

Virtualizing Time, Space, and Power for Cyber-Physical Cloud Computing

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Raja Sengupta

Universität Salzburg



UC Berkeley



RED Workshop, Salzburg, Austria, April 2011



The JAviator

javiator.cs.uni-salzburg.at

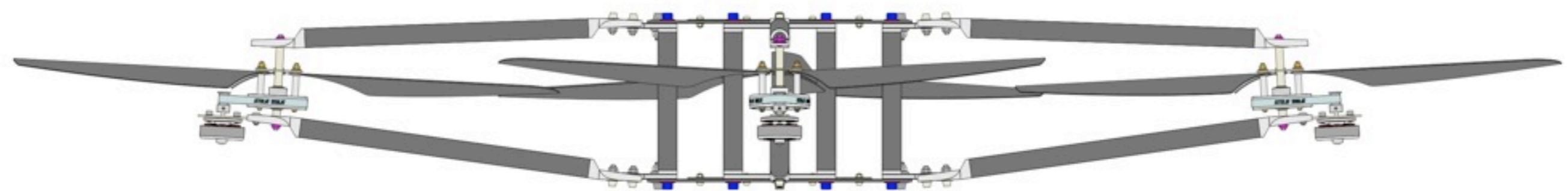
Quad-Rotor Helicopter



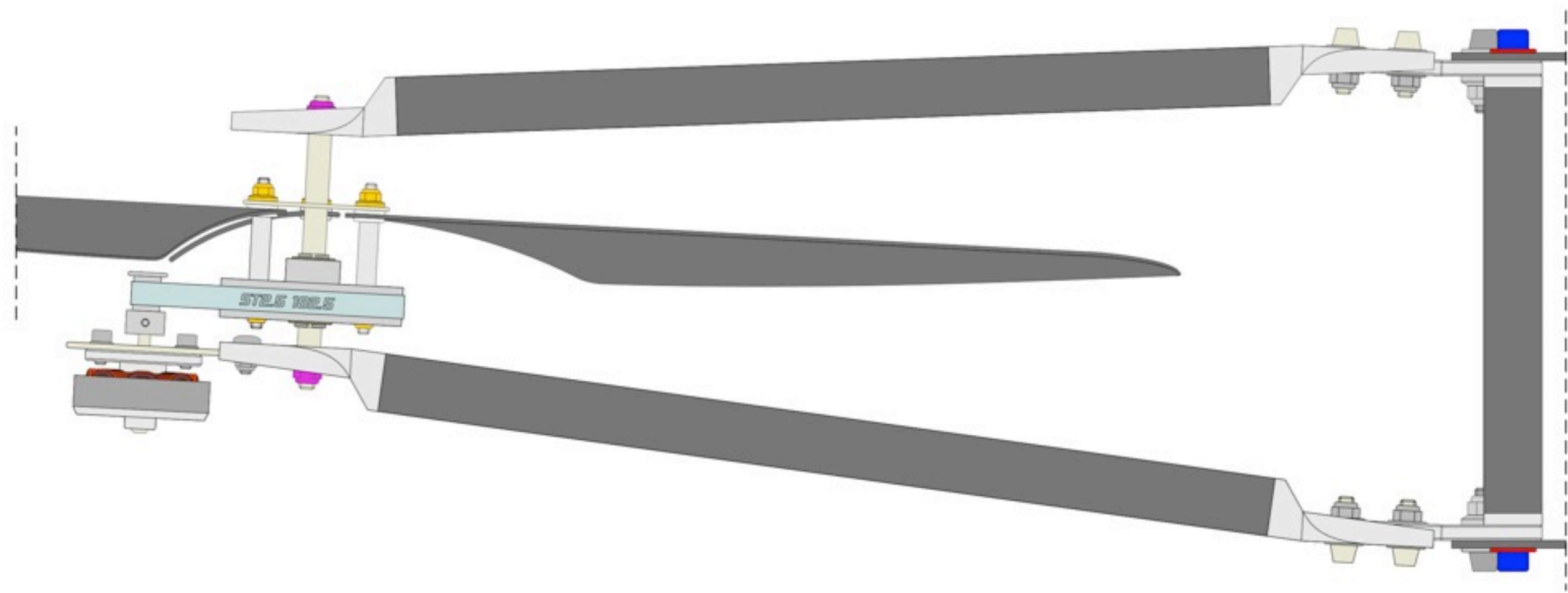
- all carbon, titanium, aluminum design
- custom motors
- 1.3m diameter
- ~2.2kg weight
- +2kg payload
- ~40min (empty)
- ~10min (full)

[AIAA GNC 2008]

