Space Stations

Osher, Fall 2024

Howard Seltman

Outline

- Week 1: Science and Science Fiction Background
- Week 2: Early Space Stations
- **Week 3: Mir, ISS Planning and Construction**
- Week 4: ISS Operations
- Week 5: China, Science & Tech Summary, and the Future

Today’s Topics

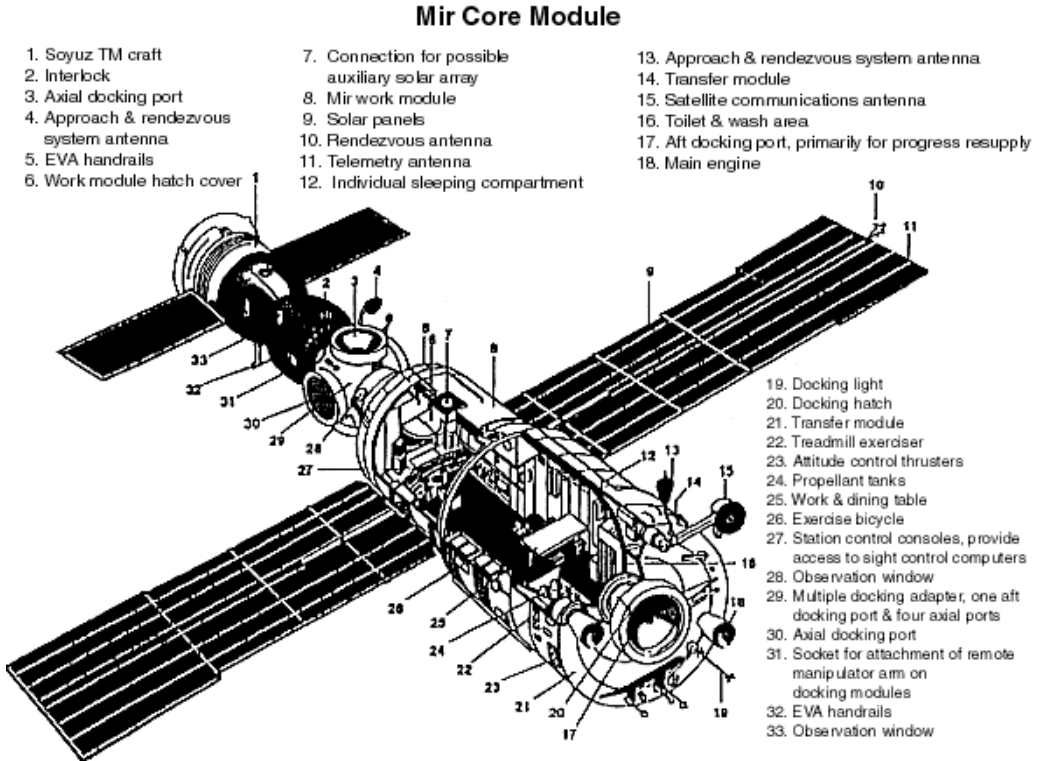
- Russian Mir Space Station
- Background of the ISS
- How we get to space
- ISS Construction

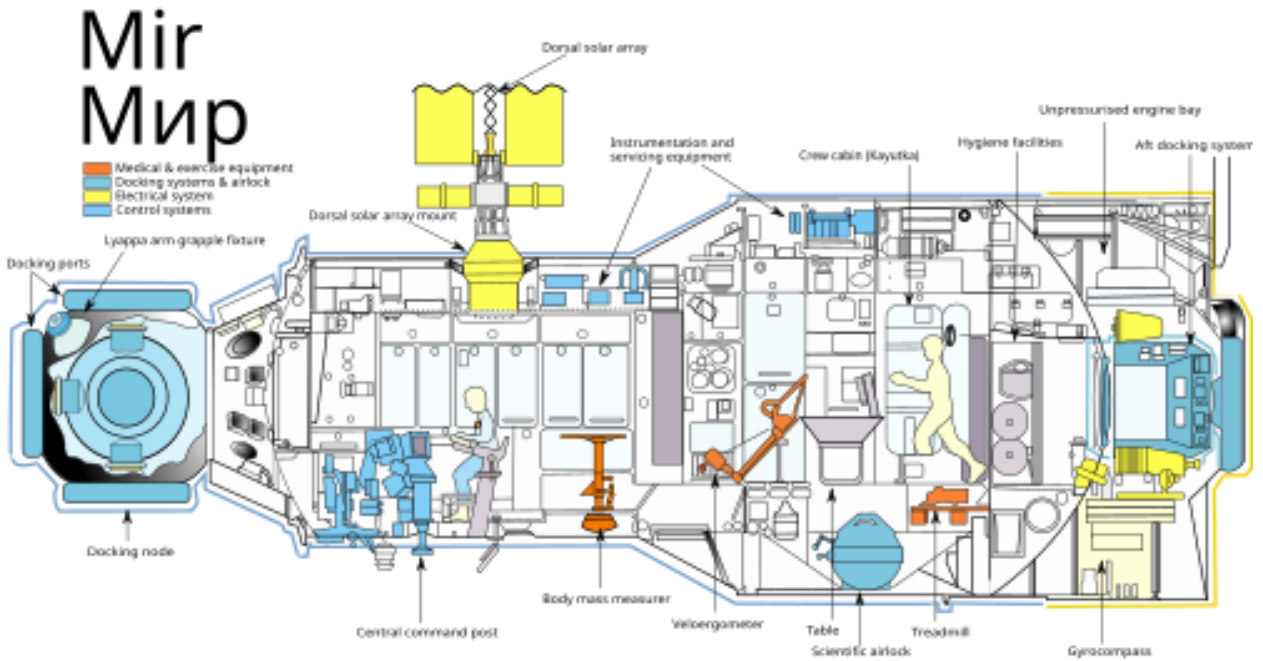
Soviet Mir background

- Soviets refocused on space stations when the U.S. achieved the first moon landings
- Six successive successful Salyut stations (1, 3-7) built up expertise
- Announced to mark the formal opening of the 25th Congress of the Communist Party of the Soviet Union in 1976
- Called “Mir” which can mean “peace”, “new world”, or “community”
- World’s first modular space station
- Intended to be continuously occupied

Soviet Mir base (core) module

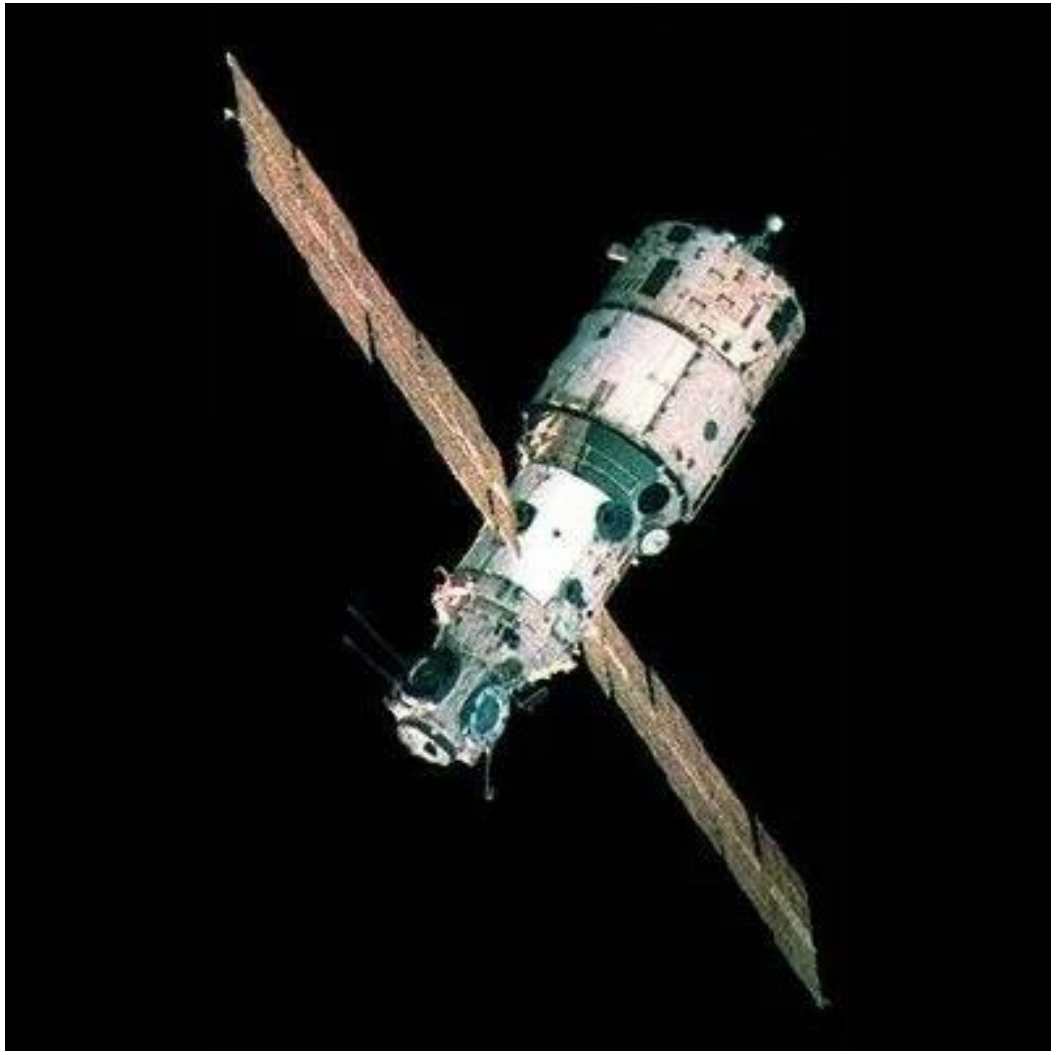
- Launched February 20, 1986 (coplanar with Salyut 7)
- Proton rocket launch limitations were 20 tons and 13 ft diameter
- First element was a habitat module, 43 feet long
- Two axial and four radial docking (berthing) ports
- Designed for five-year lifetime





