Building a Solar System Internet

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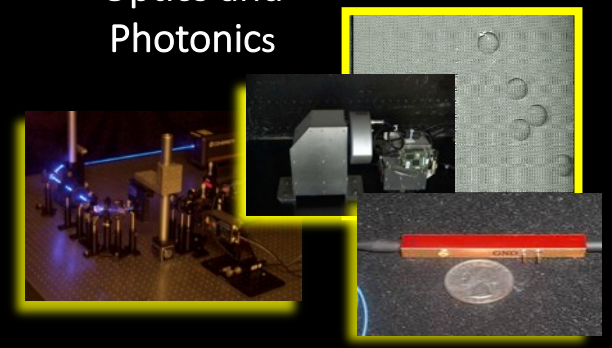
NASA GRC

This Presentation …

- … will explain why networking in space is harder than it is on Earth
- … will offer an overview of networking on Earth
  - suggestion: take a course and / or do some reading to learn more …
- … will explain how we're building an internet in space
  - in which cats are expected to continue to play a vital role
- … will include terrible art and / or jokes
  - sorry
- … includes a disclaimer: certain liberties are taken for the sake of conversation
  - some degree of nuance and / or accuracy may be lost as a result

Communications and Intelligent Systems Division (LC)

Optics and Photonics

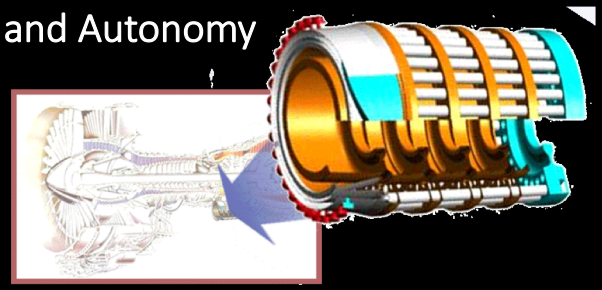


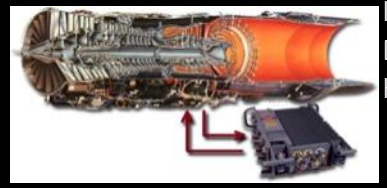
Optical Instrumentation
Optical Communications
Health Monitoring

Architectures, Networks and Systems Integration

Communications Architectures
Network Research
Modeling and Simulation/Tech Demos
Spectrum and Link Analysis

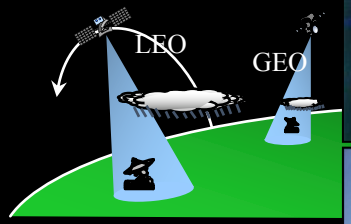
Intelligent Control and Autonomy

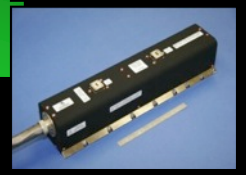




Intelligent Controls
Dynamic Modeling
Health Management

Advanced High Frequency



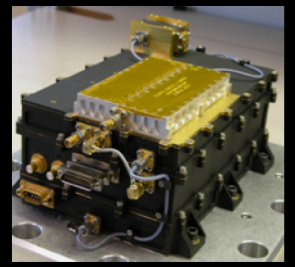


Antennas/Propagation
RF Systems and Components
3-D Electromagnetic Modeling

Smart Sensors and Electronics Systems

Thin Film Physical Sensors
High Temp/Harsh Environment Focus
Wireless Technologies

Information and Signal Processing



Radio Systems – SDRs, Cognitive Comm
Bandwidth and Power Efficient Waveform Development

Communications and Intelligent Systems Division (LC)

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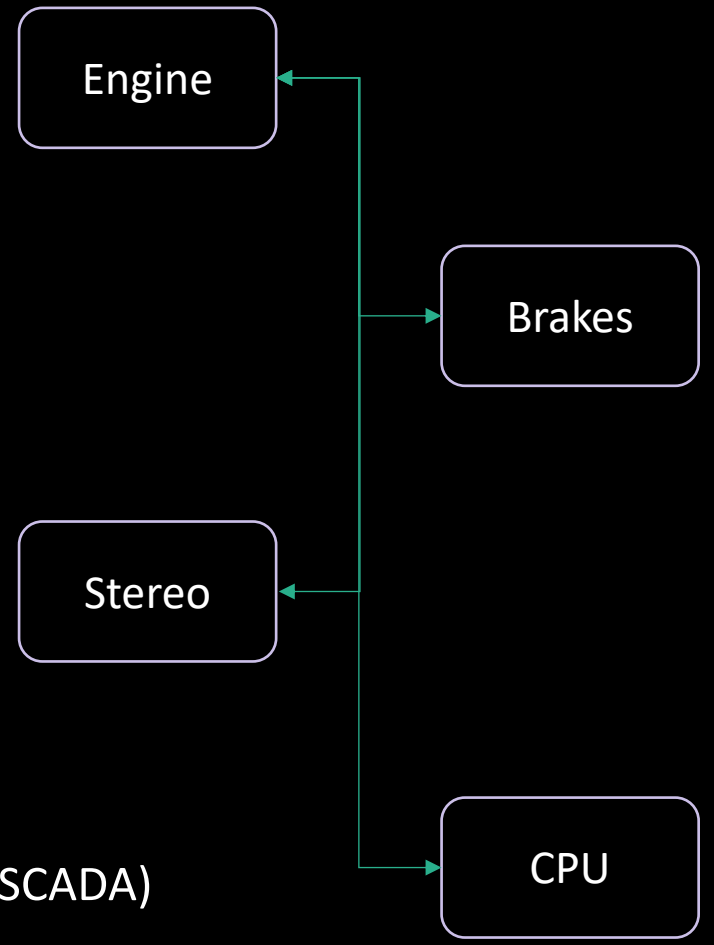
WE ARE HERE
(LCA)

Why Networking?



- Networking is an aspect of a distributed system
  - Need a way to communicate between pieces
  - As there are more pieces, things become more complex
- Networks exist in just about every modern system
  - Automobiles:
    - Example: Controller Area Network (CAN)
  - Aircraft:
    - Example: ARINC 664
  - Industrial:
    - Example application: Supervisory Control And Data Acquisition (SCADA)
- Networks are needed for …
  - Monitoring, autonomy, cooperation, automation, command and control, etc ...
- If it needs to talk to something else, it needs a network to do it!