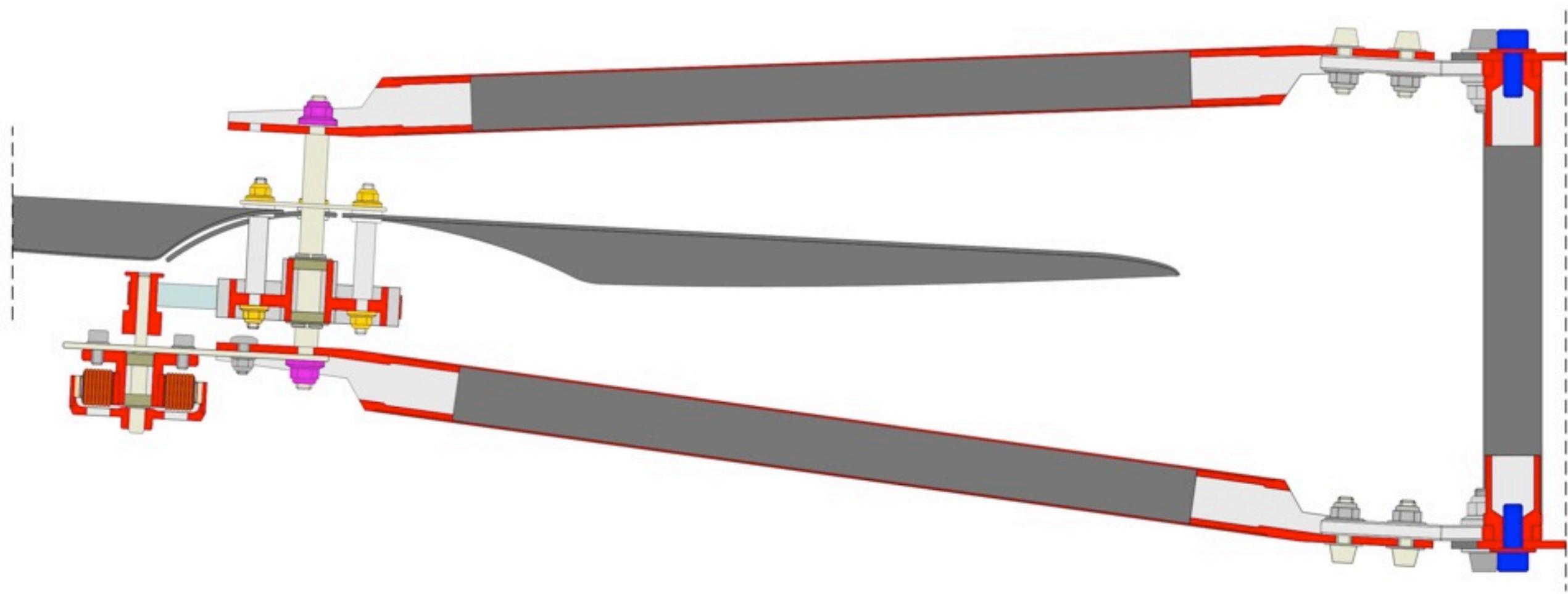
Open Source Blueprints



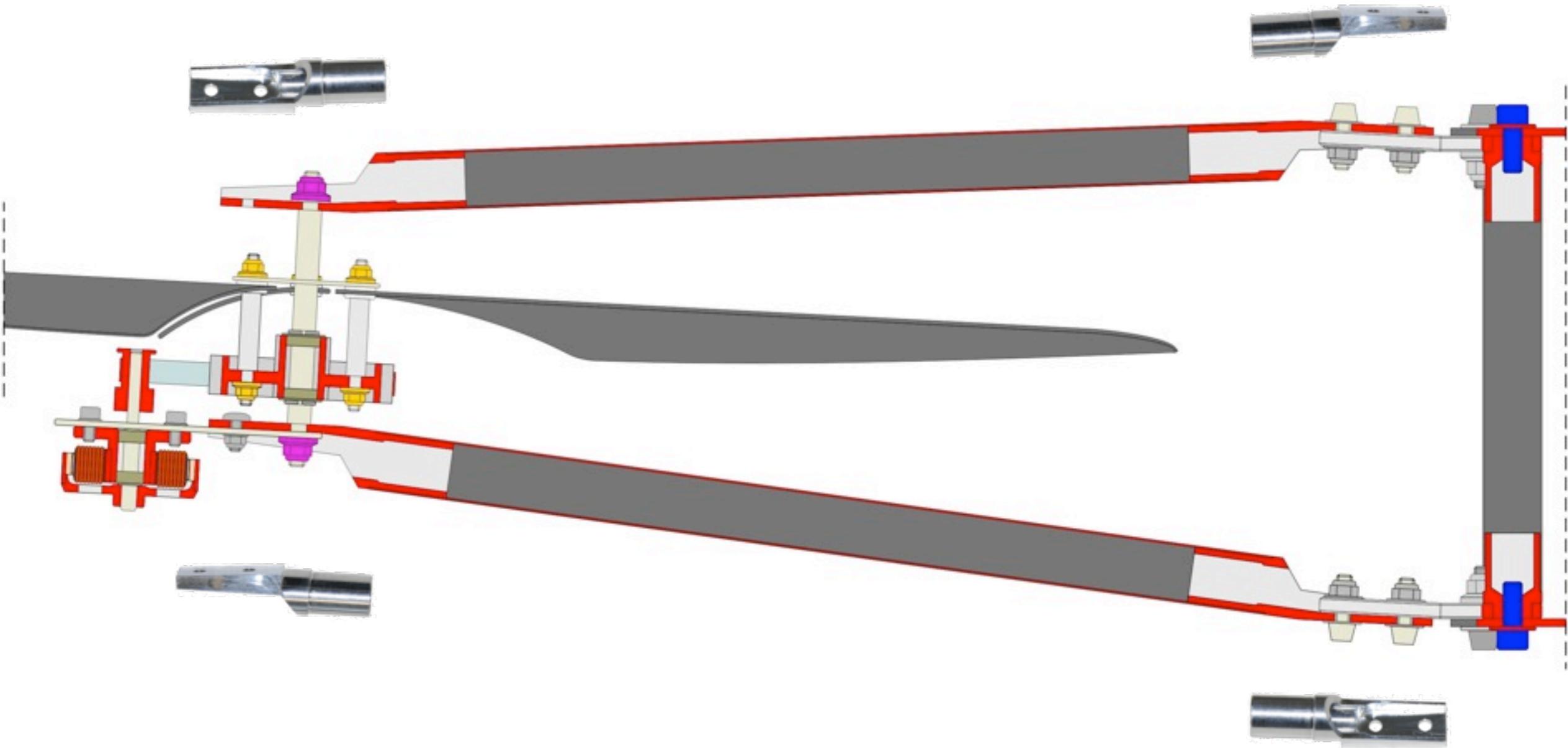
Minimal # of Different Parts



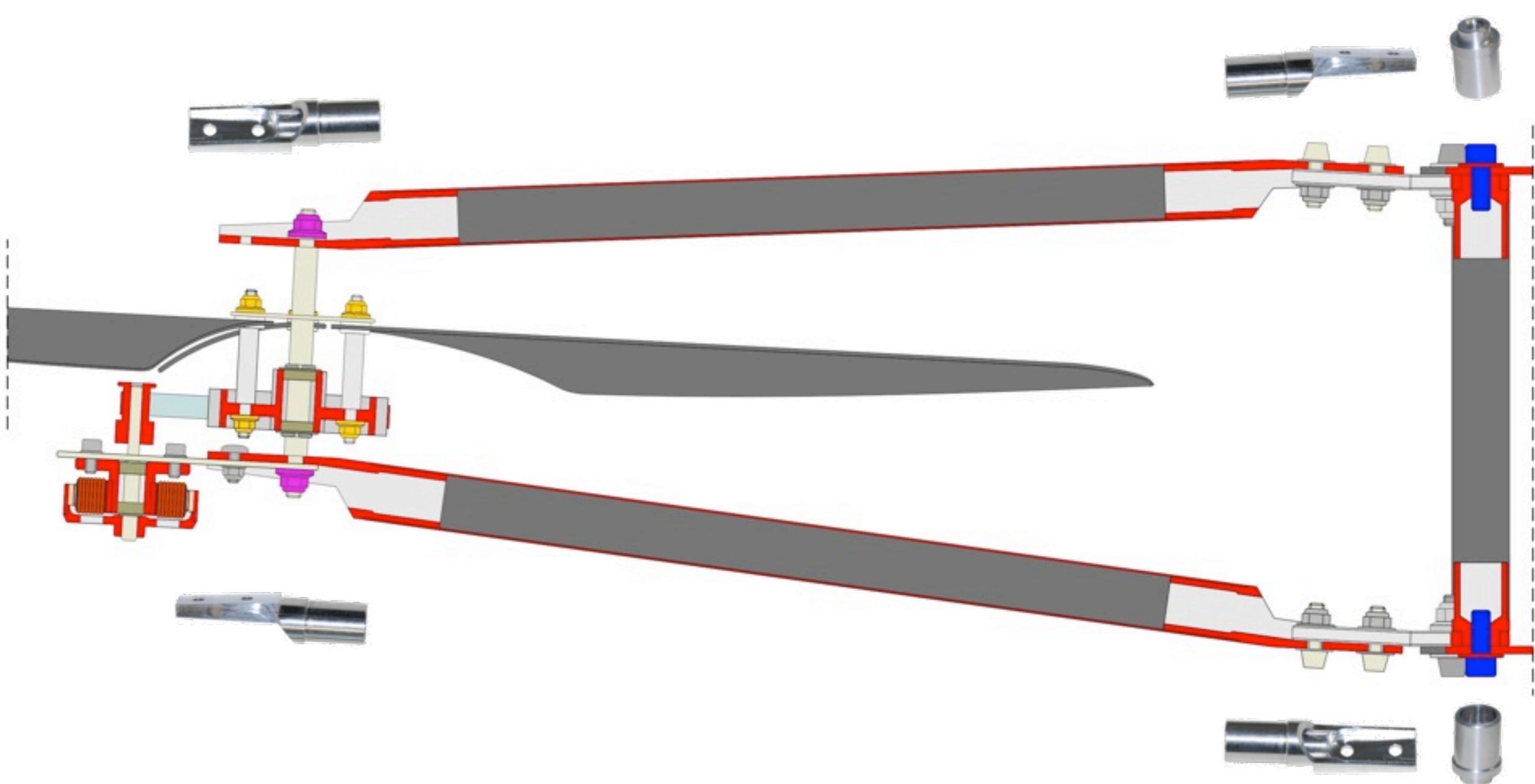
Minimal # of Different Parts



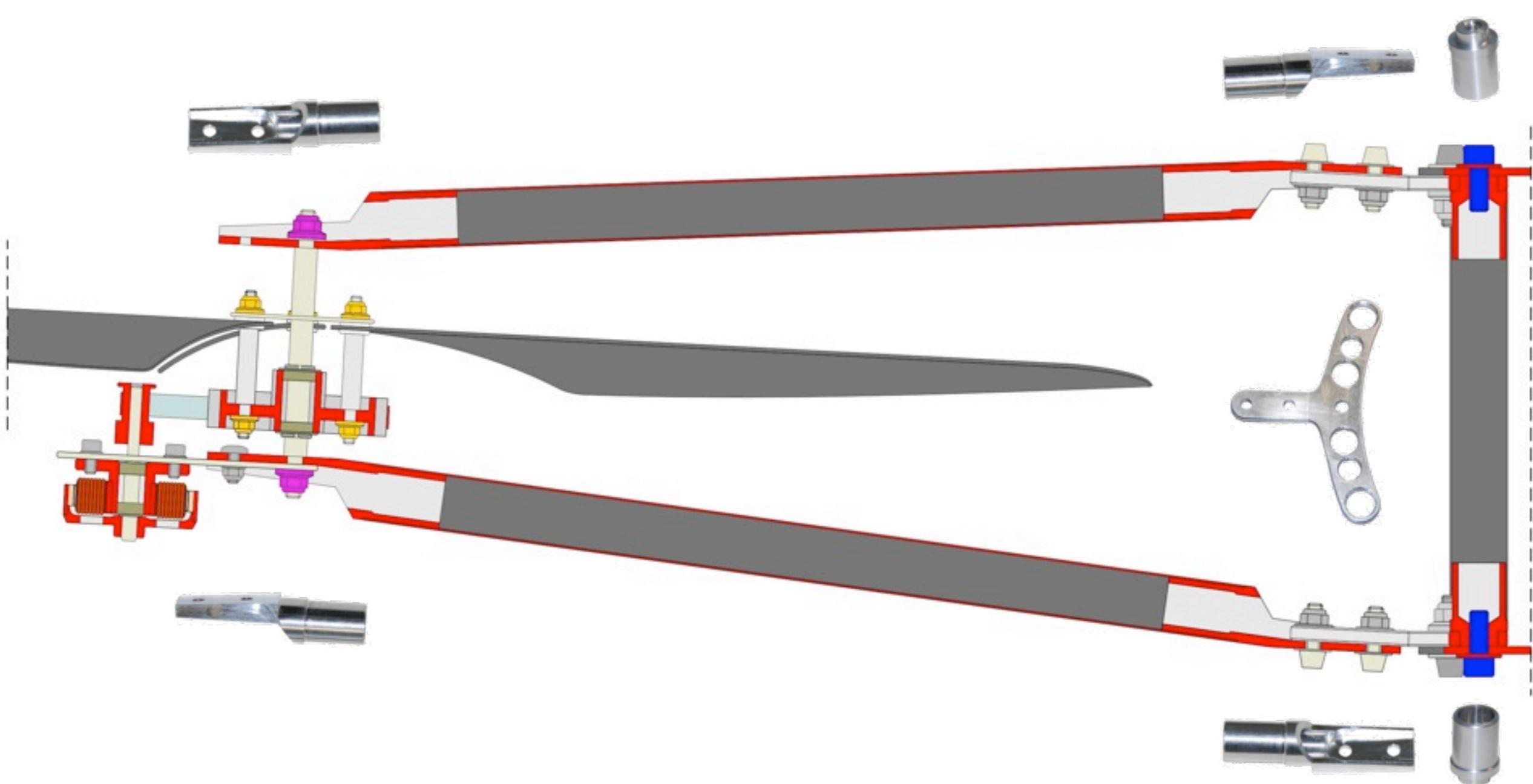