Soviet Mir base module equipment

- Two accordion-fold solar arrays twice as big as Salyut 7 (400 sq. ft.)
- 4,500 watts peak, one axis of automatic rotation
- Charged 12 NiCad batteries (60 amp-hours) at 28 volts = 2250 watts for 45 minutes
- Seven computers for flight control and navigation



Mir’s first crew

- First crew launched March 1986 live on TV
- Two highly experienced crew: Leonid Kizim and Vladimir Solovyov
- Extra propellant for double rendezvous
- Two docking systems: old Igla, new Kurs
- Rendezvous and docking on day 2; station entered

Mir base block outfitting

- New luxuries
  - Two crew cabins with sleeping bags, desk and porthole
  - Door on the toilet
- “Floor” carpeted, “walls” green, “ceiling” white
- Fold-up dining table
- Fold-away gymnasium
  - 10 km cycling and 5 km walking per day
  - 2.5 hr/day in a four-day cycle
- Thermal regulation with redundant warm and cold internal loops and external loop

Mir’s first crew moves in

- Checked out all of the systems
- Unloaded newly-docked Progress
- 200 kg water automatically transferred
- Soyuz raised the orbit of Mir
- Soyuz fuel replenished from Progress
- Raised the orbit more with Mir’s engines
- In communications for up to 20 minutes per orbit but up to 9 hours out of communications because only one of three geostationary relays had been launched
- First Progress left and second arrived 6 days later with supplies and mail

Mir’s first crew visits Salyut 7

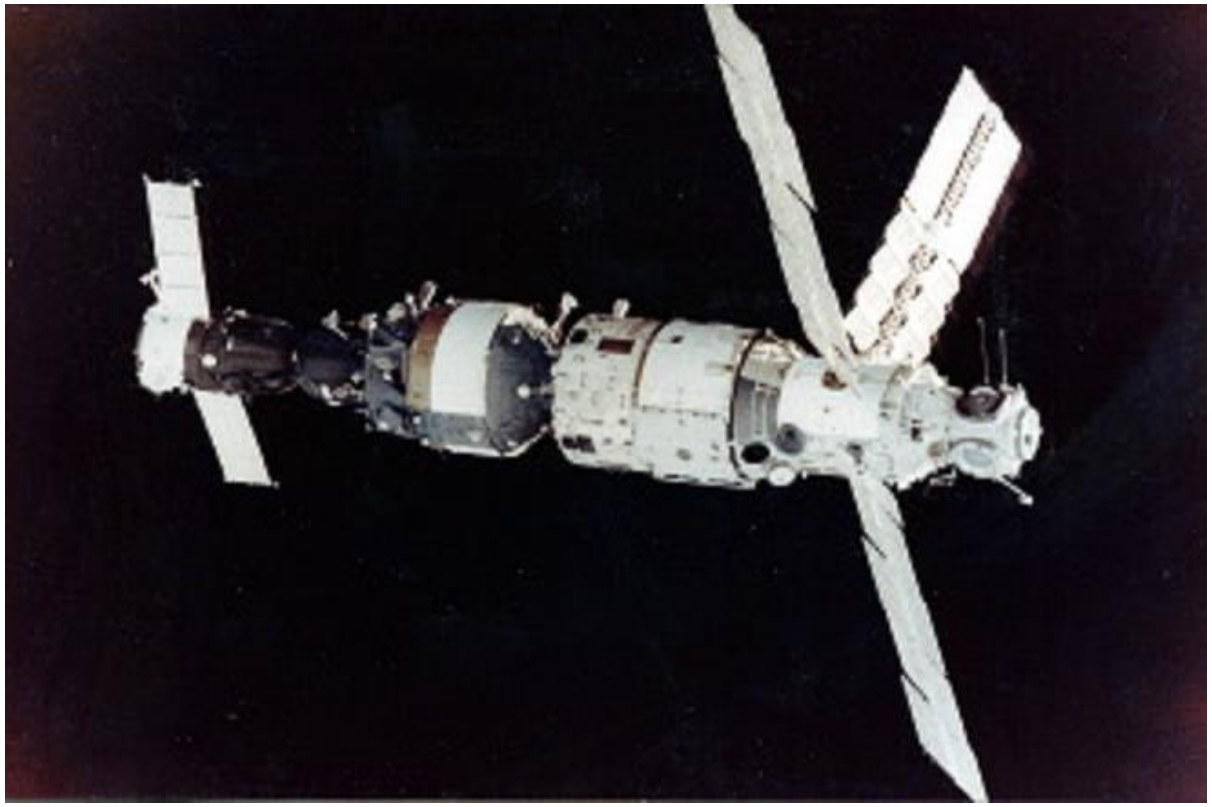
- Salyut 7 had been 2000 miles ahead in the same orbit
- On day 50, the Soyuz undocked from Mir and docked with Salyut 7
- They turned up the heat, slept in the Soyuz, then moved to Salyut
- Replaced multiple components that had exceeded their expected lifetime
- Performed multiple experiments and 2 EVAs (one live on TV)
- Tested a self-deploying girder
- Earth observation including Chernobyl
- Loaded 400 kg of equipment (camera, furnace, film, etc.) into Soyuz and returned
- Left the station on automatic

Crew returns to Mir

- Returned to Mir on day 99 after 49 days on Salyut
- Unloaded Salyut 7 equipment
- Kizim broke the record for cumulative time in space (362 days)
- Because of delays in preparing the next module, plans for continuous operation were dropped and the crew returned home on day 125

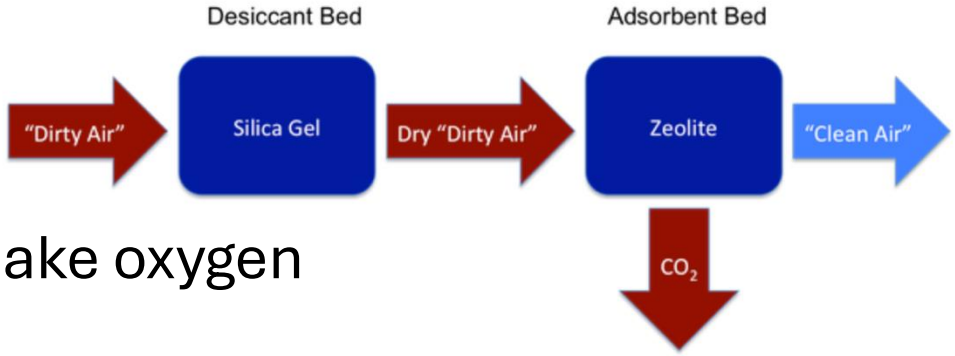
Mir becomes modular: Kvant 1

- Feb. 1987: Soyuz TM-2 (Expedition 2) reactivates station, perform experiments
- April 5: Kvant (“quantum”) 1 laboratory arrives (on a service module)
- Docking problem fixed by EVA (cloth bag)



Kvant 1 equipment

- Kvant 1 experimental equipment
  - Semi-industrial-scale electrophoresis equipment
  - Max Planck Institute's High Energy X-ray Experiment
  - Armenian UV telescope to study quasars
- Kvant 1 life support equipment
  - Vozdukh ("air") scrubs carbon dioxide
  - Elektron apparatus electrolyzed urine to make oxygen
  - Alternative systems (single use):
    - Vika heats lithium perchlorate to release O_2 (needed when >3 people on board)
    - Lithium hydroxide canisters absorb CO_2 (makes lithium carbonate)



- Six large gyrodynes stabilized attitude for astronomic observations
- Additional solar array came as cargo, but not installed because one cosmonaut developed a heart irregularity

Mir Expedition 2 activities

- April 1987: Progress docked to Kvant
  - Four modules attached at once
  - Unloaded water, fuel, food, film, replacement parts, and science apparatus
- Mid-June: two spacewalks to install third solar panel on base block
  - Attached to empty motor mount
  - Second piece attached to first on second space walk
  - Outer then inner pieces extended to 30 feet; plugged in
- July 21: Soyuz TM-3 brought a Syrian scientist and two cosmonauts (for first Mir handover)
- July 29: Return on TM-2 with swap-out of cosmonaut with heart problem
- September: Romanenko breaks 237-day record

Mir Expedition 3

- Dec. 23, 1987: Soyuz TM-4 arrives with three cosmonauts planning to stay one year
- New record for Yuri Romanenko: 326 days (broken 10 months later)
- Complained of conflicting requests from different researchers
- June 1988 Bulgarian and two Russians replaced expiring Soyuz
  - Earth observation of Bulgaria impaired by cloud cover
  - Studied effects of music, video and games on morale
  - Purified interferon

Mir Expedition 3, continued

- Dutch-British-Soviet x-ray telescope had RF interference from the start
  - EVA to replace telescope detector (not designed for repair)
  - Tools developed and sent up
  - One held the other who did the work (alternatively)
  - Cut through 20 layers of insulation
  - Found to be different from what they were told
  - Had to scrape off resin holding screws
  - Tool broke and they gave up before removing the old detector
- TM-6 delivered Valeri Polyakov, deputy head of Moscow's Institute of Medical Biology, to monitor health of current and next expedition