Networking … IN SPACE! … SPACE! … SPACE! … SPACE! … SPACE! …

- My projects are Space Communications and Navigation (SCaN)
  - Program office for all NASA space communication activities
- So … my emphasis is on networking in space
  - There *are* many challenges in common with aerospace …
  - … but space tends to have less existing infrastructure and more delay
- I specifically focus on building networks tolerant to delay / disruption
  - Keyword: Delay / Disruption Tolerant Networking (DTN)
- So, why is it harder to build networks in space than on Earth?
  - Before we answer that question, let's review …

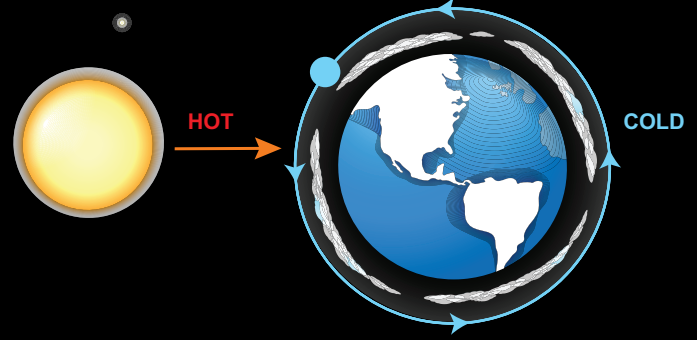
Things we like about networks on Earth

- Everything's relatively close …
  - … comparatively speaking
    - Propagation through copper cable: roughly 124,000 miles / sec
    - Circumference of Earth: roughly 24,900 miles
    - => signal can travel through copper around the world in around 200* ms …
- Logistics are (reasonably) easy
  - Lots of people in fleets of vehicles
  - Hot-swappable components on network / server equipment
- The Earth shields network equipment from radiation
  - 'cause atmosphere

* ignoring things like queuing delay / making a bunch of assumptions that probably aren't true / etc. … so it's wrong, but we'll just go with it for now

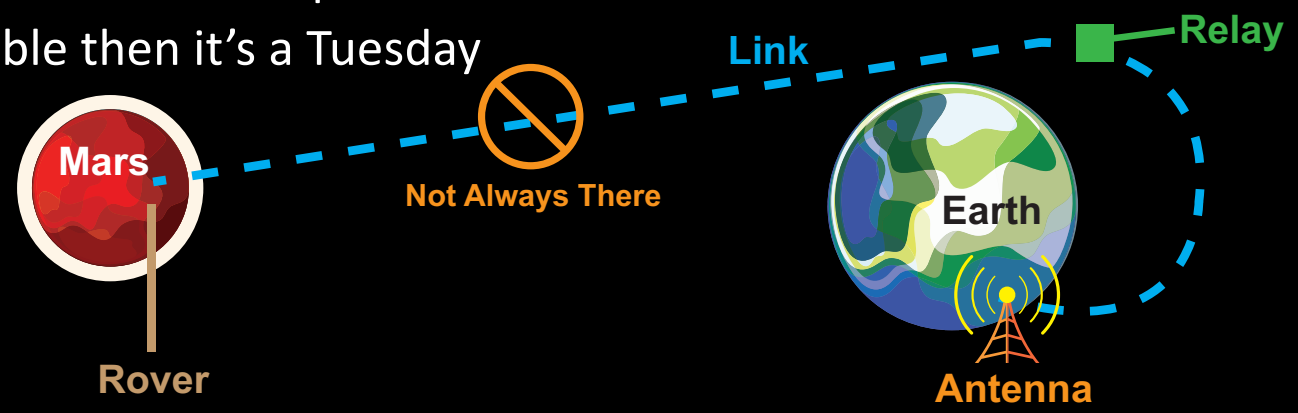
Things we dislike about networks in space

- Everything's relatively far …
  - Assuming signal propagation through space at the speed of light …
    - Jupiter: ~530 million miles => roughly 47 minutes One Way Light Time (OWLT)
    - Neptune: ~2.85 billion miles => roughly 4.25 hours OWLT
- Logistics are (very) hard
  - "Hey Larry, go swap out that card in that satellite orbiting Venus, would you?"
    - Related: "Hey Susan, could you go reboot the relay satellite around Neptune for me?"
  - Launches take a long *(!)* time to plan and execute
- Space does not shield network equipment from radiation
  - Cost to develop a radiation hardened part isn't offset by widespread demand
    - Result: usually an astronomical non-recurring expense (NRE) involved to develop
- Other considerations as well …
  - SWaP: Size, Weight, and Power
  - Also a problem: thermal



Things we dislike about networks in space (II)

- Line of sight is tough
  - Physics 101: Signals can't go through planets …
    - Relevant XKCD: https://what-if.xkcd.com/13/
  - In a perfect universe, we'd have lots of assets and could relay everything
    - We don't have nearly that many assets …
    - … though next-generation designs *are* working to improve availability and capacity!
  - This means that we can't talk to everything all the time
    - On Earth, if something is unavailable then it's a problem
    - On Mars, if something is unavailable then it's a Tuesday



TL/DR: Space is kind of hard

- Summarizing some challenges …
  - Disconnection
    - Satellites, rovers, etc. may not be available all the time
    - Often no complete end-to-end path between two assets
  - Delay
    - It takes a *really long time* for a signal to move between planets
  - Logistics
    - Space assets are considered (more or less) irreplaceable and are engineered to *last*
      - "Irreplaceable" => stuff is designed to *minimize risk* and to *get the job done*
      - Technology normally isn't included without a demonstrable need … which does make sense!
        - Unnecessary complexity does not generally a successful mission make
    - It takes (a lot of) time to get technologies mission-qualified, infused, and widely deployed
  - Technology
    - New generations of gear need to be adapted to work in space before we can use them
      - Adaptation takes time and money

Scope

- To keep things to a reasonable length, we are going to focus on …
  - Delay
  - Disruption
- That is not to say that other challenges are not important …
  - Only that we're focusing on the challenges that networking technology can fix
- So, moving right along …
  - … let's dive in to some more detail on networking!
- Before we can talk about networks in space, though …
  - … we need to talk about networks here on Earth

What's in a network, anyway?