Minimal # of Different Parts



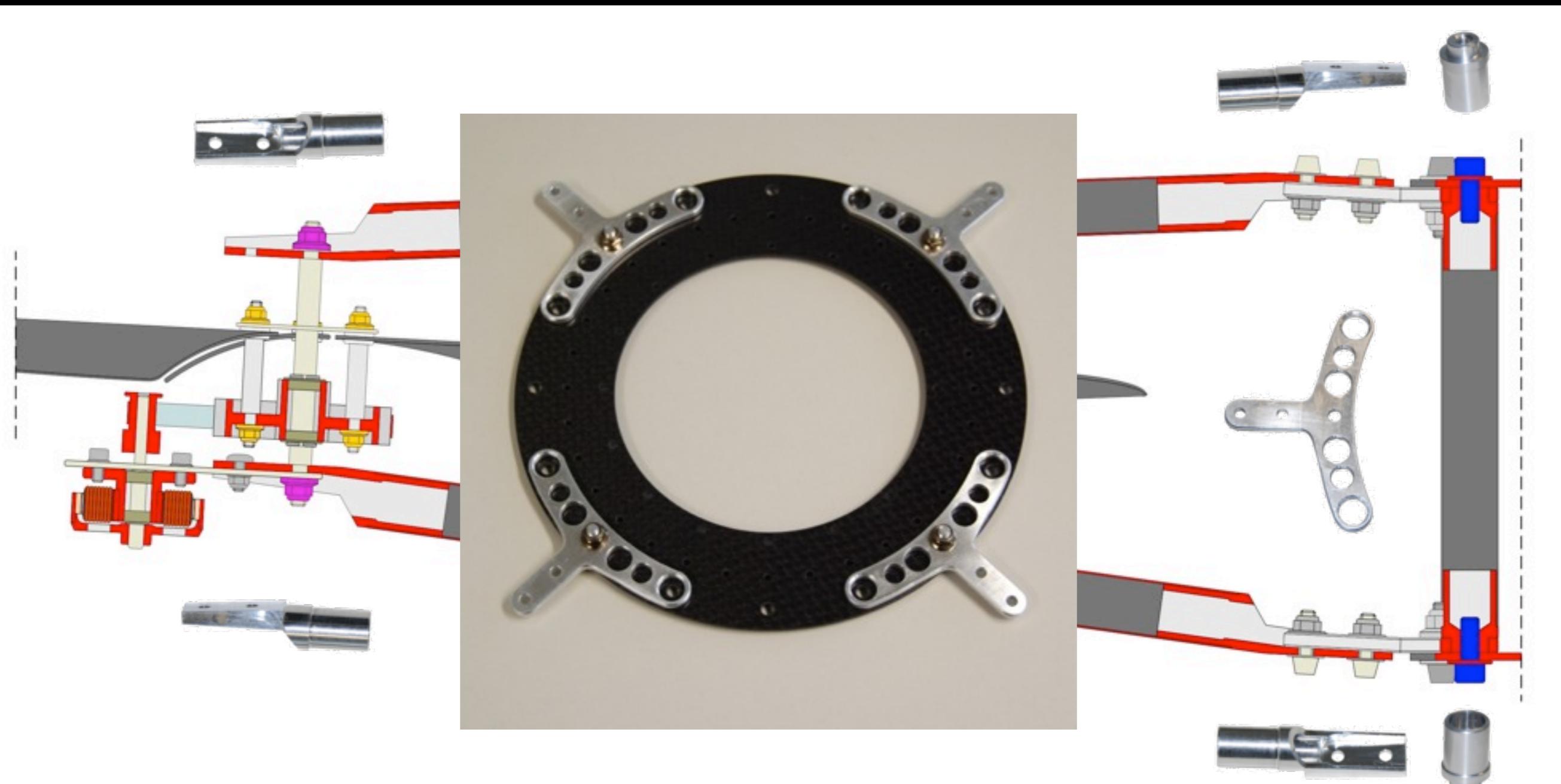
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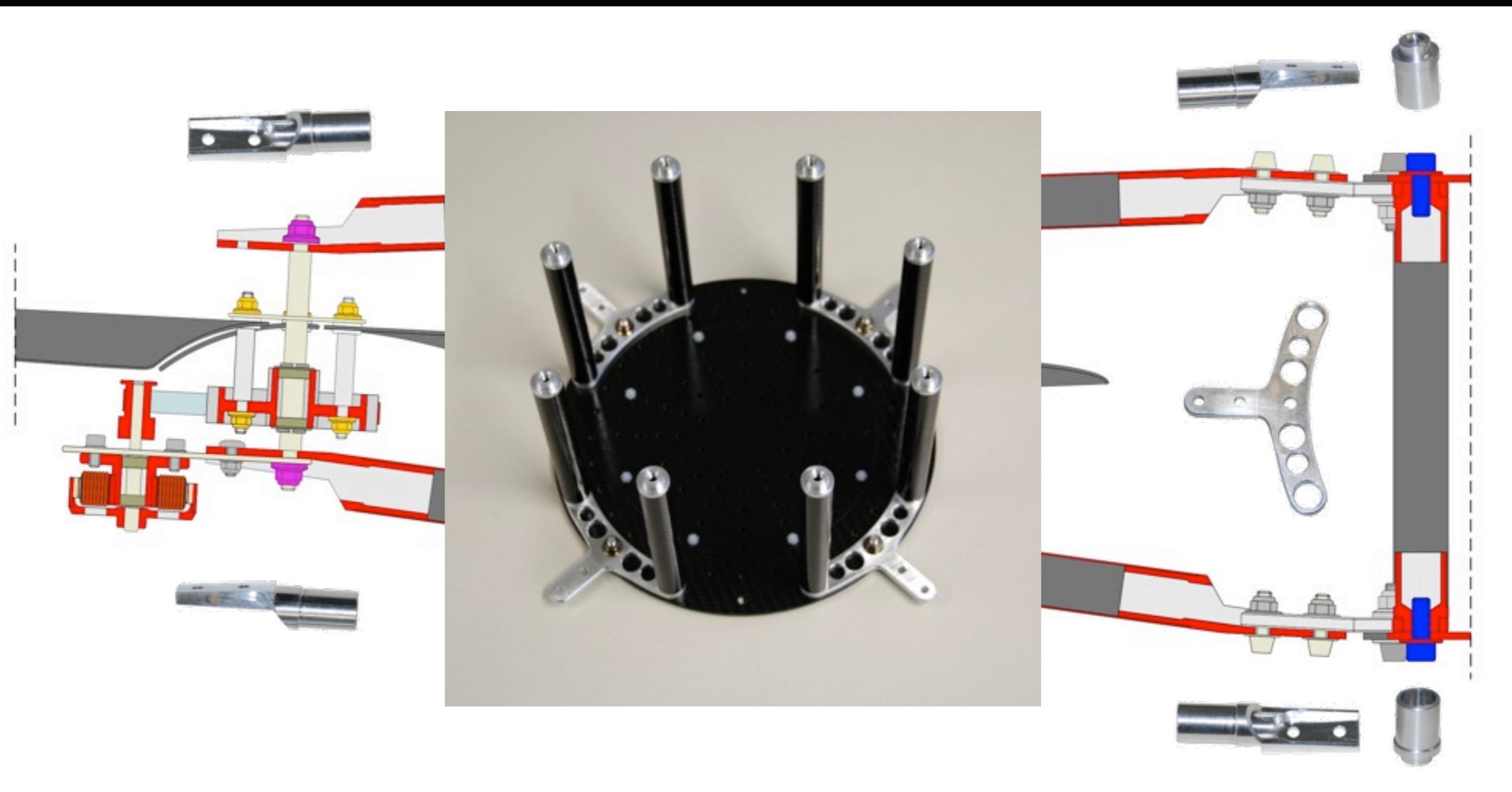
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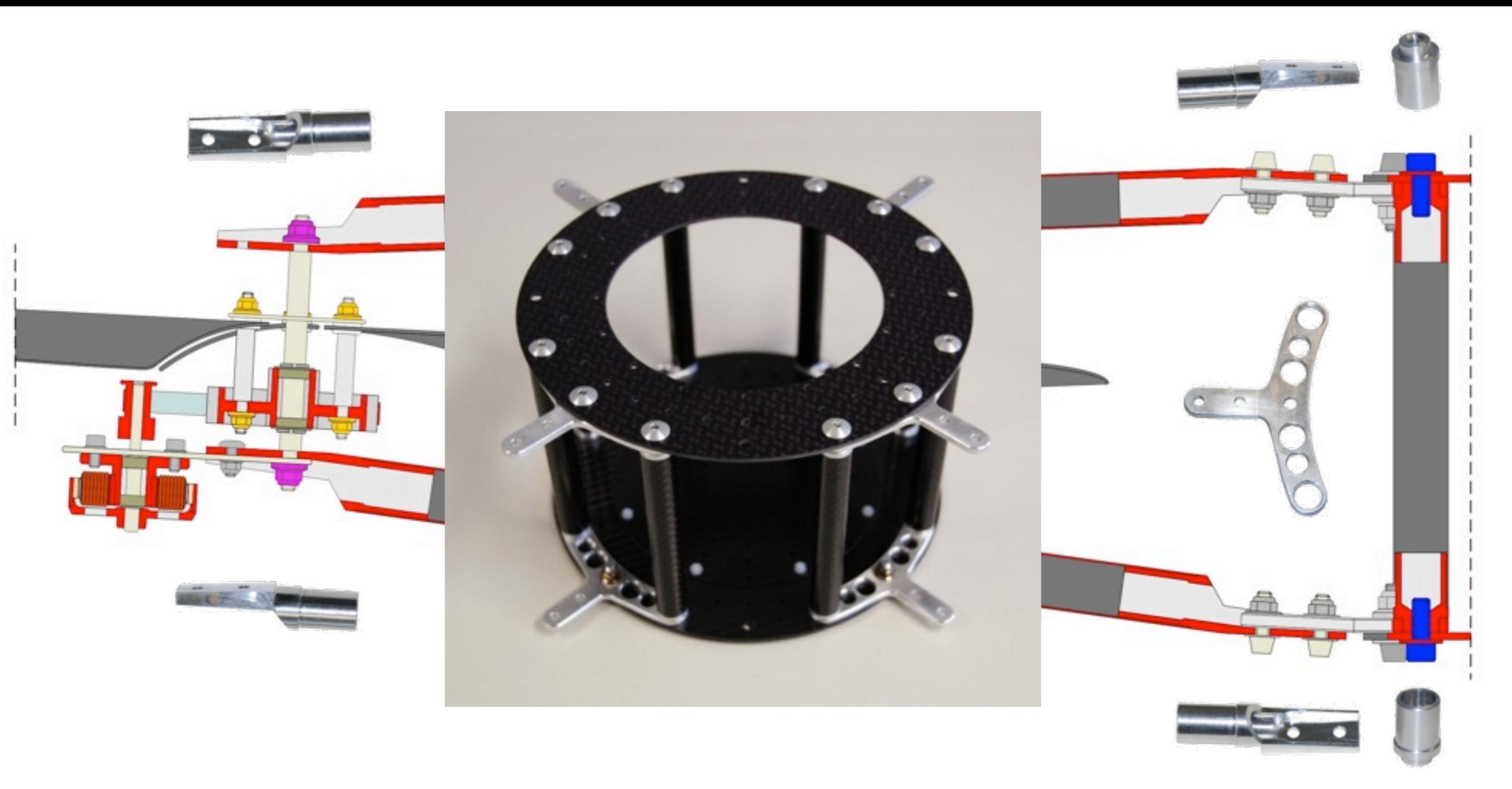