Soyuz TM-5 return to Earth

- TM-5 set to return Sept. 5, 1988 with two short term crew, cosmonaut Vladimir Lyakhov and Afghan Abdulahad Momand
- Orbital module jettisoned
- Navigation computer received conflicting signals from primary and backup infrared horizon sensors (coincided with orbital dawn)
- Automated retrofire system required horizon confirmation 30 seconds prior to firing, so it aborted
- Once the conflict cleared, they were in the wrong position to land
- Fired engines two orbits later, but they shut off after 6 of 230 seconds
- Restarted, but shut off 50 seconds later due to misalignment
- Decided to wait 24 hours; found that the wrong program had been running
- Crammed into descent module with no way to return to Mir, 50ºF, only dried rations from emergency landing kit, no toilet
- Revised program sent up and entered manually, worked fine

Mir Expedition 3, continued

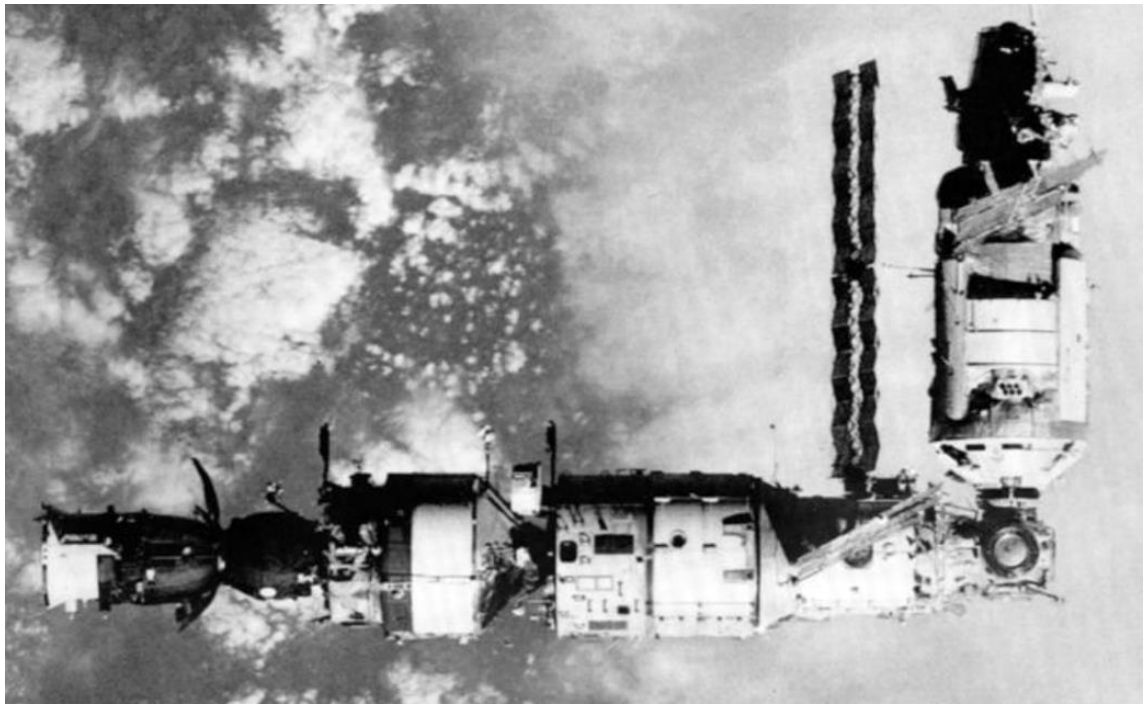
- November 1988, Jean-Loup Chrétien, Aleksandr Volkov and Sergei Krikalyov arrive making a crowded crew of six
- The old crew served a feast of jellied salmon, quail meat and candied fruit for the newcomers, who in turn served vegetable soups, fish, ham, pate, and a range of cheeses
- Expedition 3 crew returned to Earth in December after 365 days in space

Mir Expedition 4

- Back to three crew members (two new, one old)
- Announced no more free rides
- Performed ship maintenance and many experiments
- Replace some of the batteries (all were wearing out)
- Due to delay of Kvant 2 and Kristall, there would be no expansion soon
- Put station into automatic mode and ended the 3-expedition occupancy of 27 months in April 1989

Mir Expedition 5: Re-occupancy and expansion

- Launch September 1989: One week restarting the station
- In November Kvant 2 arrived on its own propulsion unit
  - Needed to spin the module to extend a faulty solar array segment
  - Docked axially
  - Used its Lyappa arm to move itself to a radial berthing port
  - Internal EVA to move radial docking mechanism to a new position



Mir Kvant 2 module

- Equipment
  - Six external gyrodynes
  - Elektron and Vika oxygen generators
  - Toilet and shower
  - Urine processor
    - Collection system
    - Distillation equipment
    - Treatment: H_2SO_4, non-chlorine oxidizer, osmotic membranes

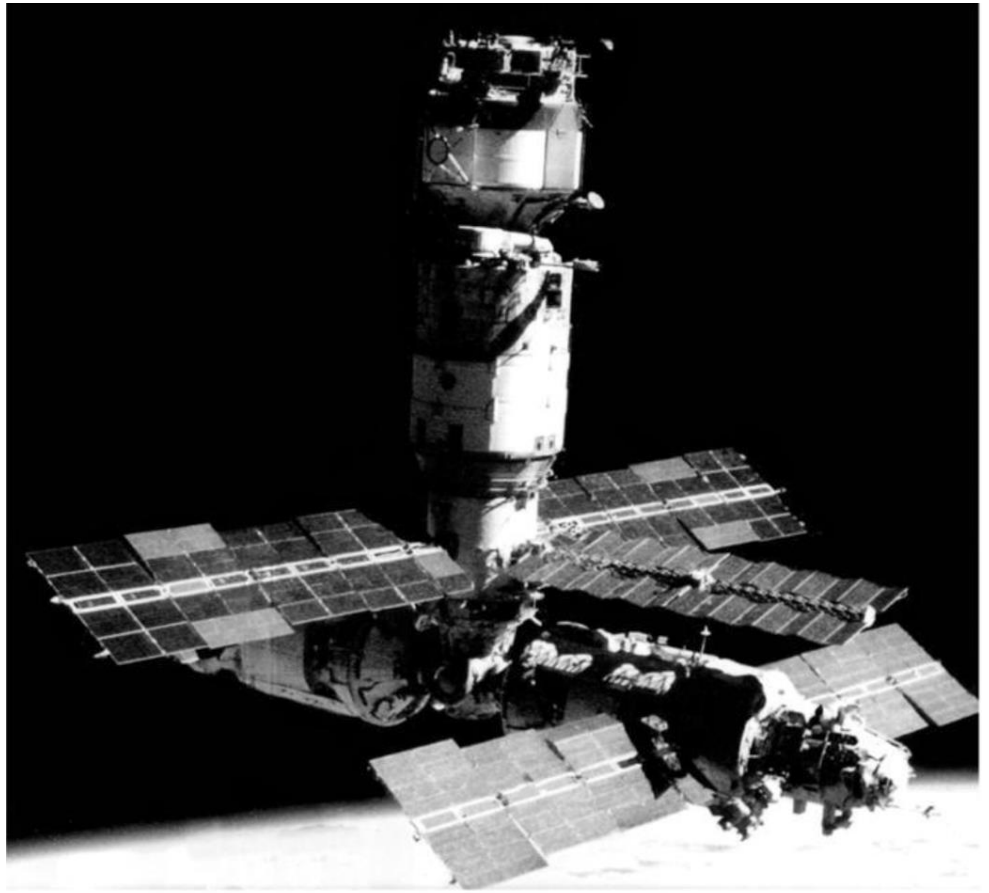
- Deliveries
  - Manned Maneuvering Unit
  - New model of computer
  - Lots of scientific equipment

Mir Expedition 5

- Five EVAs including testing Manned Maneuvering Unit
  - Five months on station
  - Celebrated 1990 with crispy pickles, fresh lemon, canned sturgeon, blackcurrant juice and fresh fruit

Mir Expeditions 6 (February to August 1990)

- Soyuz arrived with peeled insulation partially blocking sensors
  - Some insulation removed by EVA
- Ran a commercial American protein crystal growing experiment that needed more time than on a Shuttle
- Attached Kristall module in June
  - Two more solar panels
  - Materials processing lab
- Brought back pure semiconductor crystals
- Performed resonance testing
- Quail eggs hatched
- Six months on station; uneventful return



A view of Mir from Soyuz-TM 11 during a fly-around.