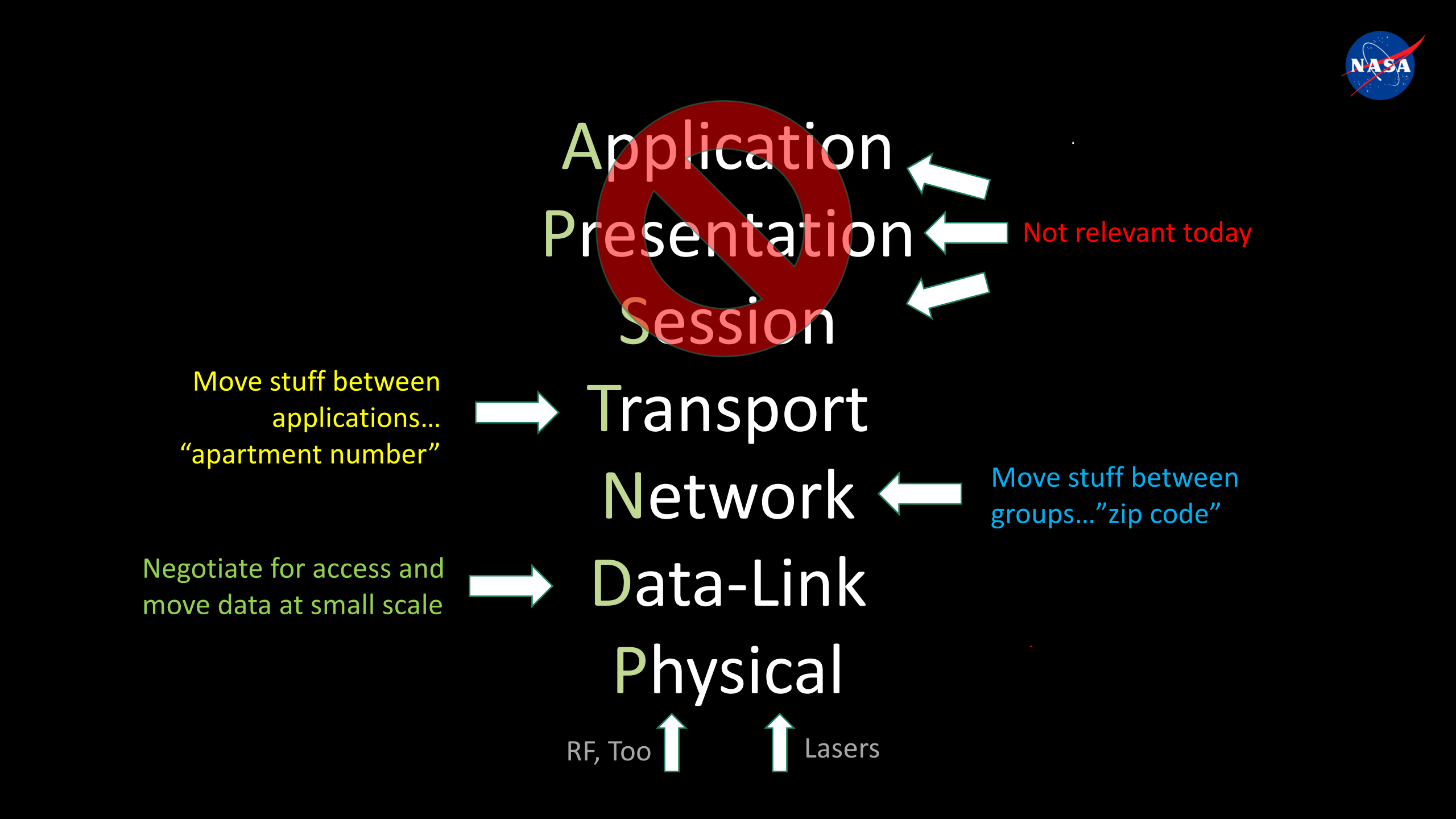
- Network: a bunch of things that all talk to one another
  - Protocol: agreed-upon, common language that the things use to talk
- In the ideal case, the network is broken into layers
  - "Stack" - a bunch of layers sitting on top of one another
  - Each layer is responsible for something different
  - Can swap out one technology in a lower layer for another …
    - … without everything above that layer collapsing in on itself
    - See also: "encapsulation"
- Most common mental model is the OSI model
  - "Open Systems Interconnect"
  - It's a useful abstraction, but *is not the only correct one!*

All
People
Seem
To
Need
Data
Processing

How to remember the layers of the OSI model

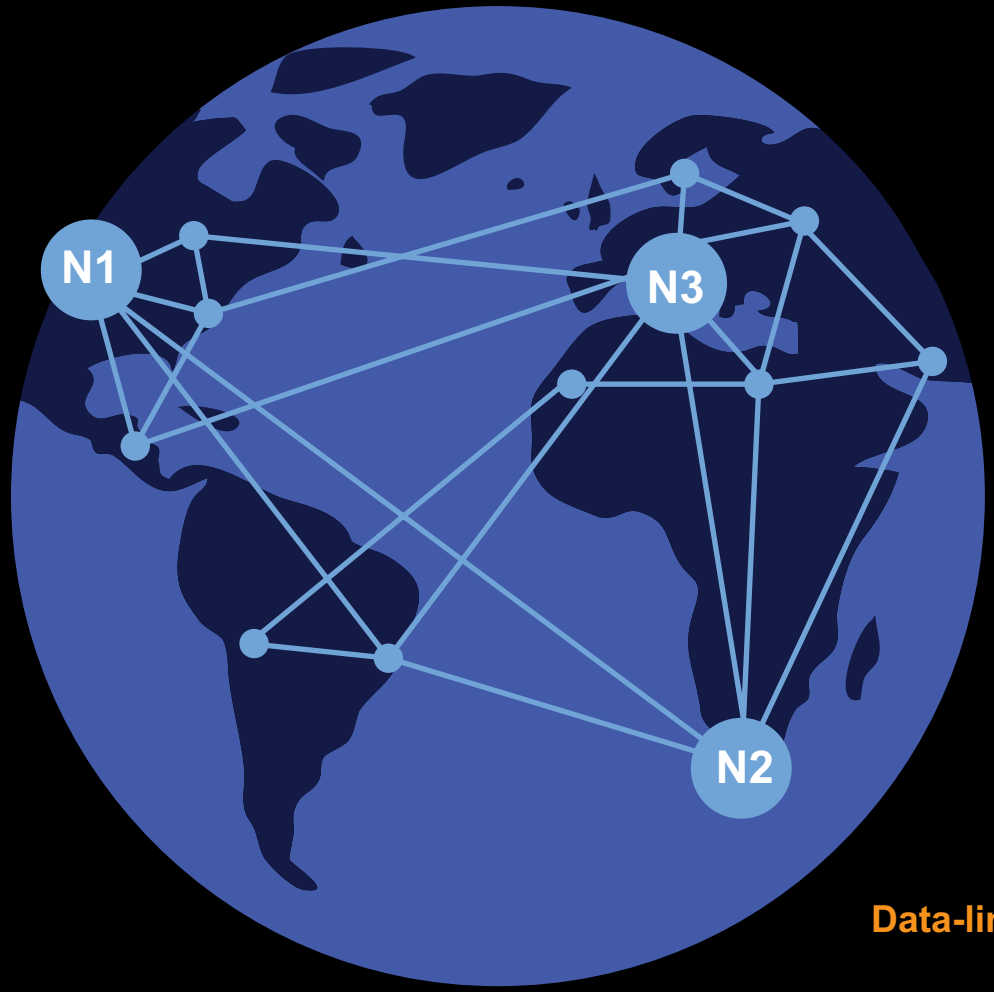
Actual layers of the OSI model

Application *(7)*
Presentation *(6)*
Session *(5)*
Transport *(4)*
Network *(3)*
Data-Link *(2)*
Physical *(1)*


Application
Presentation
Session
Not relevant today
Move stuff between applications… "apartment number"
Transport
Network
Move stuff between groups…"zip code"
Negotiate for access and move data at small scale
Data-Link
Physical
RF, Too
Lasers