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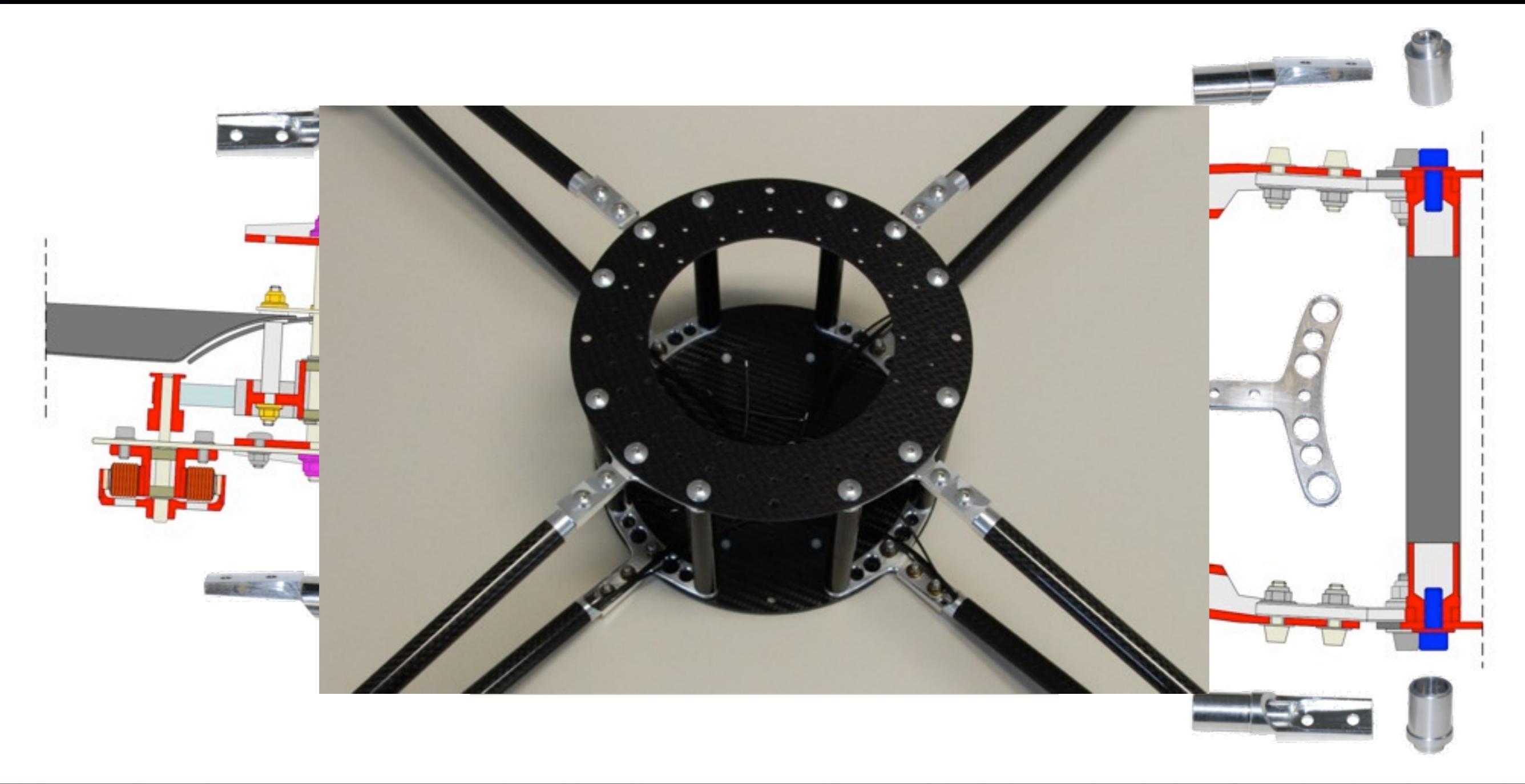
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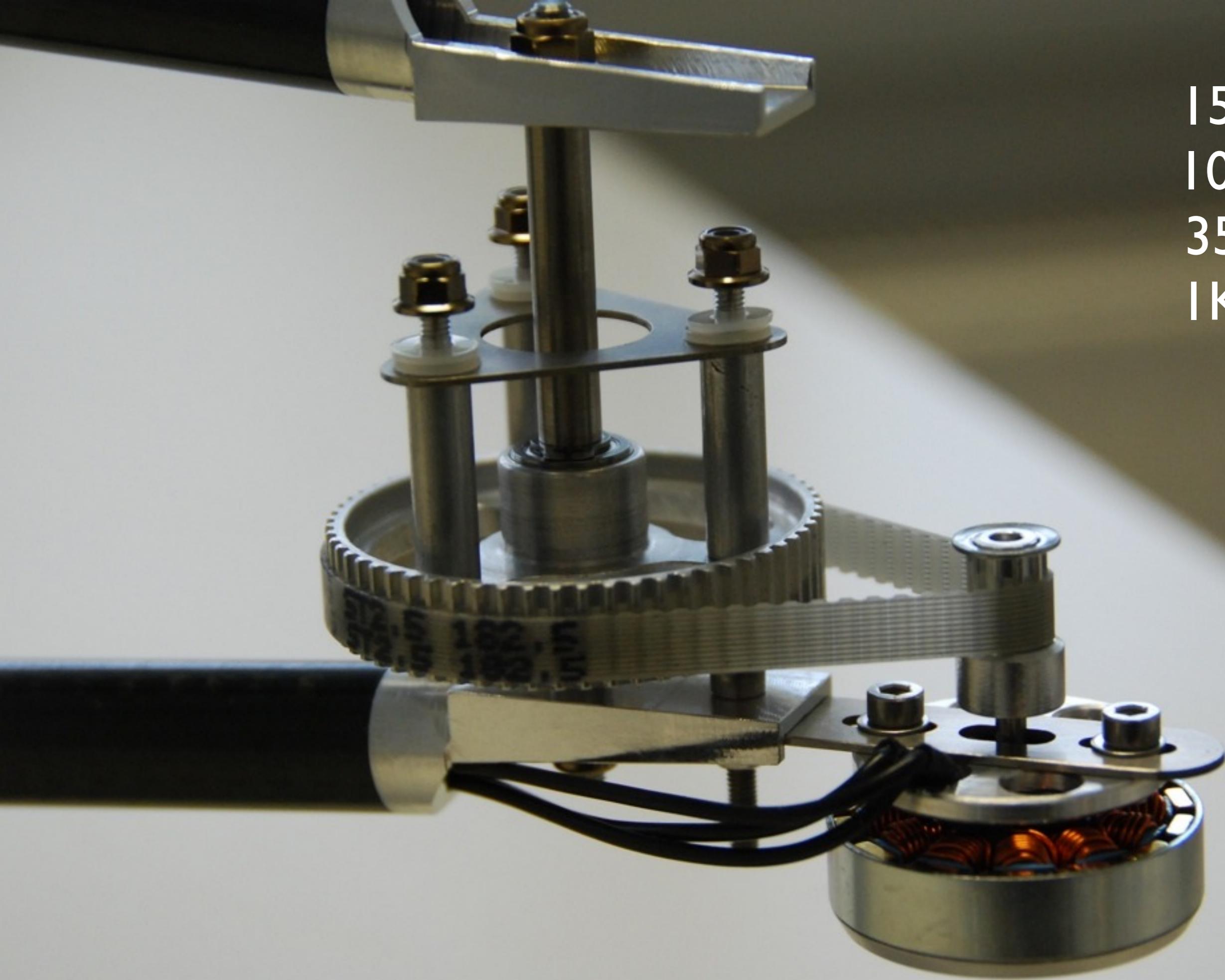
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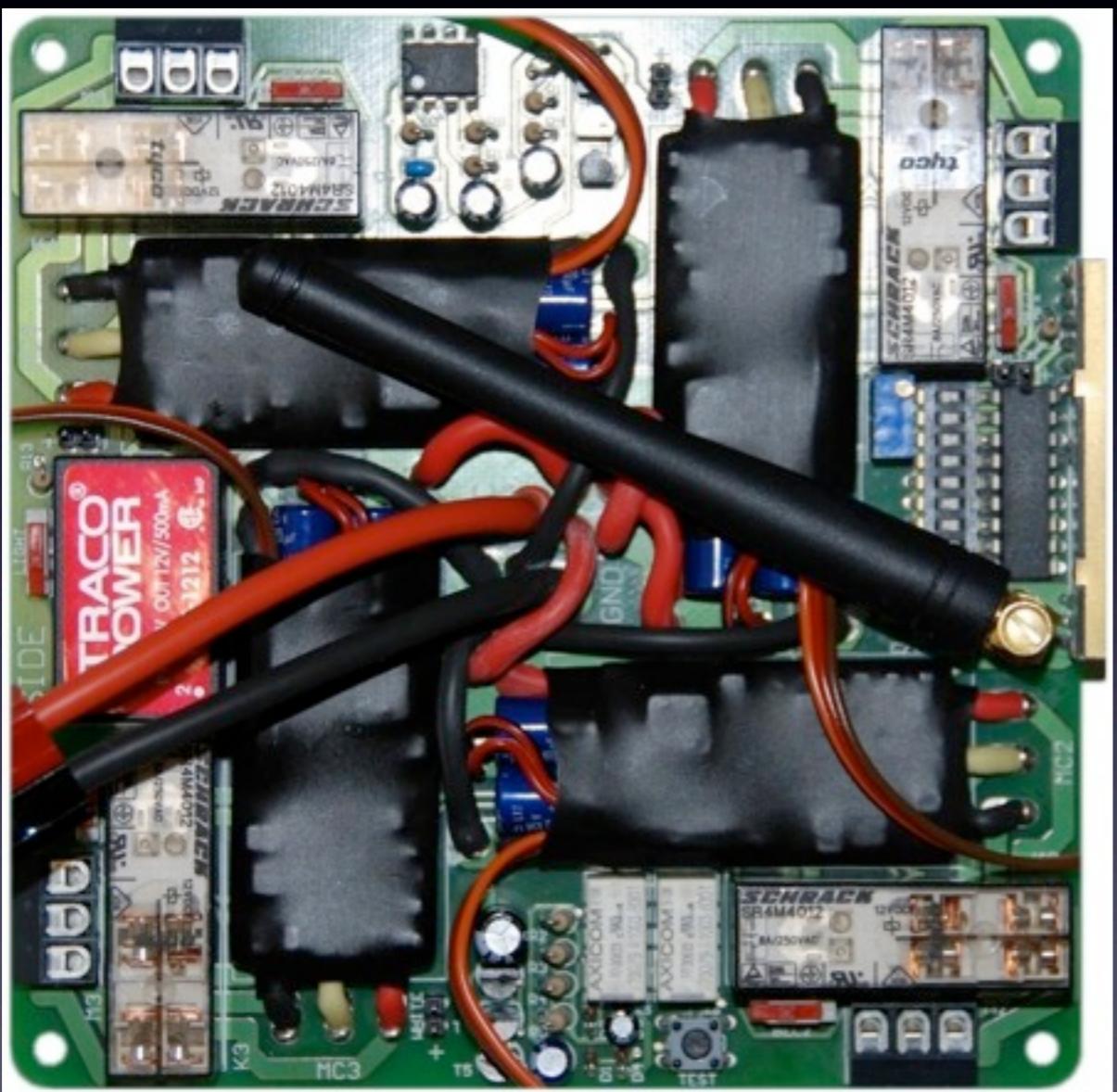