Mir Expedition 7

- Expedition 7 (August to December 1990)
  - Manakov and Strekalov, both Gennadi Mikhailovich
  - Linked Kristall's attitude control system to the Mir complex
  - First Progress equipped with a Raduga return capsule
  - Successfully recovered 250 pound of experimental material

Mir Expedition 8 (December 1990 to May 1991)

- First commercial space flight (Japanese TV broadcaster)
- EVA replaced broken airlock hinge
- Mounted the Strela crane on the core module

https://www.youtube.com/watch?v=s3lTflyh_Es&t=1215s

Expedition 9 Arrives May 20, 1991

- Anatoli Artsebarsky, Sergei Krikalev, and British food scientist Helen Sharman
- Old crew and Sharman depart May 26 [1:33]

https://www.youtube.com/watch?v=kcmjp0Tehnk

Expedition 9, continued

- Six EVAs
  - Repaired damaged docking antenna
  - Constructed the “Sofora” truss on the Kvant 1 module to demonstrate orbital construction work
- Alexander Volkov brought up Kazakh and Austrian visitors
- Visitors returned with Artsebarsky October 10, 1991
- Krikalev volunteered to stay on with Volkov as Expedition 10

Expedition 10: Homeland in upheaval

- The Soviet Union dissolved on December 26, 1991
- Volkov was 2 months into his mission, but Krikalev was already at 7 and a half months – last two to launch under USSR flag
- Yeltsin established the Russian Space Agency
- Ukraine and Kazakhstan expropriated ground and tracking stations
- Baltic states refused berthing to tracking ships
- Funding problems stopped use of relay satellites
- Completion of Mir and building of Mir 2 cancelled
- Continued science and maintenance
- Next Soyuz in March with 2 Russians and a German (unified)
- Volkov and Krikalev returned to Russia in March 1992

Expeditions 11 and 12

- Expedition 11 (5 months)
  - Kvant 1 had 1 of 6 and Kvant 2 had 4 of 6 failed gyrodynes
  - Two new gyrodynes were installed
- Expedition 12 (6 months)
  - Paid French visitor for 12 days with Progress-delivered experiments

US and Russia agree to cooperate

- October 1992 NASA-RSA Agreement

  “The United States of America and the Russian Federation, hereinafter referred to as the Parties;

  Considering the role of the two states in the exploration and use of outer space for peaceful purposes;

  Desiring to make the results of the exploration and use of outer space available for the benefit of
  the peoples of the two states and of all peoples of the world;

  Considering the respective interest of the Parties in the potential for commercial applications of
  space technologies for the general benefit; […]

  Expressing their satisfaction with cooperative accomplishments in the fields of astronomy and astrophysics,
  earth sciences, space biology and medicine, solar system exploration and solar terrestrial physics, as well as their desire to continue and enhance cooperation in these and other fields;

  Have agreed as follows:”

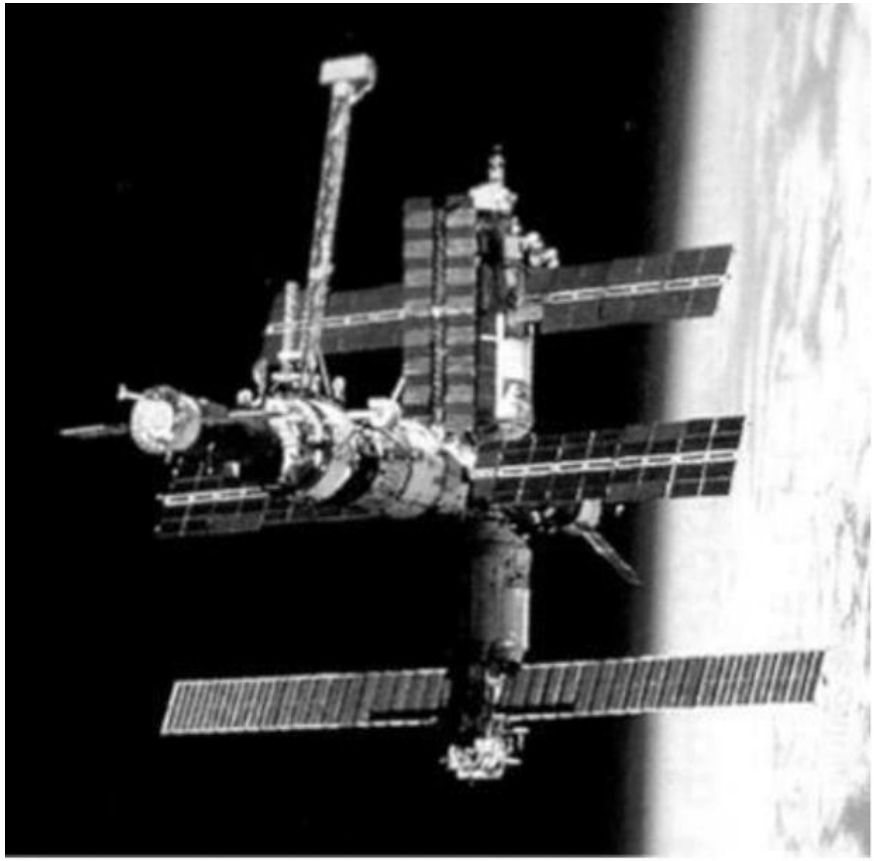
- Cosmonaut on the Shuttle in 1994; Astronaut to Mir in 1995

Expeditions 13 to 16

- Expedition 13 (6 months)
- Expedition 14 (6 months)
  - Pelted by micrometeoroids from Comet Swift-Tuttle
  - EVA found 4-inch hole in a solar panel and 65 smaller impact pits
  - Return delayed: Soyuz rocket manufacturer would not release engines until paid
  - December 1993 announcement of ISS
  - Power was reduced due to age: plan to deliver new solar panels on the Shuttle
  - First of several Boeing black-box science packages
- Expedition 15 (6 months for two, Polyakov stays on)
  - Elsewhere
    - Krikalev flew on STS-60
    - Kazakhstan agreed to lease Baikonur for $100 million in trade credits
    - Cosmonaut corps reduced to save money
- Expedition 16 arrives (4 months; Polyakov stays on again)
  - Kazakh crew member

Expedition 17: International Cooperation

- Alexander Viktorenko, Yelena Kondakova and Ulf Merbold arrive in October of 1994
- Euromir: Merbold, a German physicist, stayed 30 days
- Small fire in Vika “candle” smothered
- STS-63 launched February 1995 (five-minute launch window)
- Eileen Collins and Jim Wetherbee flew with 37 feet of Mir



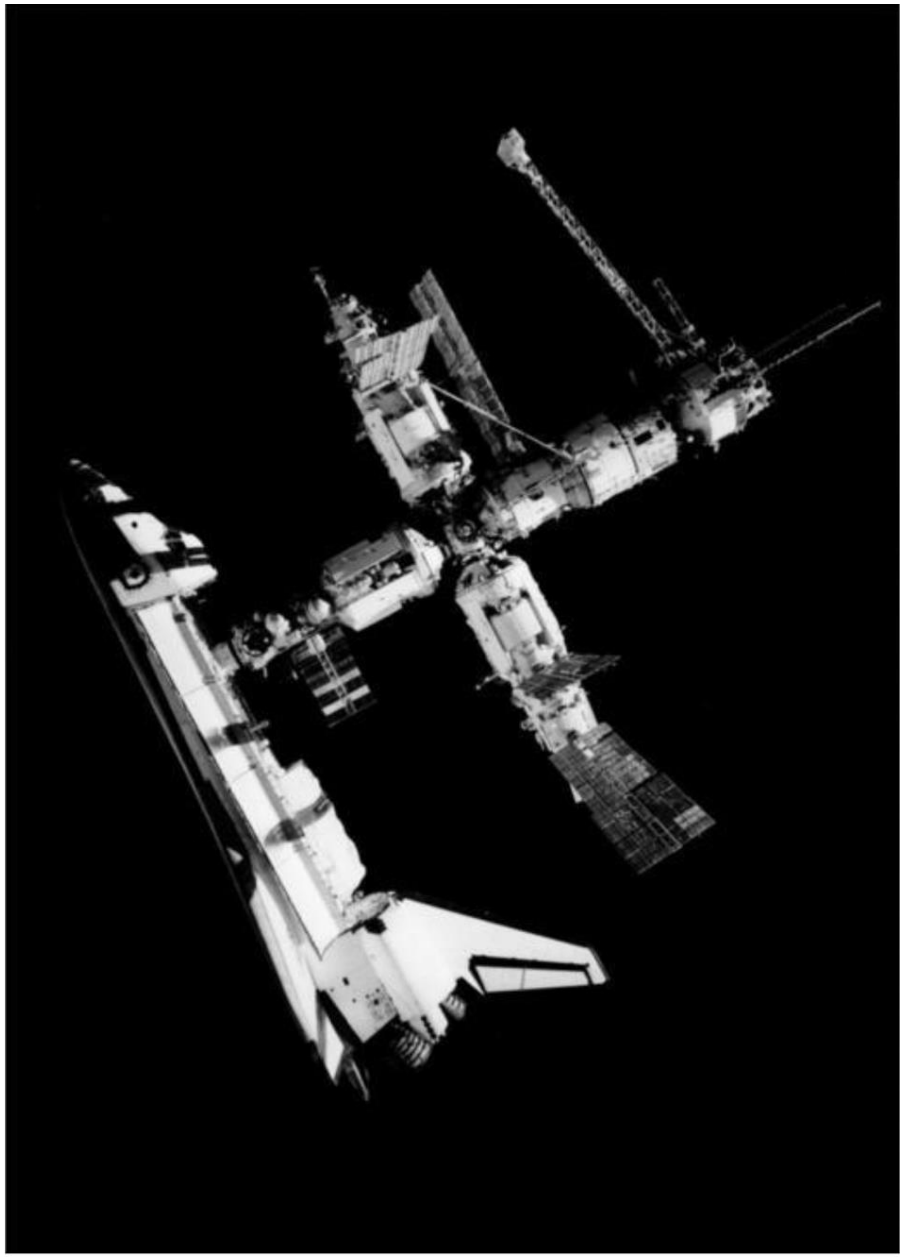
Mir as viewed by STS-63.