TCP/IP

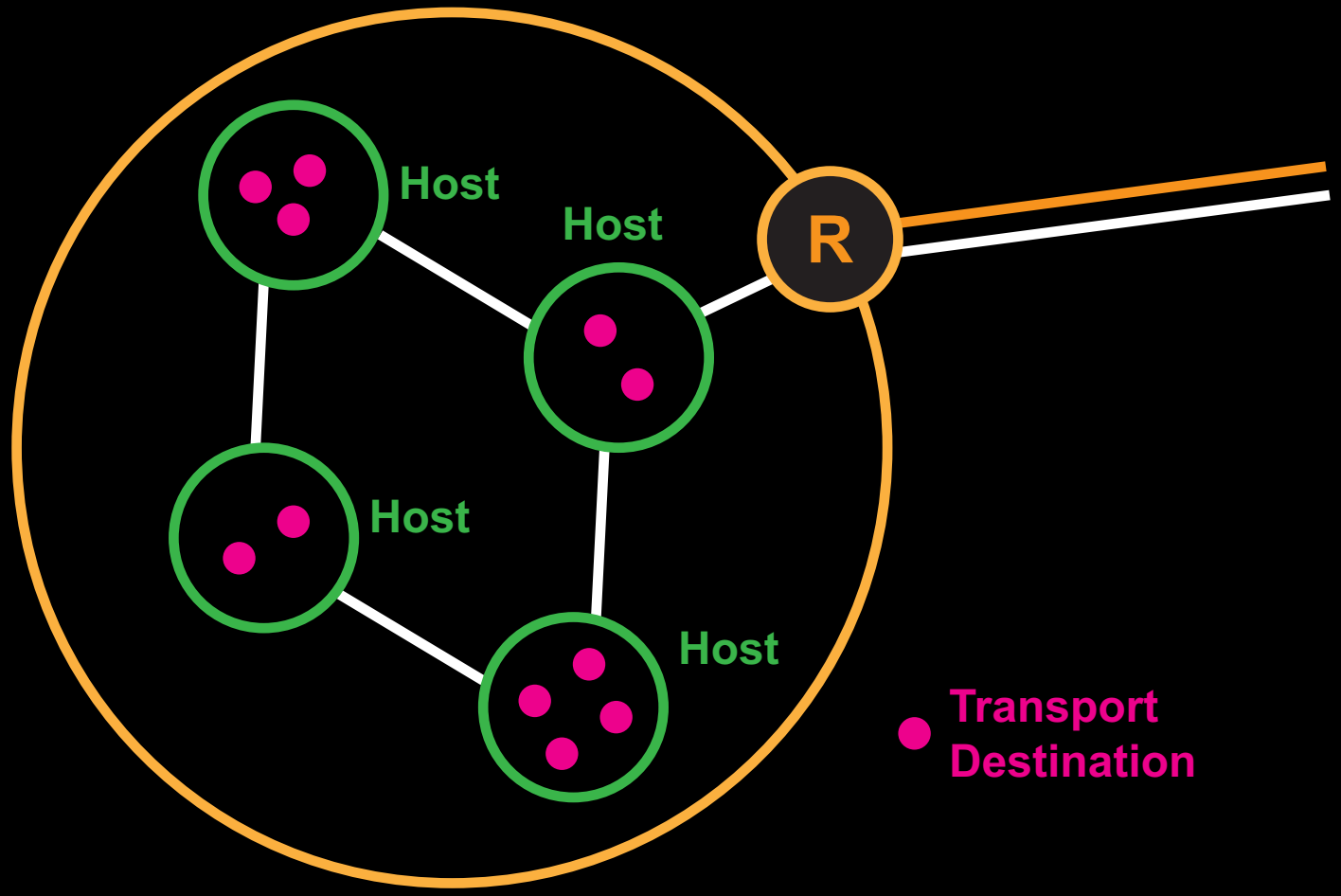
Transport Layer Network Layer



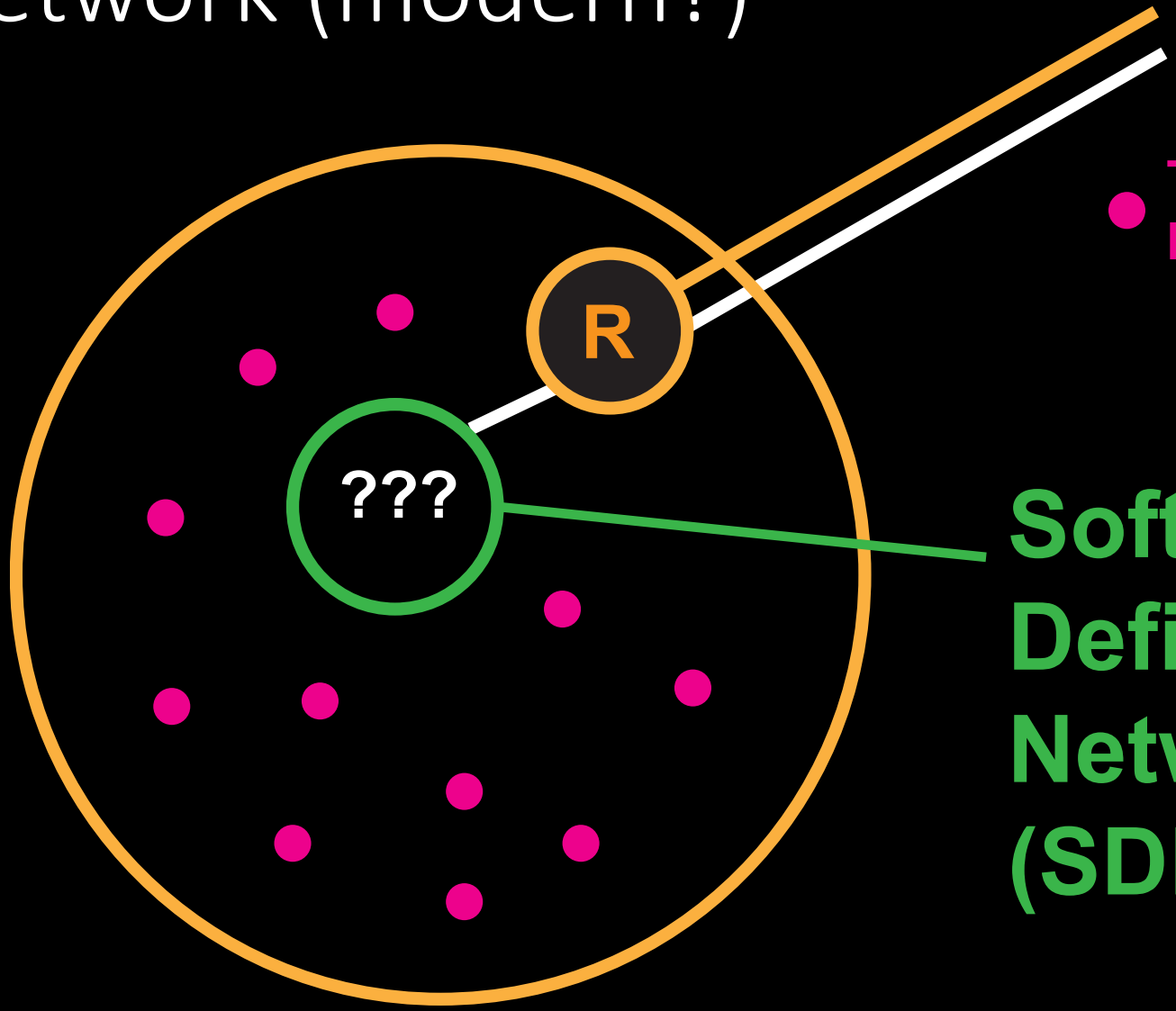
Data-link **ETHERNET**

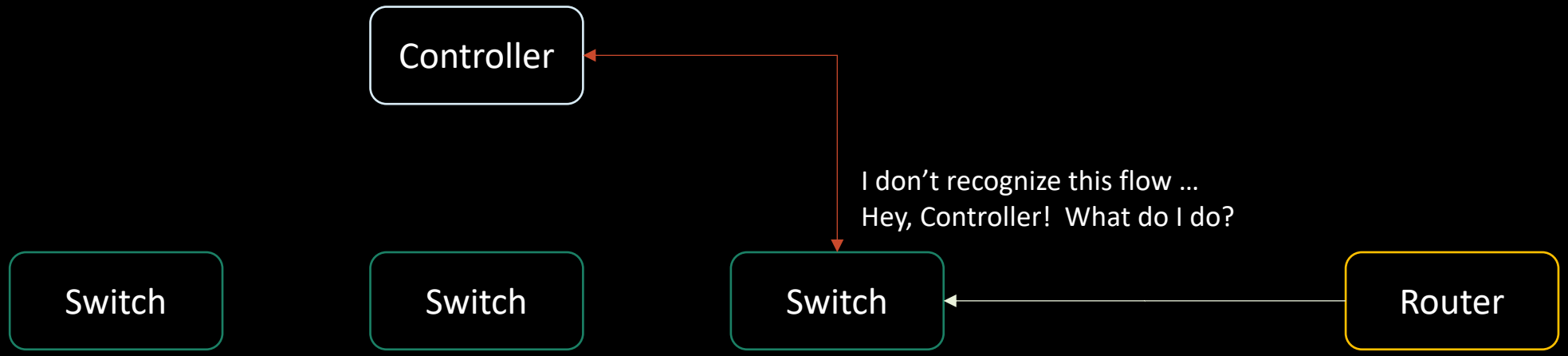
IT WORKS!

Classical network



Trendy network (modern?)




Controller
I don’t recognize this flow …
Hey, Controller! What do I do?
Switch
Switch
Switch
Router