15V
10A
35g
1Kg





Custom Electronics

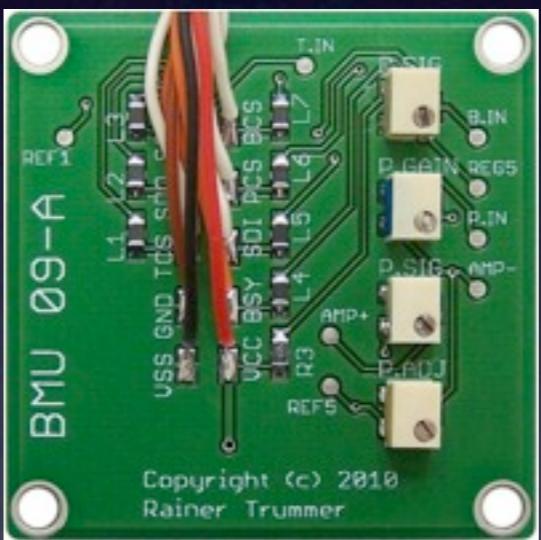
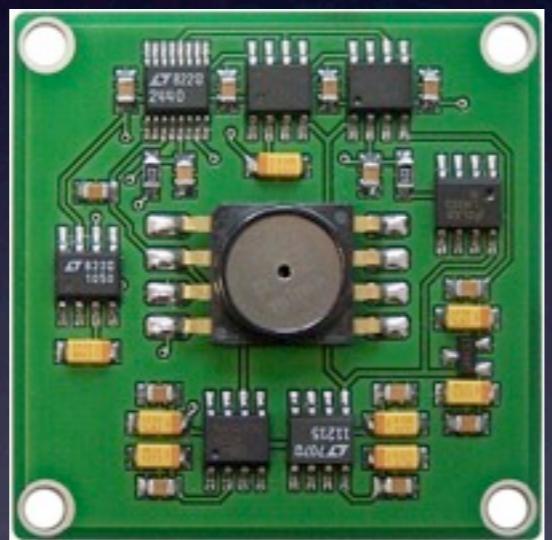