Stretch

Expedition 18: First American on Mir

- March 16, 1995: Soyuz-TM 21 arrives with Norman Thagard, Vladimir Dezhurov and Gennadi Strekalov
- Polyakov finally leaves after 437 days (14+ months)
- Thagard was a full crew member for all 4 months and was in charge of 28 experiments, mostly biomedical
- Three EVAs to move a solar panel from Kristall to Kvant 1

First Shuttle-Mir Docking with Crew Transfer



Atlantis about to undock from Mir.

- June 29, 1995: Atlantis docks with Mir with a combined crew of 10 for five days
- Brought two-cosmonaut relief crew (Expedition 19) and returned Thagard and the two Expedition 18 cosmonauts who stayed 3 months on Mir
- Expedition 19 repaired the solar array with new tools
- Attached Spektr power module

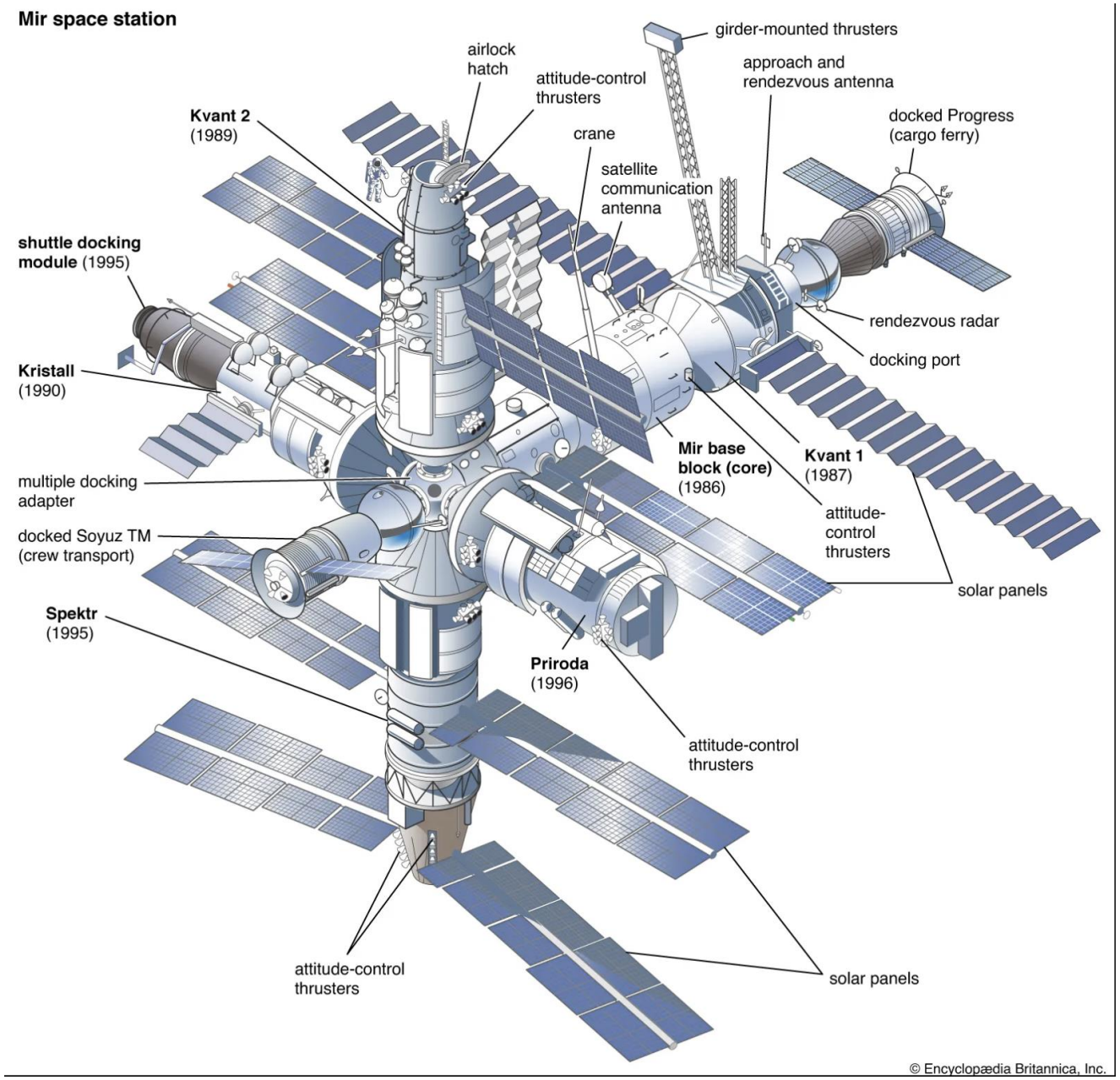
Shuttle-Mir Program: ISS Phase 1

- March 1995 To June 1998
- Seven NASA Astronauts
- Up and down on Shuttle, except Thagard up on Soyuz, Reiter up and down on Soyuz
- Expedition 20:
  - Five months with Thomas Reiter (ESA, not NASA)
  - Atlantis delivers cargo including two solar arrays for Kristall plus Energiya's docking module, overcoming the need to relocate Kristall when a shuttle docked
- Expedition 21: Six months with Shannon Lucid
- Expedition 22: Six months with John Blaha, then Jerry Linenger
- Expedition 23: Six months with Michael Foale
- Expedition 24: Six months with David Wolf, then Andrew Thomas

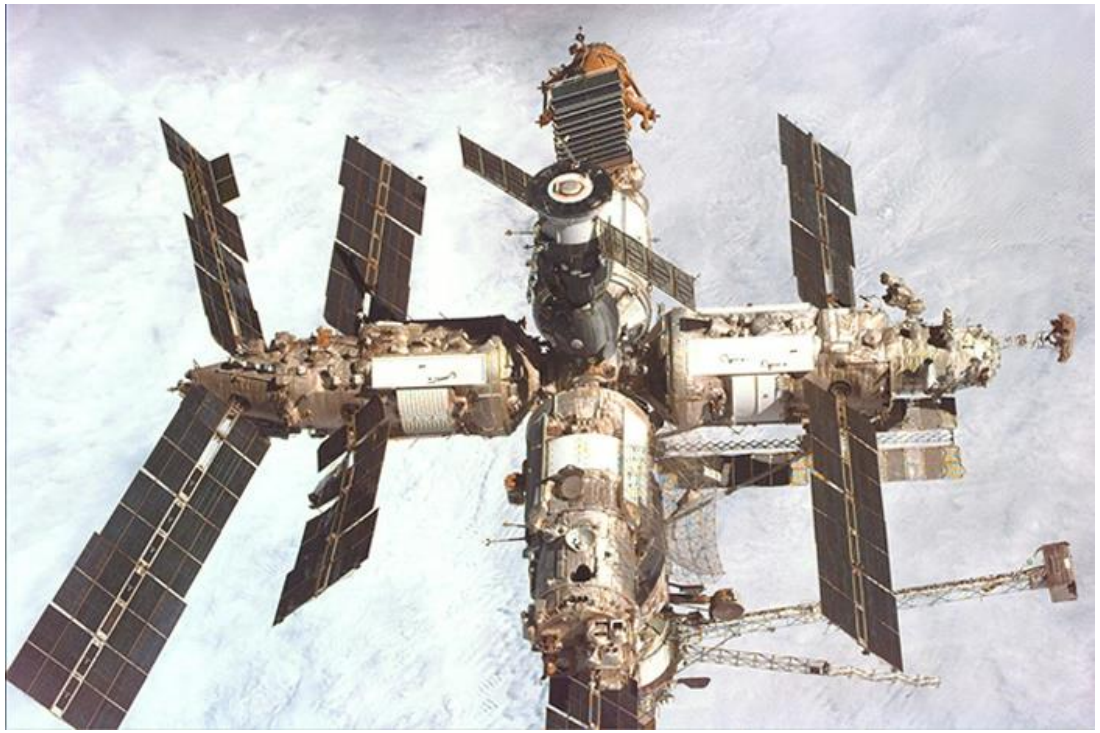
Some Mir Milestones

- Expedition 21
  - Priroda module attached April 1996 (Remote sensing, partially US funded)
  - Booster problems delayed Shuttle; extra Progress needed for expendables
- Expedition 22
  - Lucid replaced by Blaha (first in-space American turnover)
  - Solar arrays installed
- Expedition 23 (1997 with Jerry Linenger)
  - Elektron failed, backup not working: had two months of Vika canisters plus a few days of bottled emergency oxygen
  - Failed sensor started runaway 3-axis roll
  - Vozdukh out of service: needed lithium hydroxide canisters
  - Progress arrival critical

Full Mir Configuration 1996



Kristall technology module
Spektr power module
Docking module
Priroda Earth sensing module
Strela crane



Mir Key Events [AP Archive 0:55]