Okay everyone, here's how we get to cat pictures …

Controller

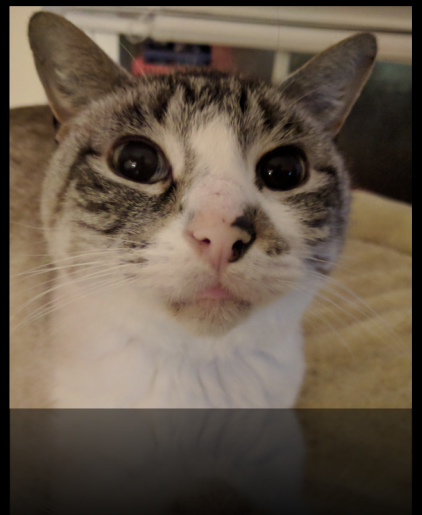
Switch

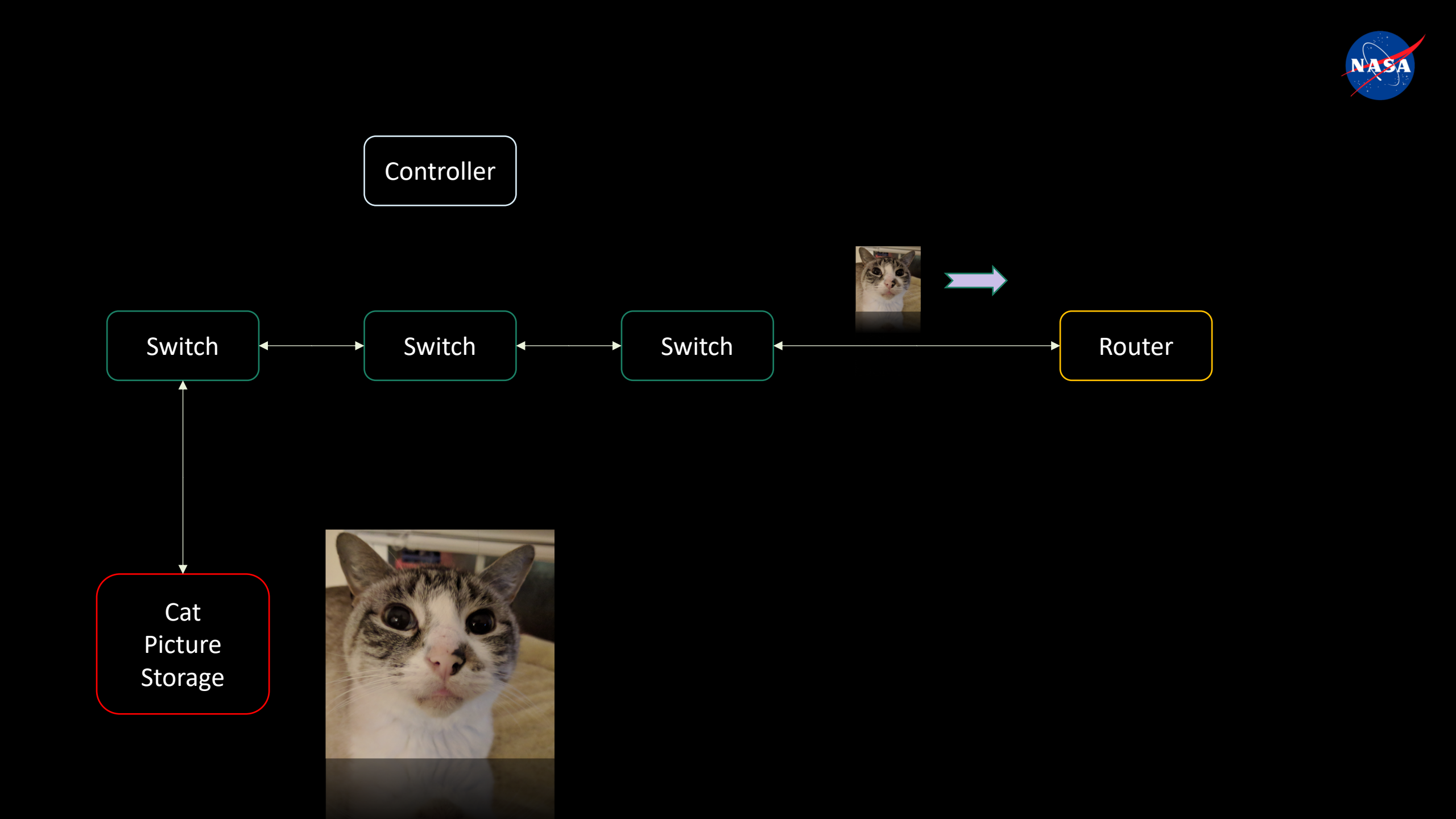
Switch

Switch

Router

Cat Picture Storage




Controller
Switch
Switch
Switch
Router
Cat
Picture
Storage

Delay and Disruption

- How do we adapt approaches to networking to deal with delay / disruption?
  - As it turns out, “it depends”
    - Is our network targeting host-centric or service-centric use-cases?
    - How do we actually want to transfer data through our network?
    - How much delay and disruption do we *actually* have?
- True story: entire branch of networking research
  - Keyword (again): Delay / Disruption Tolerant Networking (DTN)
- Relevant reading: RFC 4838
  - Initial stab at architecture for these kinds of networks
- Also: experimental protocol suite being standardized
  - Currently undergoing significant revision, but it’ll get there!
  - With that said, let’s talk about this protocol suite for a moment …

Bundles and Space

- Core of DTN approach is called the bundle protocol (BP)
  - Working on testing and research efforts across many NASA centers
    - GRC: talking from the ground, through a relay satellite (TDRS), to the space station
      - GRC has a box there called the SCaN Testbed
        - It is an experiment entirely devoted to communication research
- BP actually has provisions to deal with both delay and disruption …
  - Disruption is handled through buffering, scheduling, and pathing / routing
  - Delay is handled through protocol design
    - Pluggable protocols called “convergence layers”
