3331 0          BZMF    LAST            FIRE, AND SWITCH TO PSEUDO-AUTO.
0630   REF   3  LAST 1427     16,3322  3 1445 0          CA      TCP
0631                          16,3323  0 0006 1          EXTEND                  IF TIME IN RATE COMMAND EXCEEDS 4 SEC.,
0632   REF   2  LAST 1427     16,3324  6 3331 0          BZMF    LAST
0633   REF  39  LAST 1427     16,3325  4 1262 1          CS      RCSFLAGS
0634   REF   3  LAST 1427     16,3326  7 4742 0          MASK    PBIT
0635   REF  40  LAST 1427     16,3327  27'262 1          ADS     RCSFLAGS        BIT 10 IS 1.
0636                          16,3330  1 3334 1          TCF     +4
0637   REF   4  LAST 1427     16,3331  4 4742 0  LAST    CS      PBIT
0638   REF  41  LAST 1427     16,3332  7 1262 1          MASK    RCSFLAGS
0639   REF  42  LAST 1427     16,3333  55'262 1          TS      RCSFLAGS        BIT 10 IS 0.
0640   REF   3  LAST 1427     16,3334  4 1427 0          CS      EDOTP
0641                          16,3335  0 0006 1          EXTEND
0642   REF   1                16,3336  7 1550 1          MP      1/ANETP         1/2JTACC SCALED AT 2EXP(7)/PI
```


Space Shuttle Quintuply Redundant Flight Control Computers

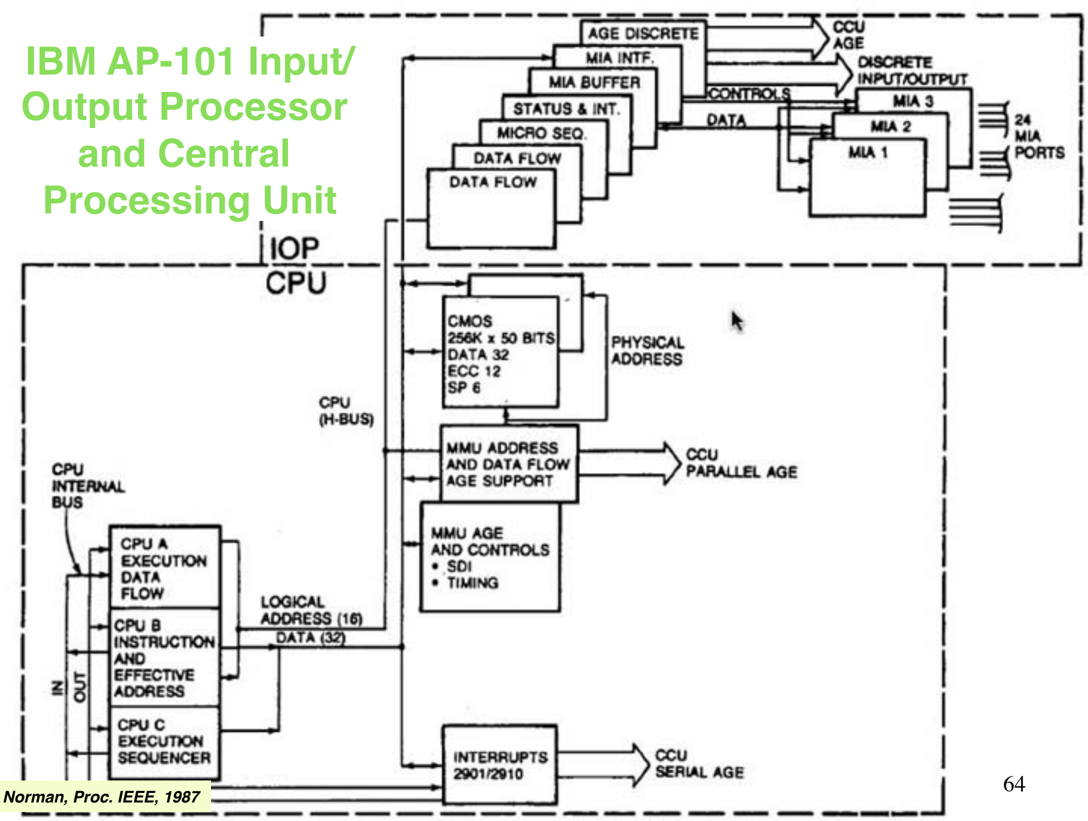
- Five identical IBM AP-101 computers
  - Magnetic core memory later upgraded to semiconductor memory
  - **Primary system:** 4 parallel computers with identical coding and complex redundancy management software
  - **Backup system:** 5th computer with independent coding of the same functions
  - Concern for generic software failures
  - HAL/S programming language

Space Shuttle Quintuply Redundant Flight Control Computers



Norman, Proc. IEEE, 1987

IBM AP-101 Input/ Output Processor and Central Processing Unit



Norman, Proc. IEEE, 1987