- January 1997 physician Jerry Linenger

https://www.youtube.com/watch?v=gKbHhzPJOVM

Mir Key Events

- Astronaut Michael Foale, May 1997 (Creative News [3:49])

https://www.youtube.com/watch?v=DqzJV_wwXrQ

1998 Mir Tour by David Wolf [Eureka 1:54]

https://www.youtube.com/watch?v=vBONpY3TxN8

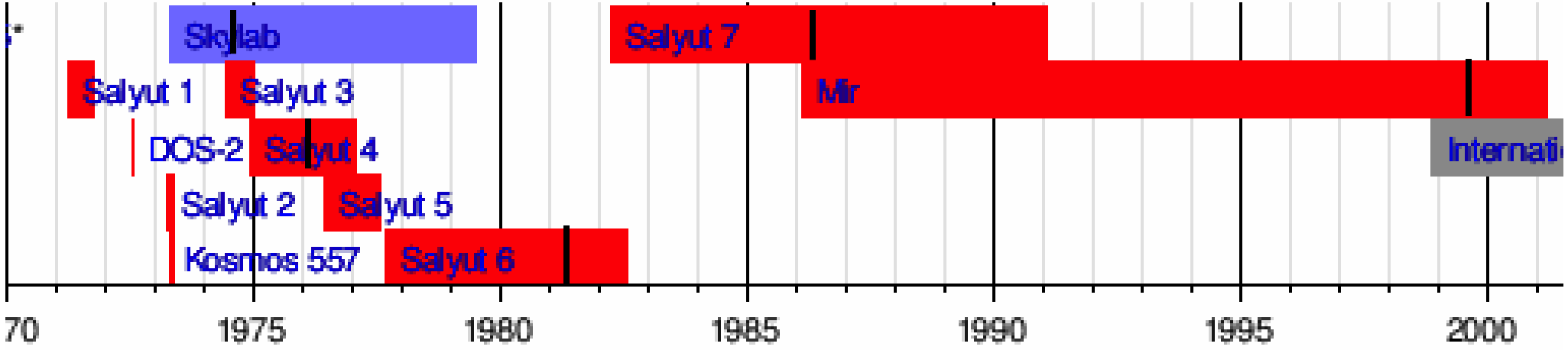
Aging Mir

- Expeditions 26 and 27 (August 1998 to August 1999) were the last for continuous occupation of Mir (10 years)
- At the end 80% of time was spent on repairs
- Altogether 104 cosmonauts from 13 countries
- Zarya launched November 1998 to start the ISS
- April to June 2000, Expedition 28 send by MirCorp (private) to reactivate and repair
- Insufficient funding led to Mir deorbit in 2001
- Pieces that did not burn up fell into the South Pacific “graveyard”

Mir Summary

- Seven pressurized modules, 140 tons
- Over 15 years in orbit, 12 and half occupied in four intervals
- Thirty Soyuz and nine U.S. space shuttles ferried crew
- Sixty-five robotic supply missions
- Prime crew visits were 2+ to 14 months
- Over 100 visitors including 12 Europeans, a Turk, an Afghan, a Bulgarian, a Canadian, a Japanese, and 7 Americans
- Male and female records for continuous space flight
  - Valeri Polyakov 437 days
  - Shannon Lucid 188 days (since surpassed by Christina Koch 329 days)
- Important precedent for international cooperation
- Many lessons for building the ISS

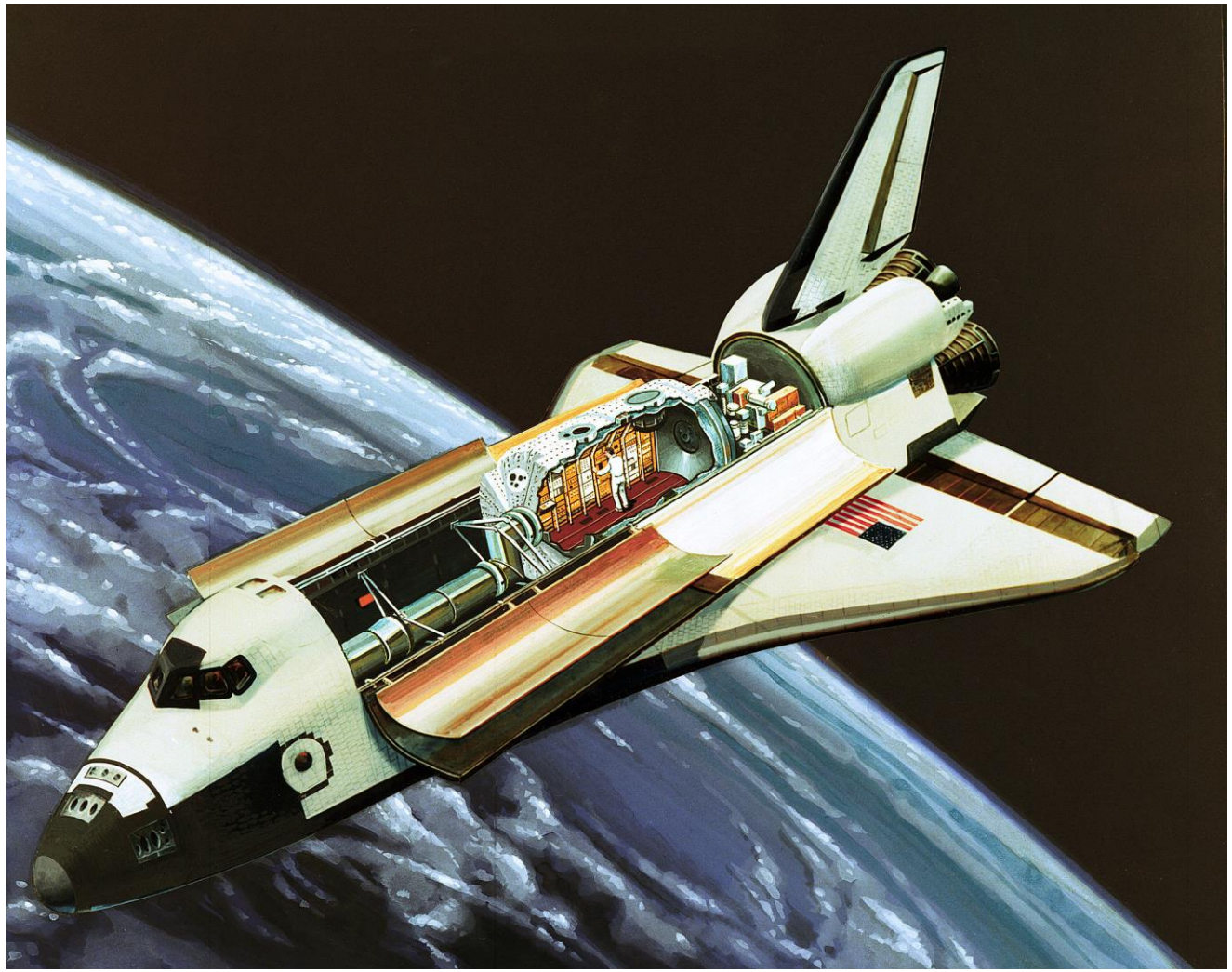
Space station timeline



International Space Station

Not Quite a Station: ESA Spacelab (1983-1988)

- Pressurized module inside the space shuttle cargo bay
- Produced by a consortium of 10 European countries
- Modular
- Six unmanned missions
- Sixteen manned missions
- Life sciences
- Material sciences
- Microgravity
- Astronomy
- Earth observation



Background

- U.S. “Freedom” station
  - Announced in Reagan’s 1984 State of the Union address [1:38]
  - Shuttle had been operating since 1981 (time of Salyut 7)

https://www.youtube.com/watch?v=SD4egsoOdAw

Background

- U.S. “Freedom” station
  - Joint with Japan (NASDA), Europe (ESA), and Canada (CSA) and including two Russian Soyuz capsules for emergency rescue vehicles
  - Partially built, but not launched
  - NYT June 1993: “Fate of Space Station Is in Doubt As All Options Exceed Cost Goals”
    - Congress said the only wanted to spend $9 billion over then next four years
    - NASA had spent $9 billion and estimated $31 billion to finish by 1999
- Russian “Mir 2” station
  - Converted to ISS in 1993, due to economic issues in Russia
- Russian Mir station: last crew left June 2000, deorbit March 2001

International Space Station Authorization Act of 1995

- The Congress finds that
  - the development, assembly, and operation of the International Space Station is in the national interest of the United States
  - the International Space Station represents an important component of an adequately funded civil space program which balances human space flight with science, aeronautics, and technology
- The Congress further declares that the use of free market principles in operating, allocating the use of, and adding capabilities to the Space Station, and the resulting fullest possible engagement of commercial providers and participation of commercial users, will reduce Space Station operational costs for all partners and the Federal Government's share of the United States burden to fund operations.