    - Pick the right protocol for the job, depending on what the link looks like
  - Additional provisions to allow for reports of successful transmission, etc.
    - “Madam, could you please sign for that bundle?”

The Bundle Protocol: Delay

- BP runs on top of something else
  - The something else is a “convergence layer”
- Convergence layers are chosen based on the link
  - For a link with small delay, closed-loop style protocols can be used
    - Closed-loop: one can expect to get feedback and use that to guide future decisions
    - A lot of back-and-forth chatter can happen to get things set up and keep things moving
      - Acknowledge data has been received, negotiate capabilities, stuff like that
  - For a link with a huge delay, open-loop style protocols should be used
    - Open-loop: one has no idea if the data actually made it or not
    - Rationale: back-and-forth chatter could take *days*, so stuff happens in bulk
      - Many protocols (e.g. TCP) can’t handle a round trip time (RTT) of more than a few minutes
        - Result: there is a hard limit to the effective range at which TCP can operate

Closed-Loop Protocol (e.g. TCP)

Hey, I'm going to send you something

'kay.

I sent you something

I sent you another thing

Got 'em.

I sent you a better thing

Got it.

Okay, I'm bored. Bye.

Later.

Open-Loop Protocol (e.g. LTP)

Friday, December 4th, 2026
3:27 PM

I sent you something

I sent you another thing

I sent you a better thing

Monday, December 7th, 2026
11:46 AM

I got things A, B, and C

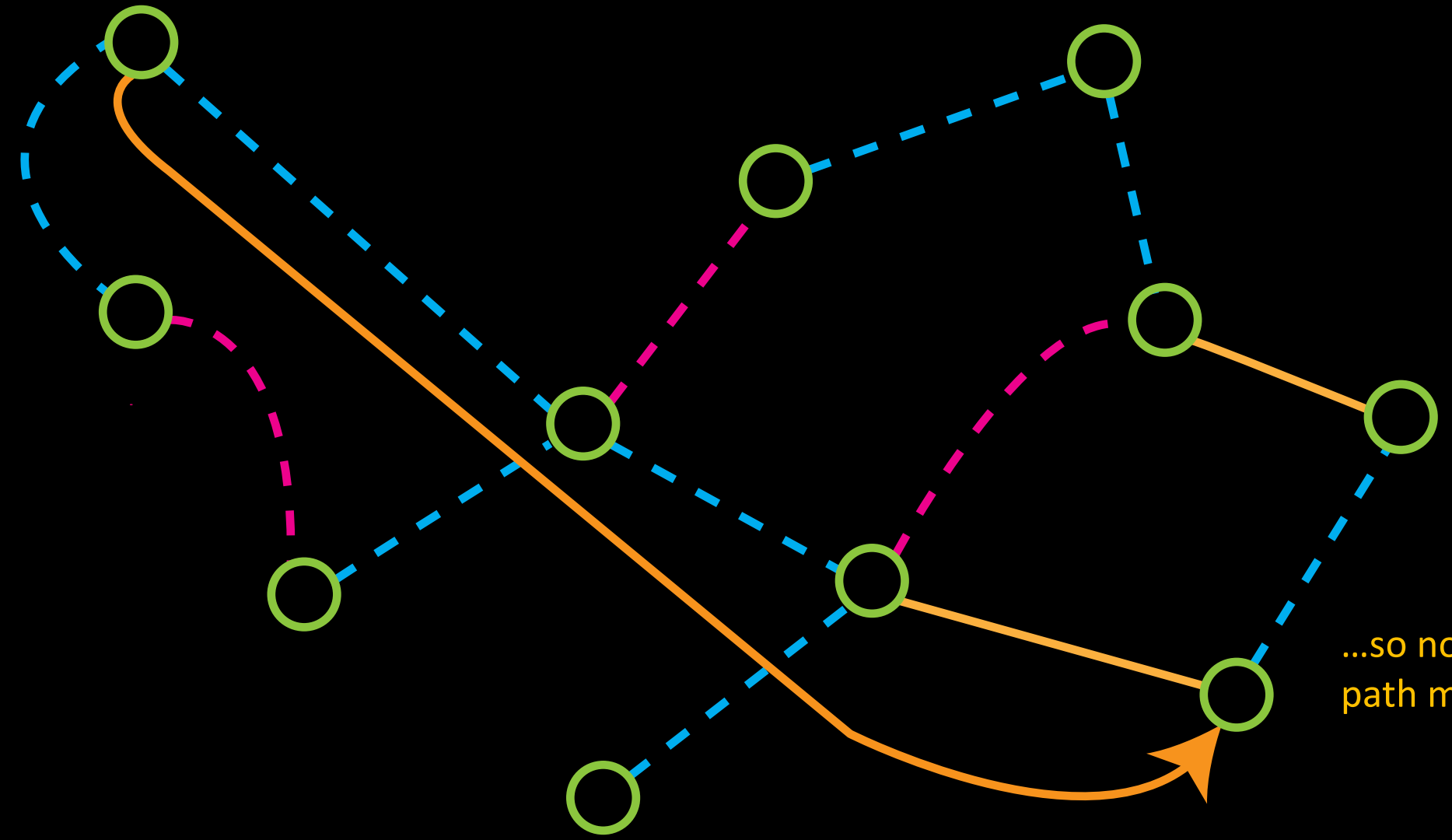
Thursday, December 10th, 2026
7:39 AM

Whatever. I left Saturn like *5 days* ago.