Power



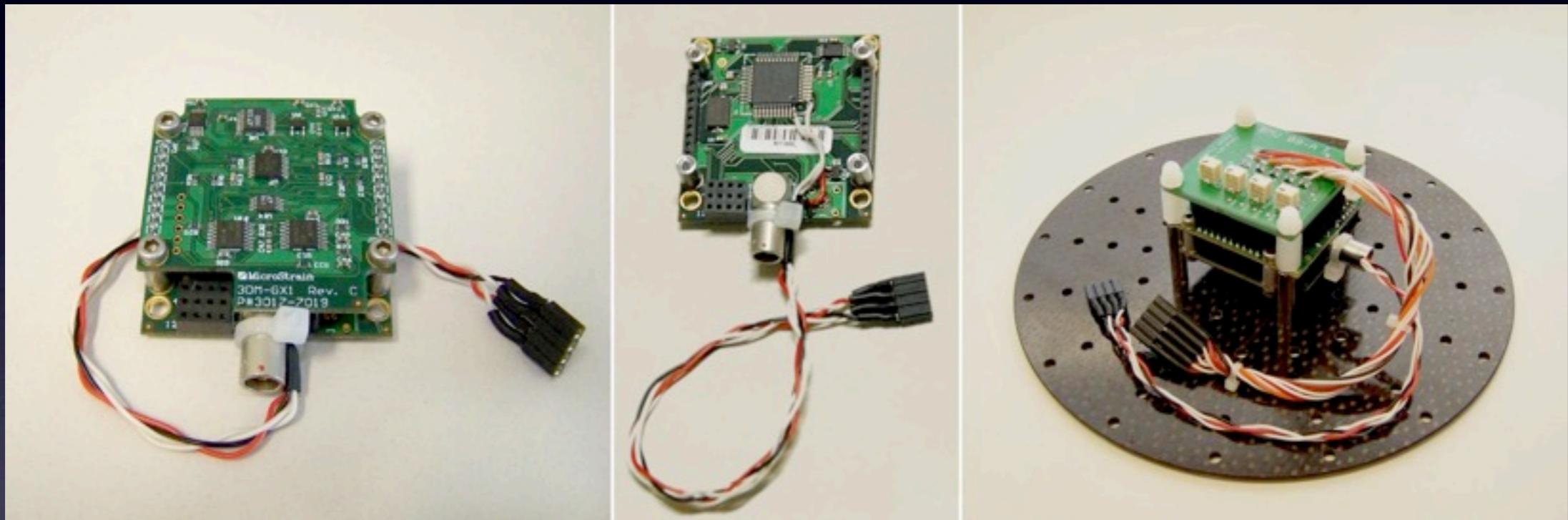
Remote

Custom Electronics



Barometer

Off-the-Shelf Stuff



Gyro

Off-the-Shelf Stuff



Ultrasonic

Off-the-Shelf Stuff

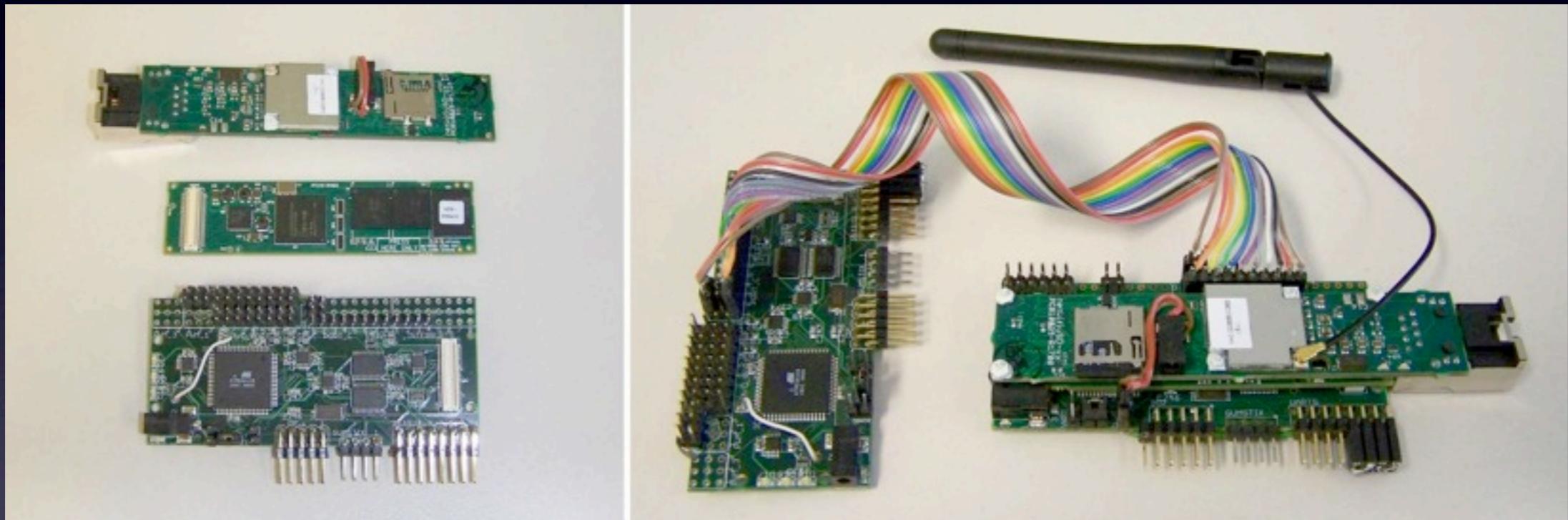


UWB RFID

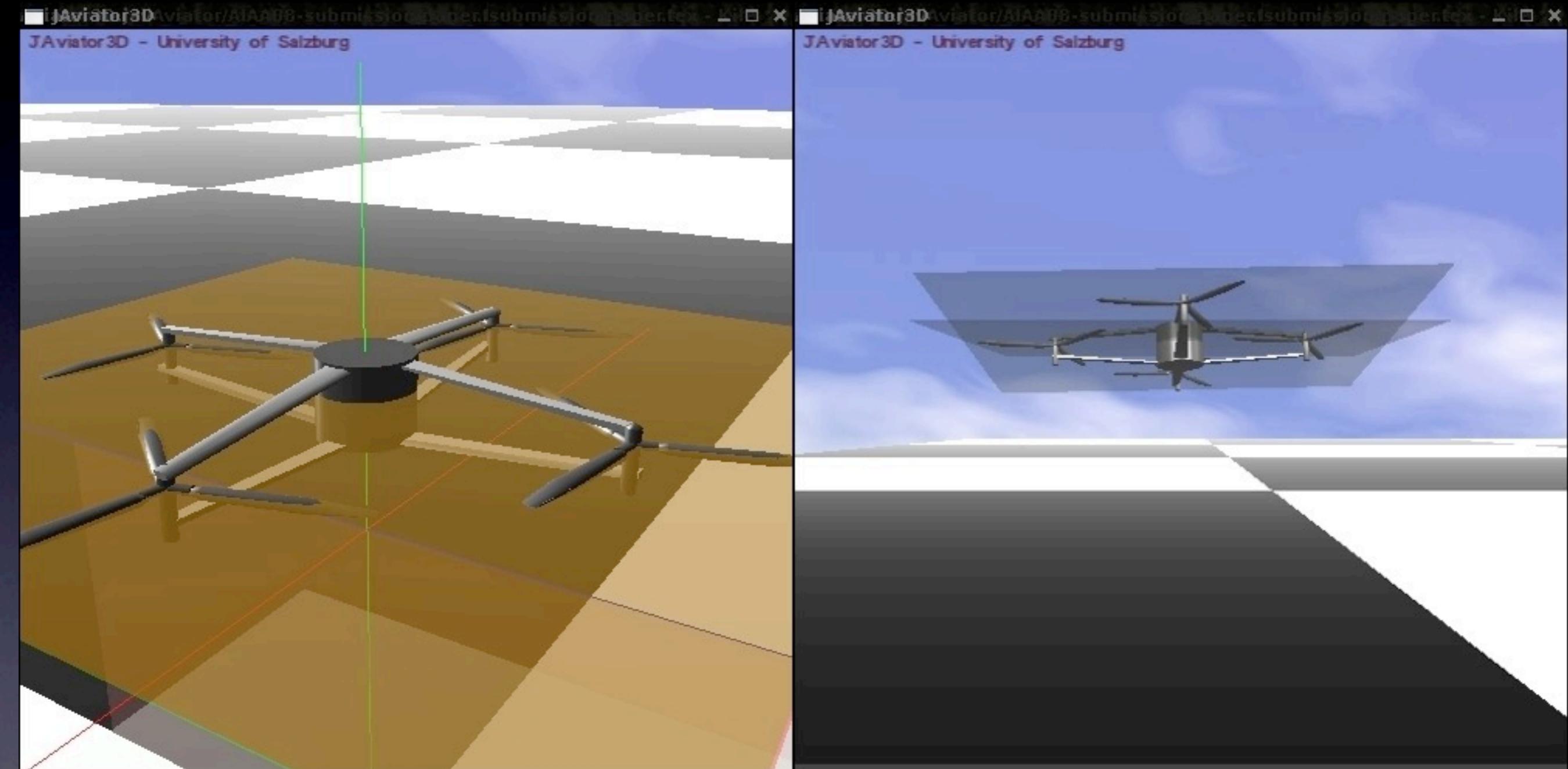


Laser

Off-the-Shelf Stuff

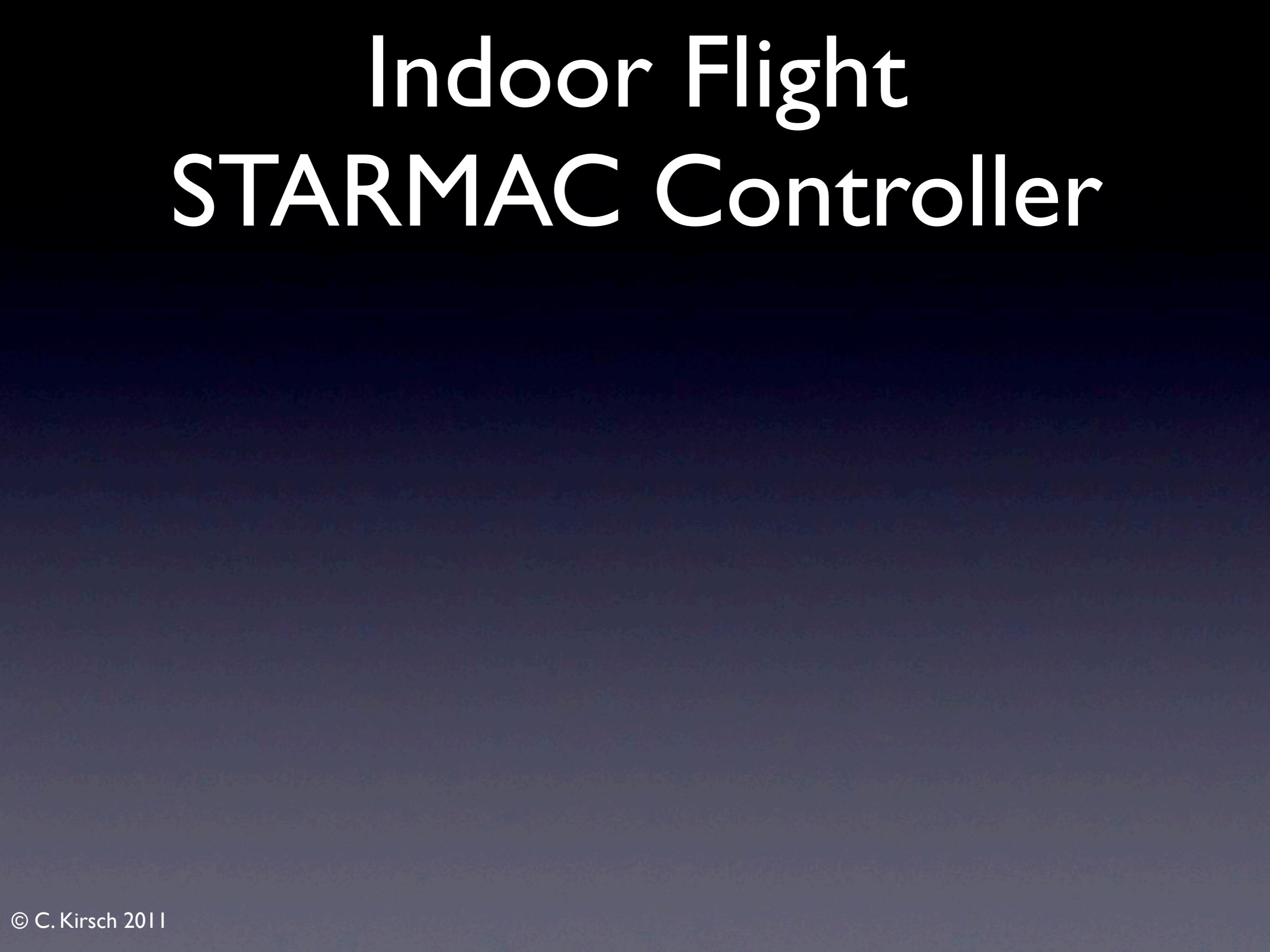


Gumstix

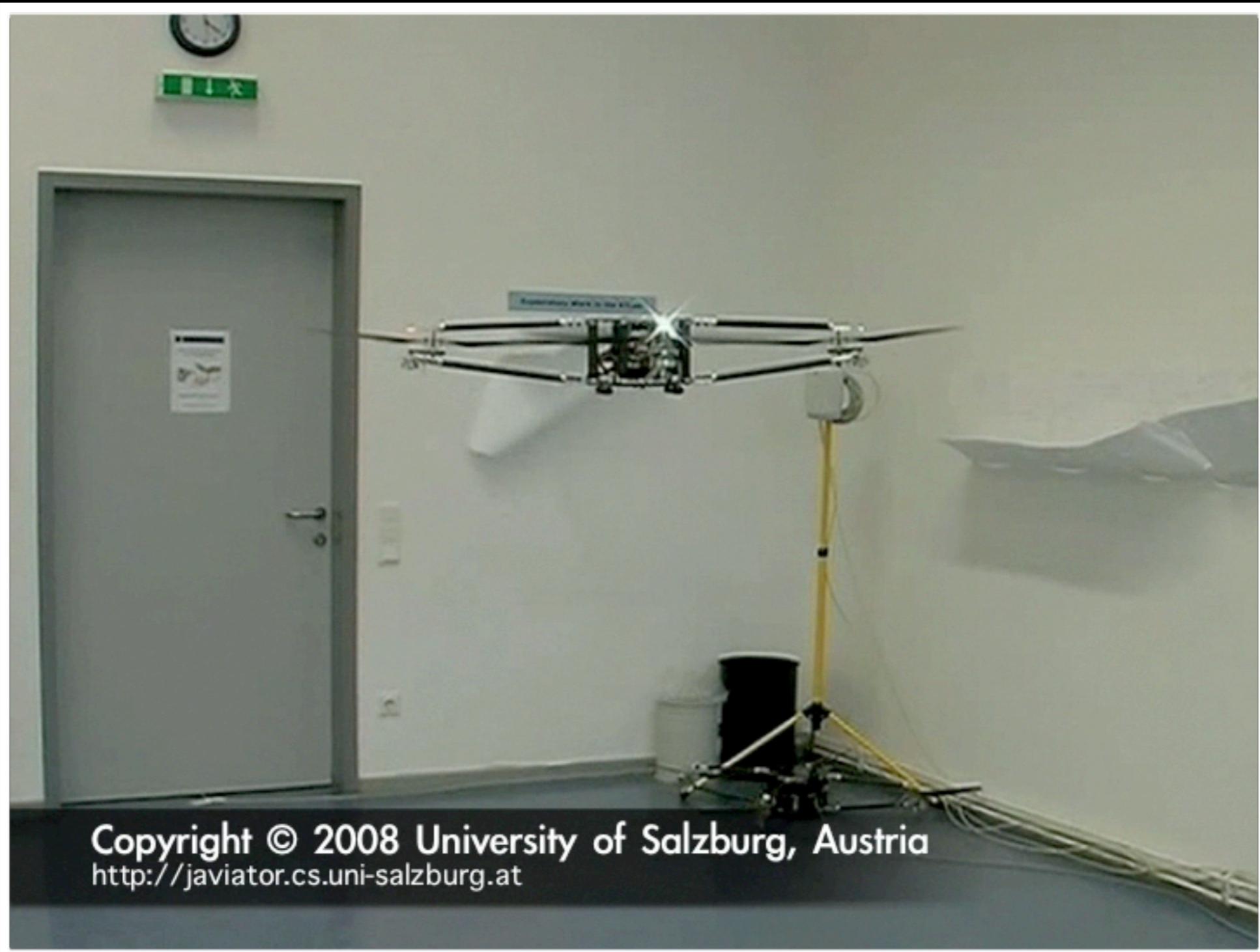