Space Station Intergovernmental Agreement

- Agreement among the governments of Canada, states of the European Space Agency, Japan, the Russian Federation, and United States of America concerning cooperation on the civil International Space Station -- signed at Washington January 29, 1998
- Peaceful purposes in accordance with international law
- Enhance the scientific, technological, and commercial use of outer space
- Countries own what they provide
- Each country pays for its contribution and an equitable share of operating expenses
- Each partner has the right to have qualified personnel serve as crew
- Cross-waiver of liability
- Agreement to share technical data
- States have criminal jurisdiction, but extradition is possible
- One year notice to withdraw

How We Get to Space

Vehicles Delivering Components of the ISS

- Russian Proton Rocket (3): 52,000 pounds, 24 feet in diameter
- Russian Soyuz Rocket (5): 18,000 pound 34 feet in diameter
- U.S. Space Shuttle (27): 65,000 pounds, 15 feet in diameter, 60 feet long
- Space X Falcon 9 (9): 23,000 pounds, 12 feet in diameter

Vehicles Resupplying the ISS

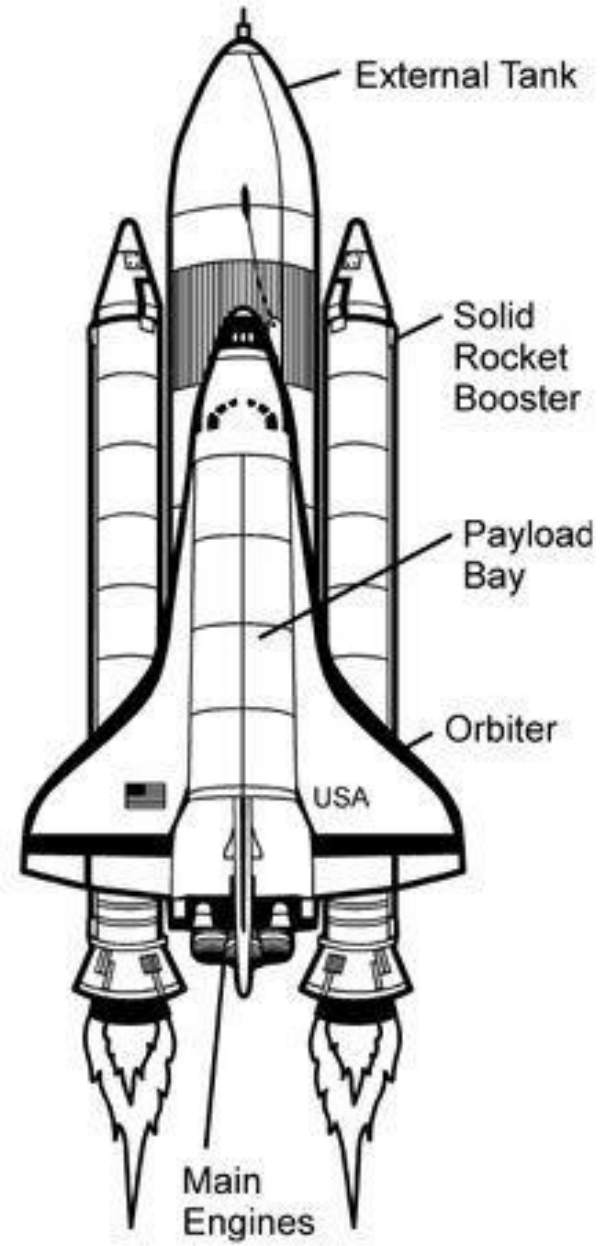
- Russian Progress supply ships
  - Based on Soyuz; 5,300 pounds of cargo; 3-4 per year
  - Two out of 92 failed to reach the ISS (up to October 2024)
  - Only one to automatically dock
- ESA Automated Transfer Vehicles
  - Five launched (2008-2014); 17,000 pounds of cargo
- Japanese H-II Transfer Vehicle
  - Nine launched (2009-2020); 13,000 pounds of cargo
- US Cygnus
  - Twenty-two launched (2013-2024) with one loss; 11,000 pounds of cargo
- Space X Commercial Resupply Services (Cargo Dragon)
  - Thirty launched (2012-2024); 13,000 pounds of cargo
- Sierra Dream Chaser Cargo System due to launch in 2025

Passenger ships: Russian Soyuz (Союз “Union”)

- Four generations from 1967 to the present (sole transport 2011-2020)
- Safe and cost-effective (one parachute failure with death, three launch aborts, one in-orbit abort, three hard landings out of >150)
- Three passengers plus about 500 pounds of cargo
- Launched on Soyuz rocket (LO_2 and RP-1)
- Kazakh steppe landing
- Always on-station as a rescue vehicle (up to 6 months)

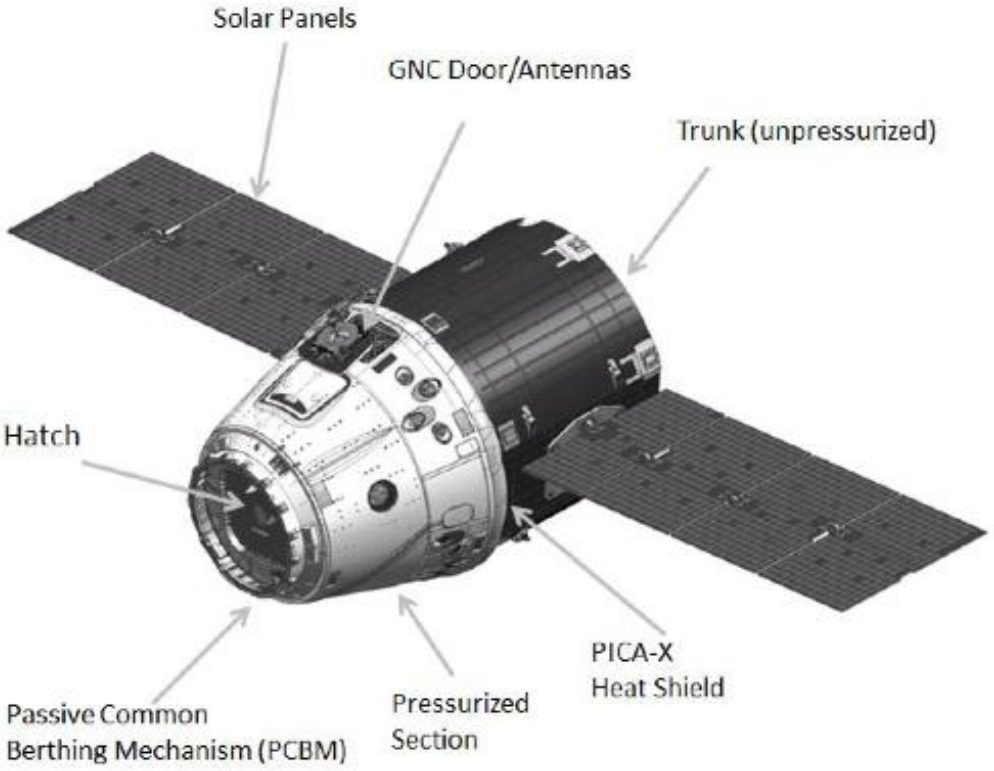
Passenger ships: U.S. Space shuttle (Space Transport System)

- Reusable (designed for 55 launches; actual maximum 39)
- Up to 8 passengers and 35,000 pounds of cargo
- Main engines: LO_2, LH_2
- Boosters: ammonium perchlorate composite and polybutadiene acrylonitrile
- Orbital Maneuvering System: two engines with hypergolic fuel / oxidizer
- Reaction Control System: 44 engines with hypergolic fuel / oxidizer
- 1986 Challenger launch failure with 7 fatalities
- 2003 Columbia reentry failure with 7 fatalities
- Canadarm remote manipulator system
- On orbit up to 18 days
- Retired in 2011



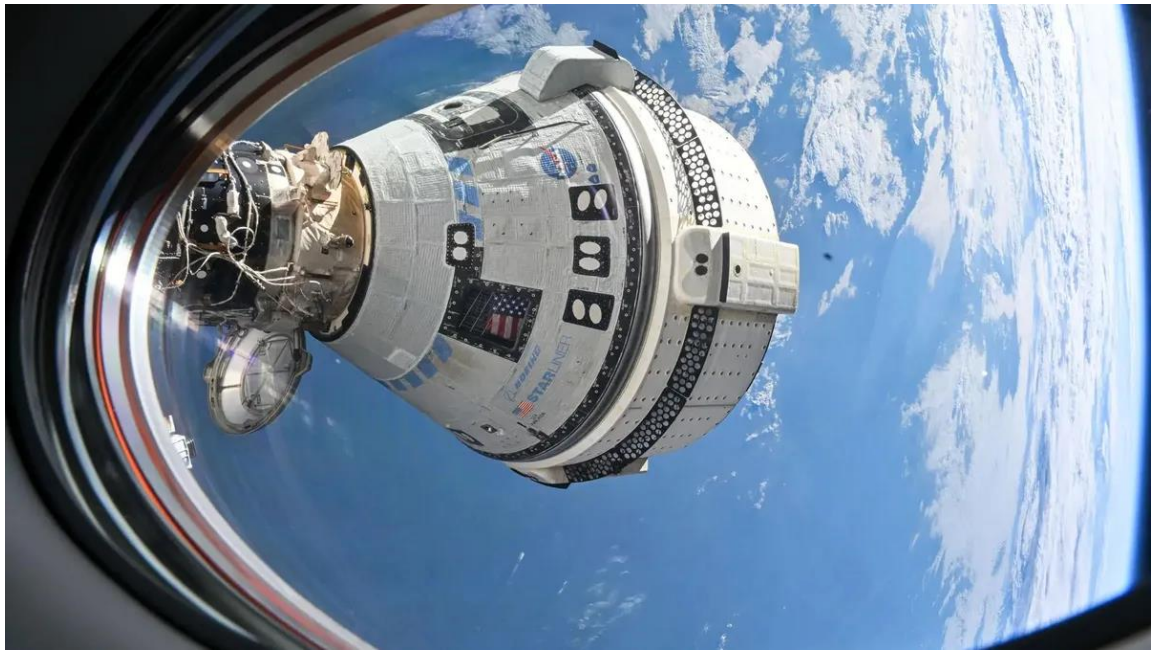
Passenger ships: Space X Crew Dragon

- First crewed flight in 2020, 13 crews to the ISS (to Nov. 2024)
- Capsule is reuseable, water landing
- Up to 7 seats; actual use: 4 seats plus cargo (13,000 pounds)
- Seven active vehicles (actual max flights: 5, one on-station)
- Launched on Falcon 9: Booster (LOX / RP-1) is reuseable, but second stage (LOX / RP-1) is not
- Stays on station as a rescue vehicle (6 months, rated 210 days)