The Bundle Protocol: Disruption

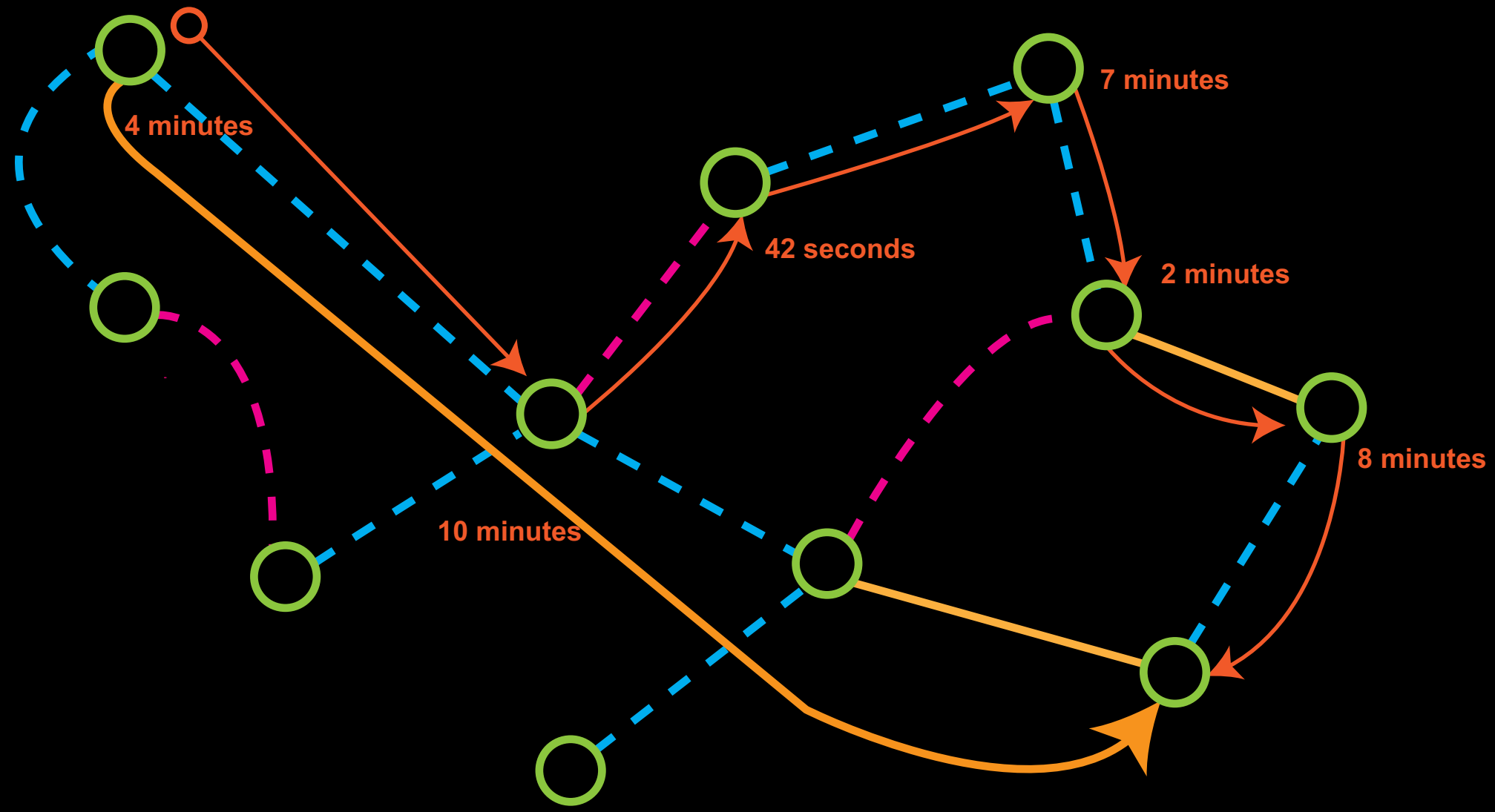
- How does one deal with links that aren't always there?
  - Usual answer: store data until the link becomes available
    - If the data is time-sensitive, then it might be dropped
  - Once the link is up, send out the most important stuff first …
    - … though figuring out what's most important is actually kind of hard
    - People and applications have a tendency to inflate their own importance
- Saving grace: link availability is *generally* predictable
  - Know where assets *should* be and what links *should* be available when
  - Contact Graph Routing (CGR): build paths based on scheduled availability
    - … sending bundles through various convergence layers at every node they pass through

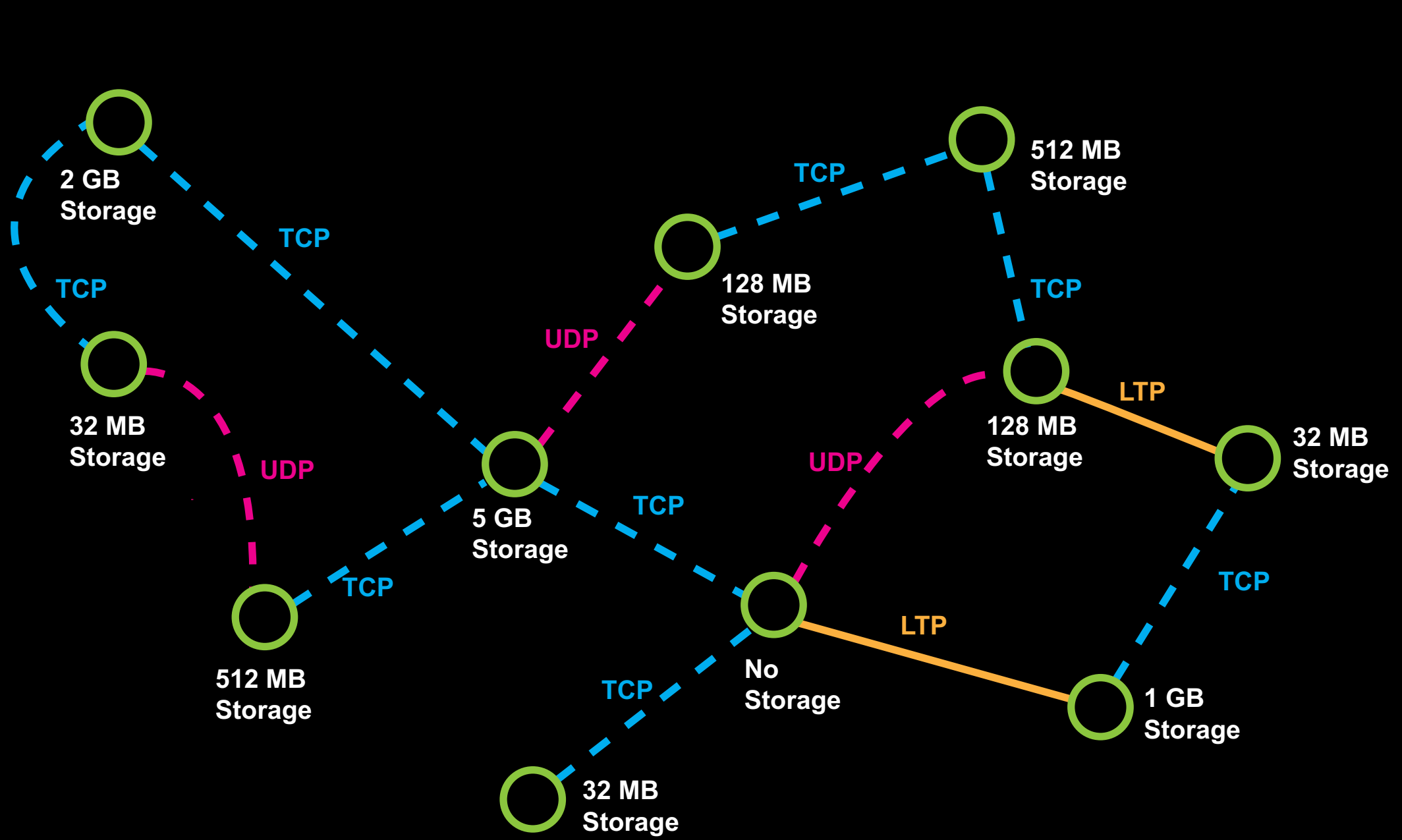
Different links are available at different times…