Indoor Flight STARMAC Controller



Indoor Flight STARMAC Controller



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<http://javiator.cs.uni-salzburg.at>

Outdoor Flight Salzburg Controller



Outdoor Flight Salzburg Controller



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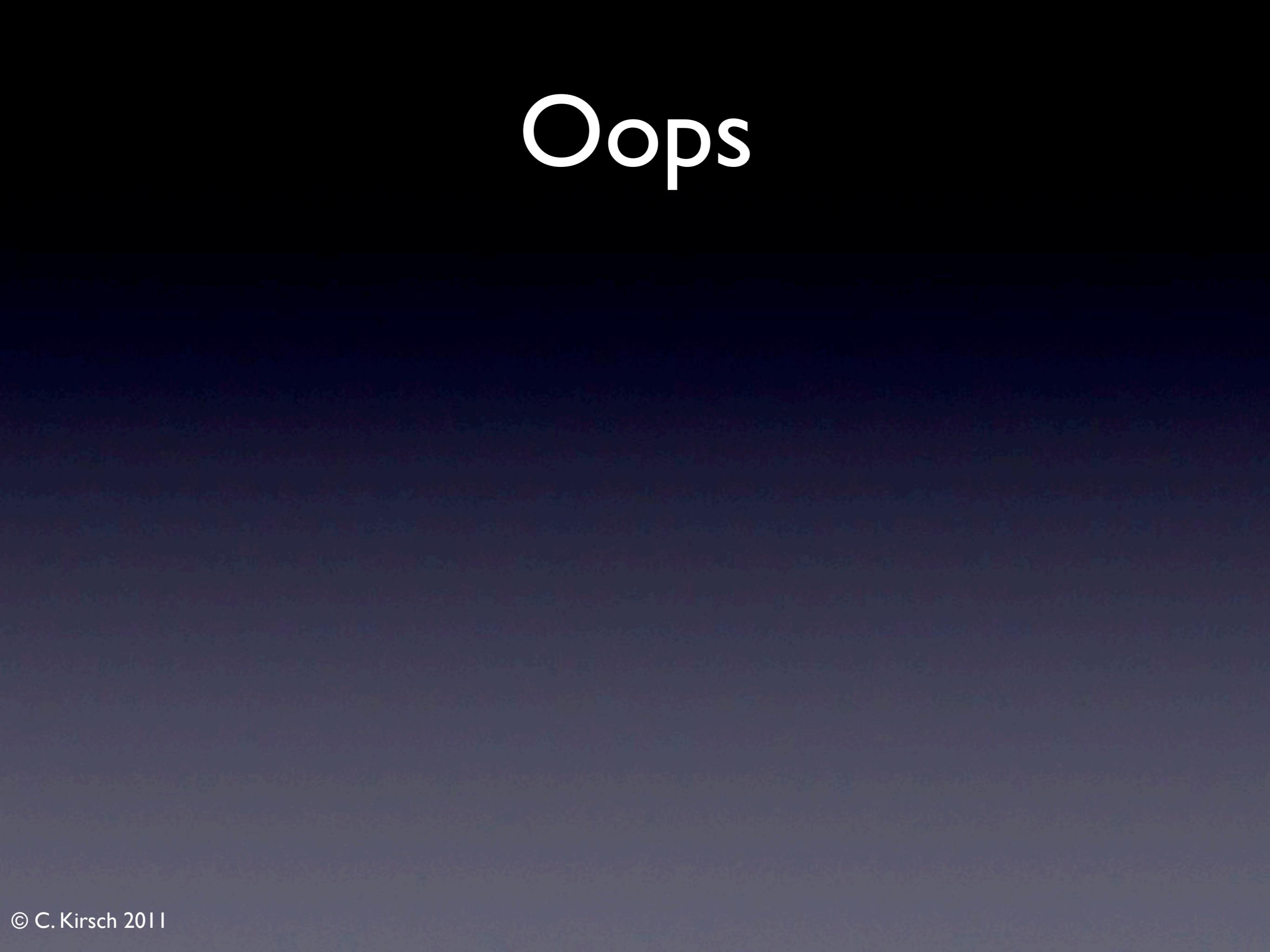
More Recent: Yawning