Passenger Ships: Boeing Starliner

- Long delayed compared to Crew Dragon
- Designed for 7 crew and 8000 pound of cargo
- Designed to be reuseable 10 times
- Launched on Atlas V or Delta IV rockets
- First unmanned test did not get to orbit due to software bug
- Second unmanned test went well
- First manned test (Suni Williams and Butch Wilmore) had problems with failing thrusters; returned empty



Construction

First steps of construction

- Zarya “Function Cargo Block”
  - Launched Nov. 20, 1998 via Proton-K rocket
  - Deployed antennas and solar panels
  - Initially provided all of the power as well as propulsion and guidance
- Unity Node 1 (built by Boeing)
  - Launched in Endeavor STS-88 in December 1998
  - Six-person crew (five Americans, one Russian)
  - 11 day mission
    - Use Canadarm to remove Unity from payload bay
    - Attach unity to Shuttle docking port
    - Rendezvous with Zarya
    - Grapple Zarya and attach to Unity
    - Ingress and three EVAs to complete all activation steps
    - Recommended video: https://www.youtube.com/watch?v=3Bqaa8n6bKY

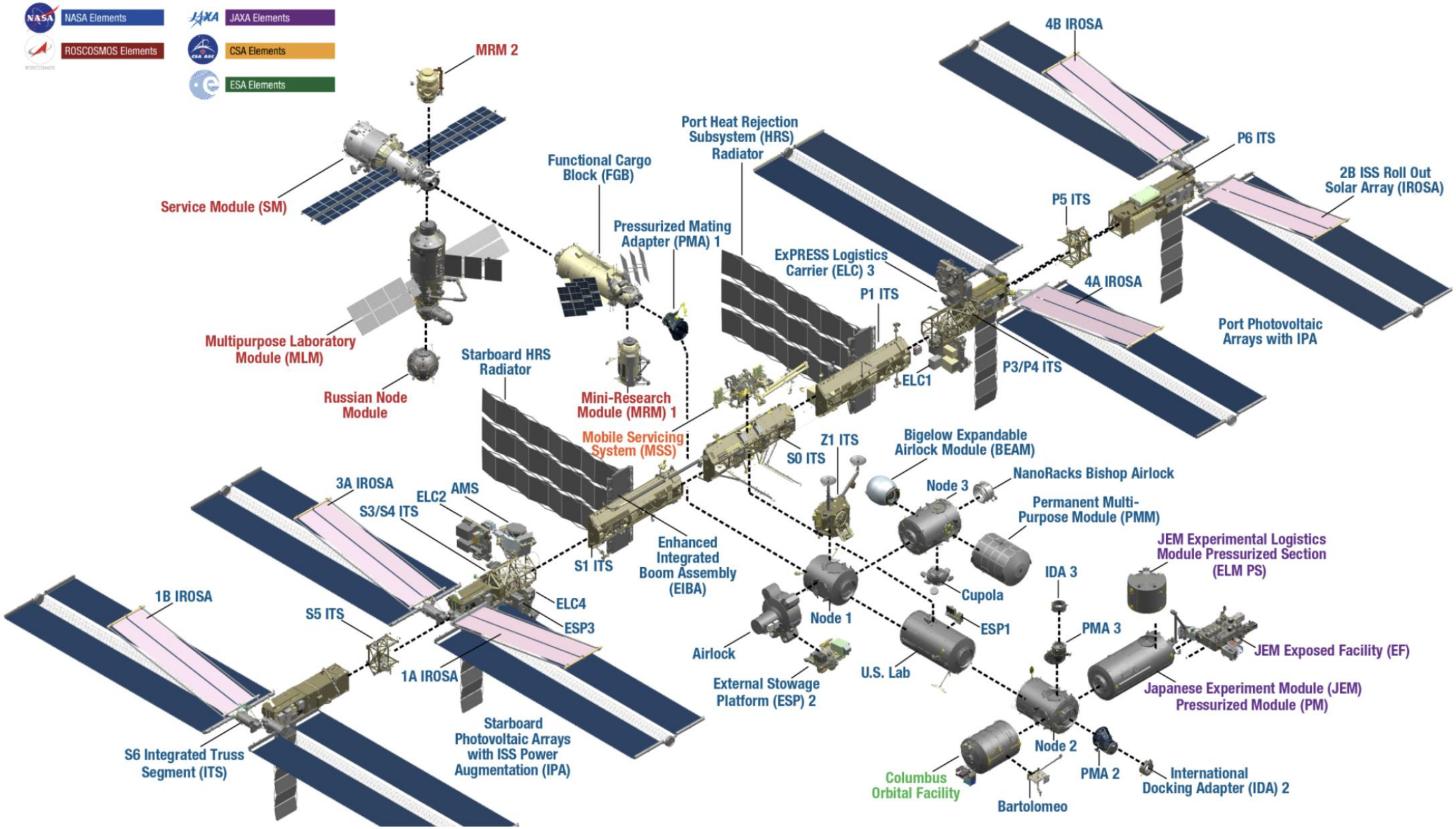
ISS construction as told by Shuttle astronauts

https://www.youtube.com/watch?v=3Bqaa8n6bKY

More on ISS Construction [1:08 Jared Owen]

https://www.youtube.com/watch?v=FhKOuxhGlmI&t=445s

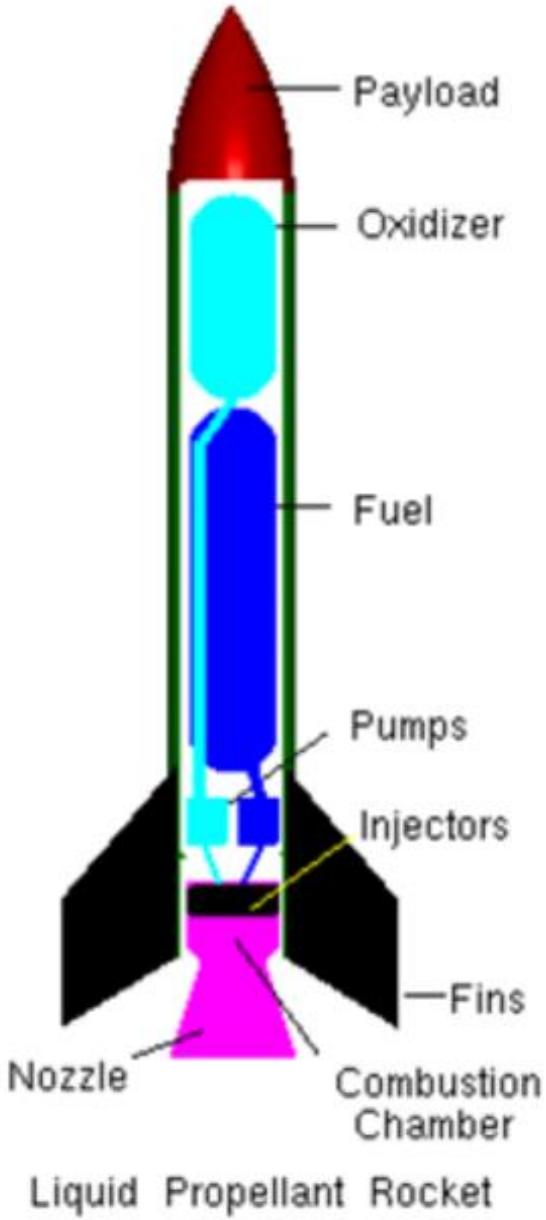
ISS Final Components



Comments and Questions

Rocket primer

- Based on Newton's third law of motion: For every action there is an equal and opposite reaction
- Main types:
  - Monopropellant produces gasses when in contact with a catalyst
  - Fuel plus oxidizer: produce gasses when mixing propellant and oxidizer
    - with an igniter (non-hypergolic)
    - without an ignitor (hypergolic fuels)
- Gasses are expelled through a nozzle, causing the rocket to move in the opposite direction
- Steering is with movable fins, movable (gimbaled) engines, movable exhaust nozzles, or extra "vernier" thrusters



Inertial guidance

- Three gyroscopes at right angles measure direction
- Three accelerometers at right angles measure acceleration
- Circuits integrate acceleration to get velocity
- Integration of velocity produces position
- Feedback relative to stored desired position keeps the rocket on trajectory
- This is a form of “dead reckoning”

ISS “Expeditions” (from Wikipedia)

- Each permanent crew is given an expedition number
- Expeditions 1 to 6 consisted of three-person crews
- Expeditions 7 to 12 were reduced to the safe minimum of two following the destruction of the NASA Shuttle Columbia
- From Expedition 13 the crew gradually increased to six around 2010
- With the arrival of crew on US commercial vehicles beginning in 2020, NASA has indicated that expedition size may be increased to seven crew members, the number for which ISS was originally designed

Mir Basic Operations

- Water vapor reclaimed by the AC unit was potable (loc 2186)
- Wash basin water was cleaned and reused
- Urine was vented, and feces periodically ejected
- N_2 and O_2 were mixed at normal pressure, CO_2 was removed with lithium hydroxide canisters; charcoal and catalysts removed CO, H_2, CH_4 and NH_3
- Resupply ships brought more N_2 and O_2, as well as fuel
- Work hours were 8 AM to 11PM, five days a week
- One of three relay satellites was in place initially, allowing up to 40 minutes of communication per orbit
- Modules contain Lyappa robotic arms to attach themselves