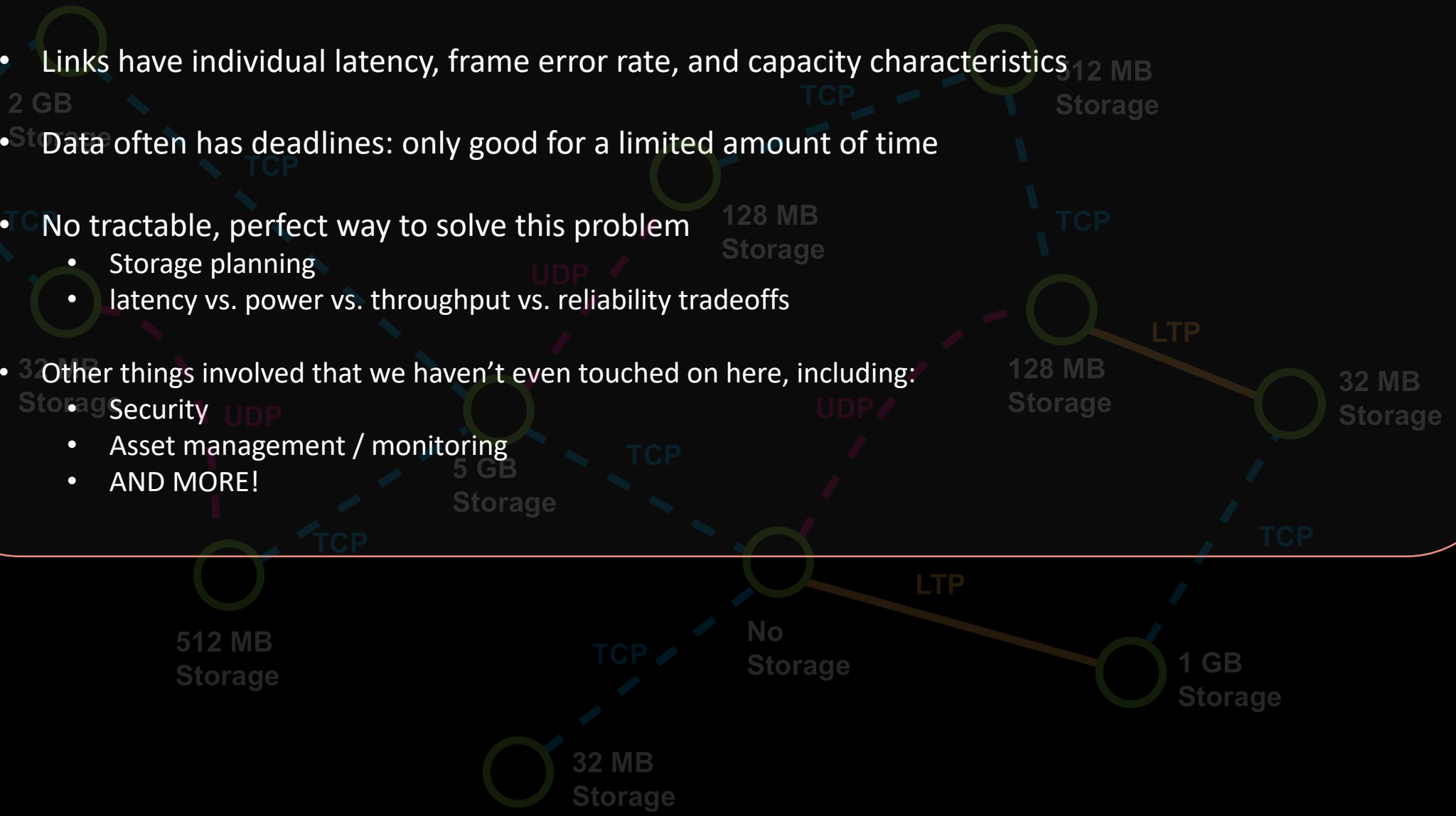
…so no end-to-end path may exist

With this in mind, we move bundles one hop at a time




2 GB
Storage
TCP
TCP
32 MB
Storage
UDP
512 MB
Storage
TCP
5 GB
Storage
UDP
128 MB
Storage
TCP
512 MB
Storage
TCP
UDP
128 MB
Storage
LTP
32 MB
Storage
TCP
TCP
No
Storage
LTP
1 GB
Storage
TCP
32 MB
Storage

- Links have individual latency, frame error rate, and capacity characteristics
- Data often has deadlines: only good for a limited amount of time
- No tractable, perfect way to solve this problem
  - Storage planning
  - latency vs. power vs. throughput vs. reliability tradeoffs
- Other things involved that we haven't even touched on here, including:
  - Security
  - Asset management / monitoring
  - AND MORE!



Current Research Efforts

- Taking Software-Defined Networking into space!
  - Plan a dynamic path of convergence layers and hops through a space network
- Adding intelligence to networks
  - Guessing what links will look like and trying to automatically tune things
  - Improving the performance of the network as a whole
- Distributed data storage
  - How does one shard and replicate bundle data across nodes?
    - Want to balance accessibility and resource utilization …
- Adding intelligence to links
  - Trying to squeeze more capacity out of radios that we have
  - Trying to find ways to avoid radio interference
- Security
  - Keeping data secure while it's waiting for links and while it's in-flight

Winding down

- And so we have reached the end of our whirlwind tour.
- Thank you for listening, and I do hope you enjoyed the presentation!
  - Questions / comments / concerns / conversation always welcome
- Reminder: NASA is always looking for good people
  - LERCIP
  - Pathways
  - Full-time employment
  - http://www.usajobs.gov