More Recent: Yawing



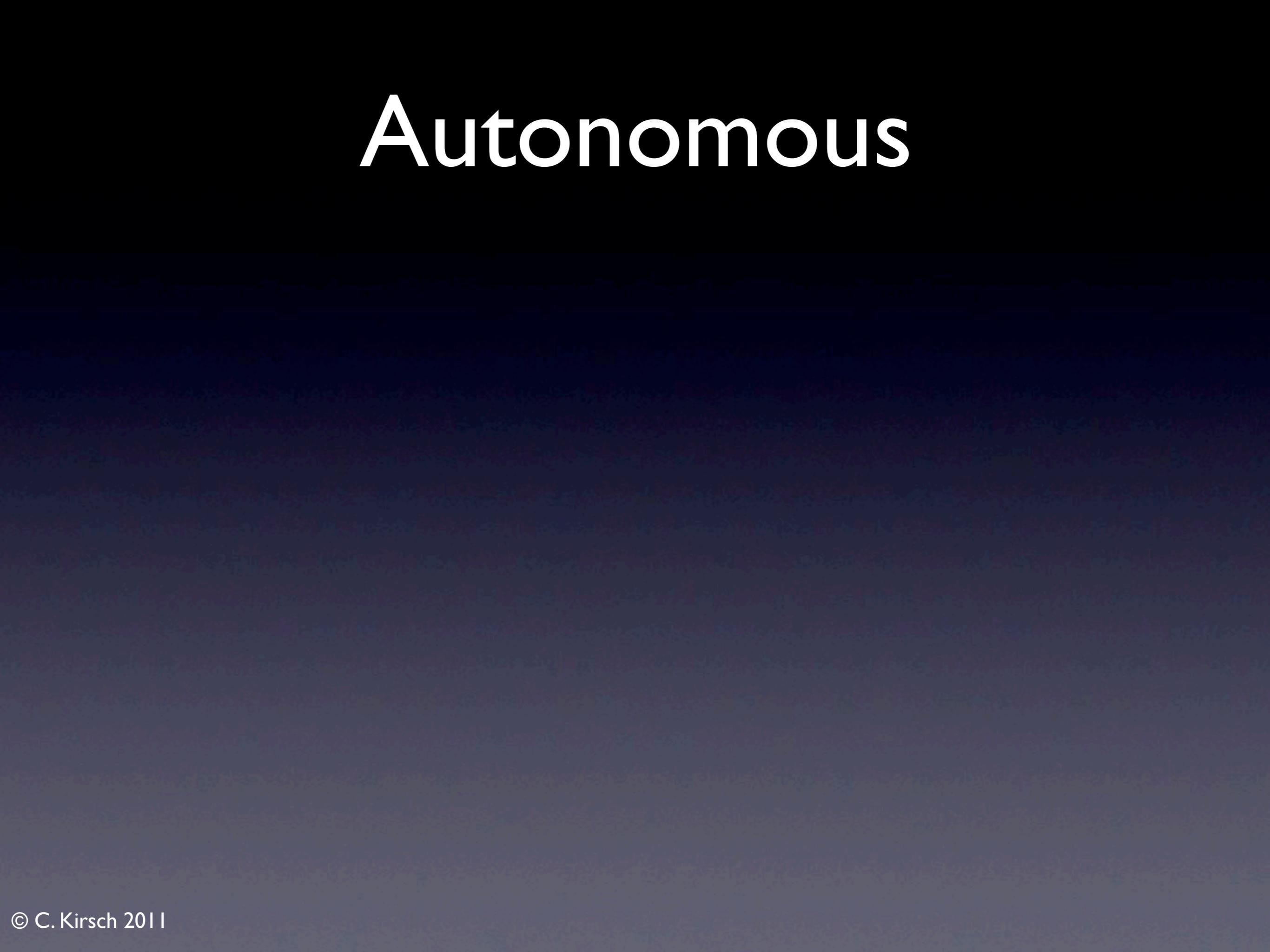
Oops



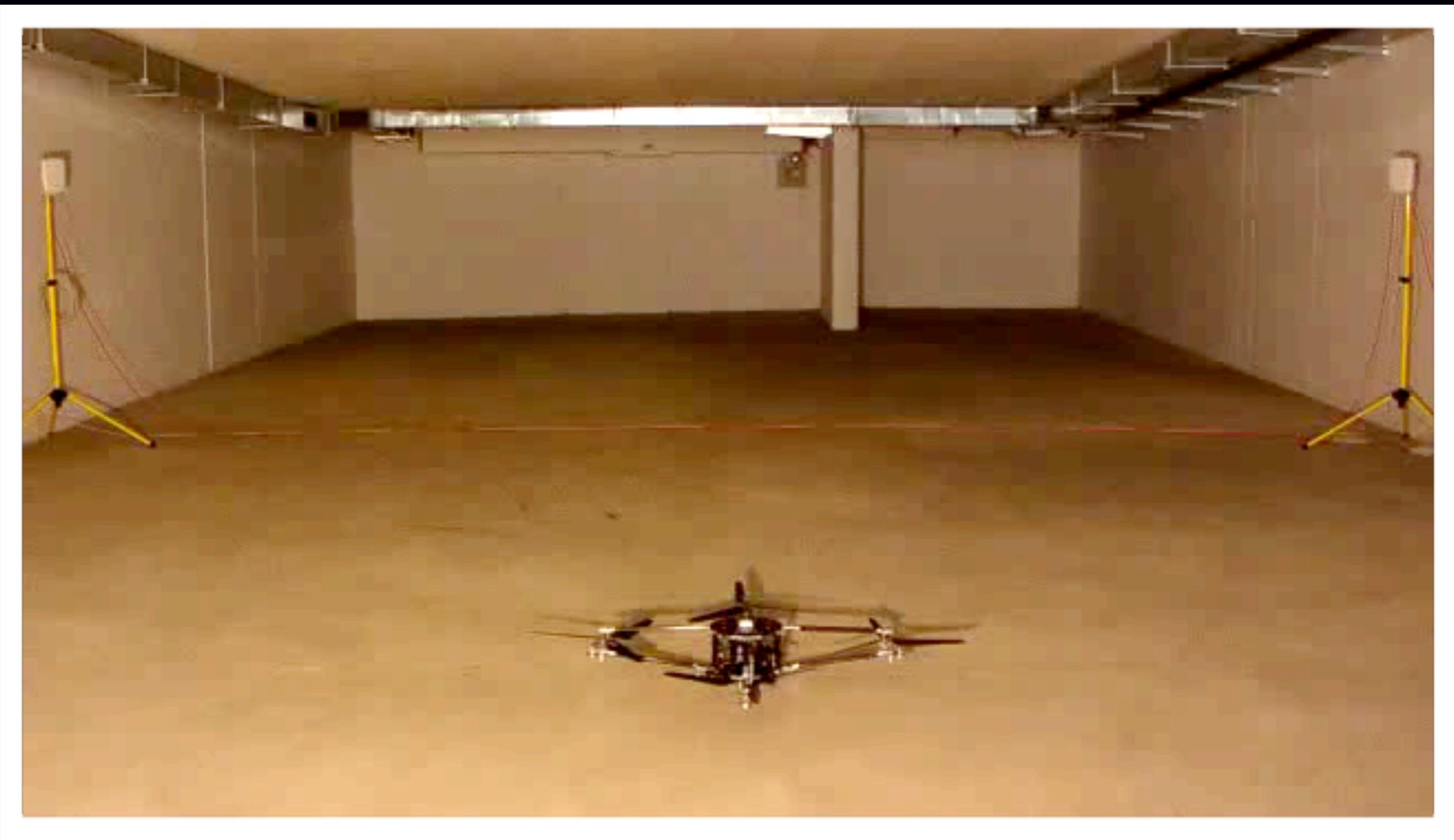
Oops



Autonomous



Autonomous



A Cyber-Physical Server



- IP address
- location

A Cyber-Physical Server



- IP address
- location
- capabilities

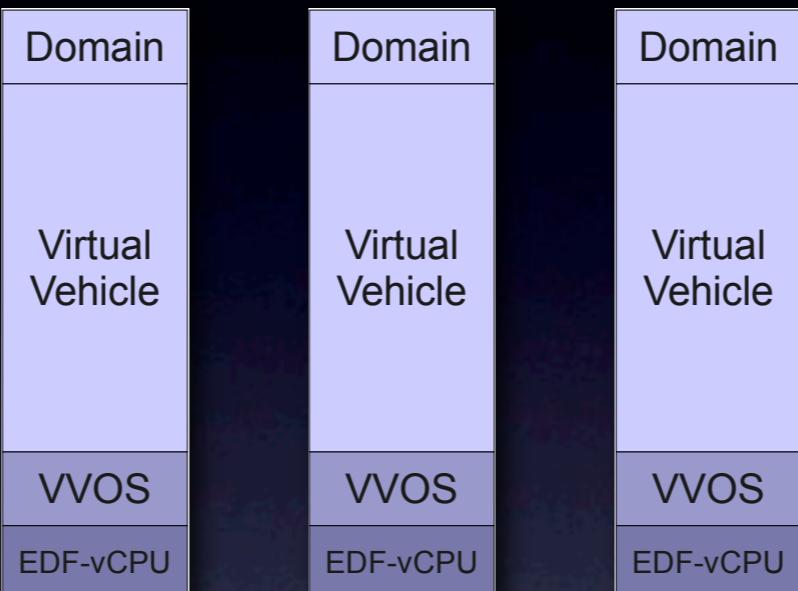
A Cyber-Physical Server



- IP address
- location
- capabilities
- motion

A Cyber-Physical Server

- IP address
- location
- capabilities
- motion



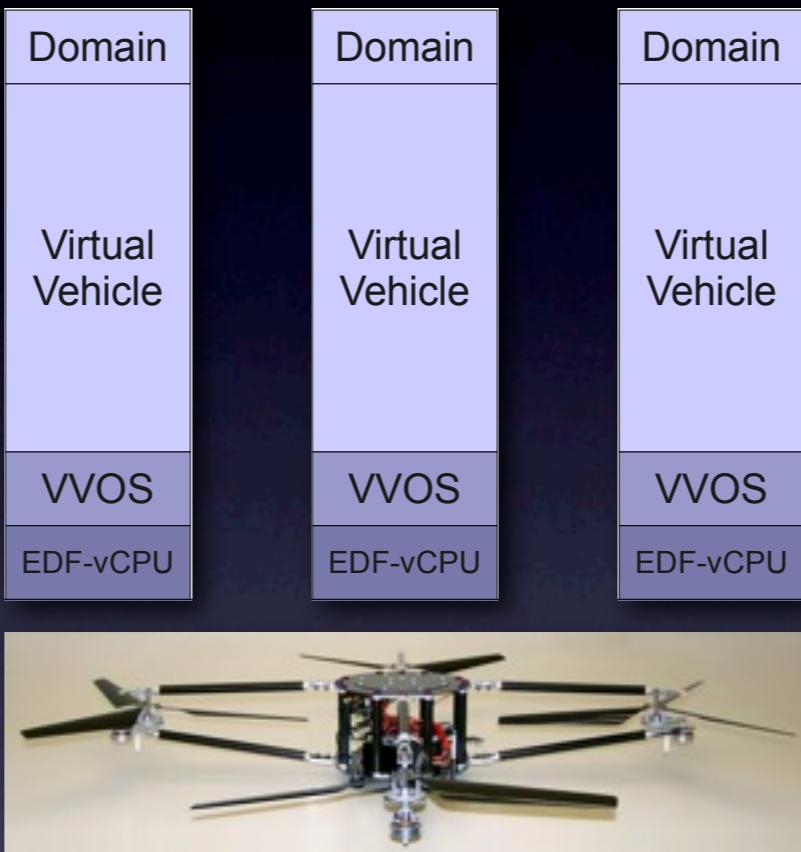
- IP address
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- location
- capabilities
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A Cyber-Physical Server

- IP address
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- motion

restricted



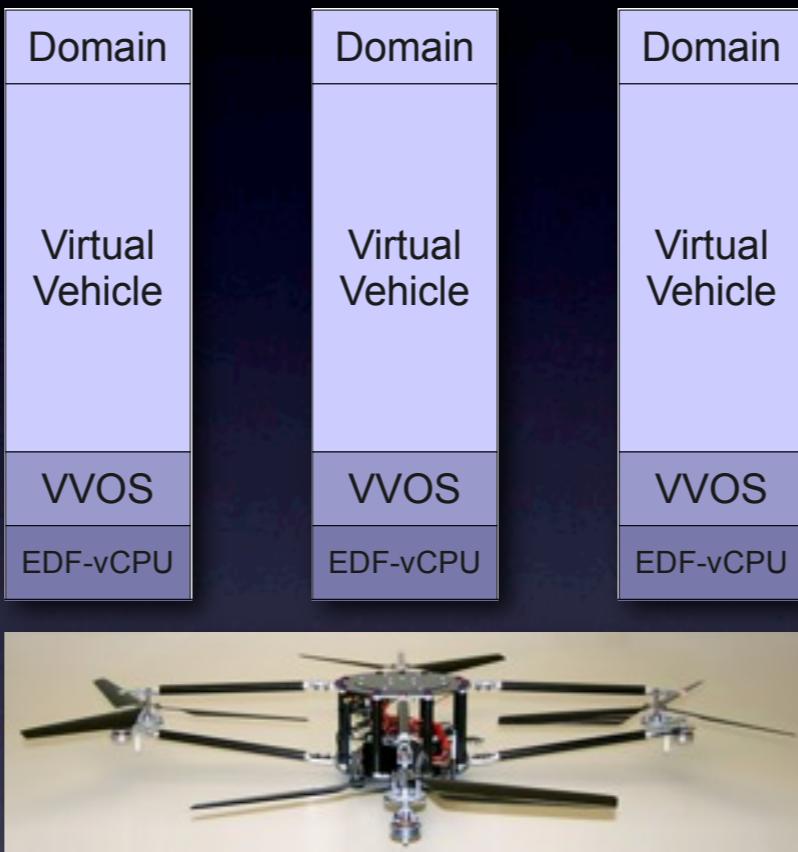
- IP address
- location
- capabilities
- motion

- IP address
- location
- capabilities
- motion

A Cyber-Physical Server

- IP address
- location
- capabilities
- motion

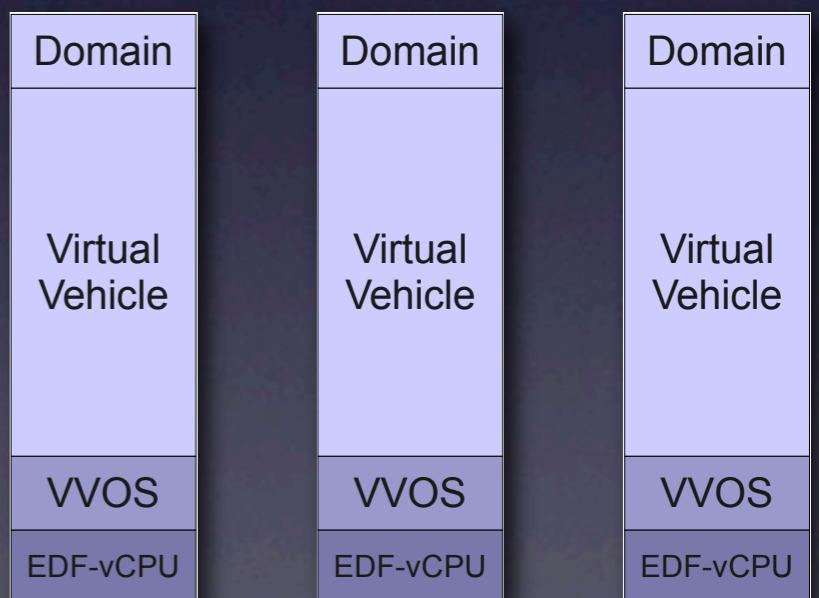
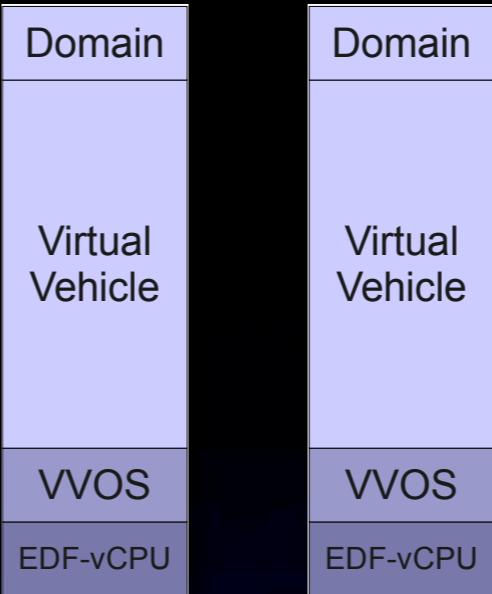
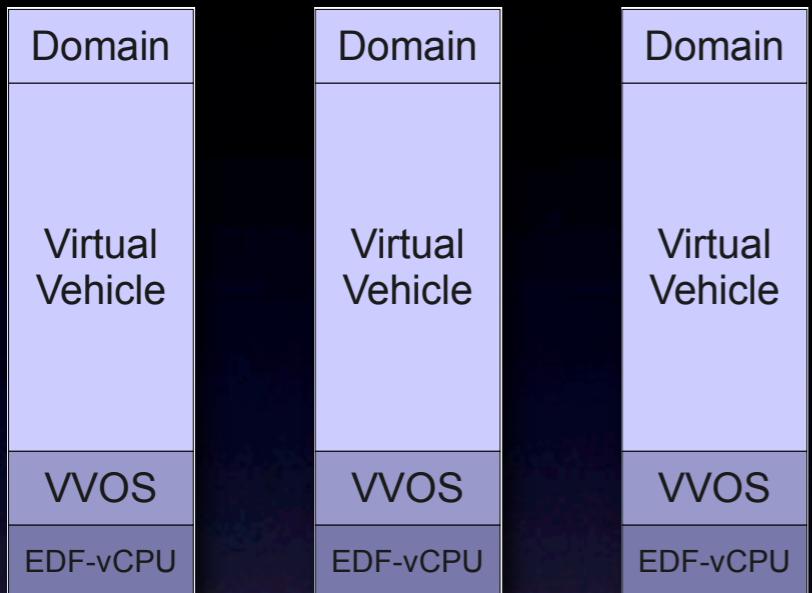
restricted



- IP address
- location
- capabilities
- motion

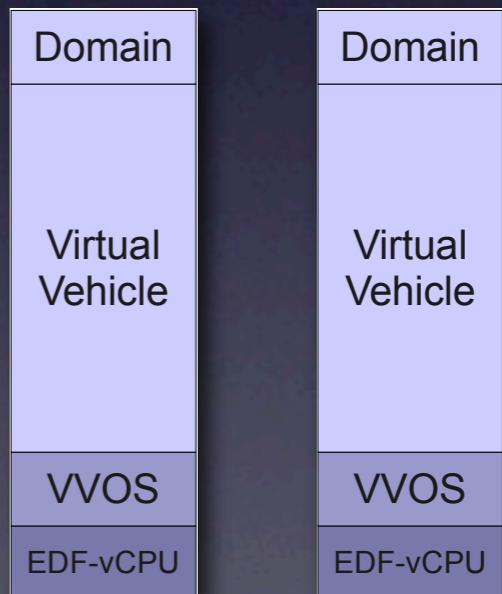
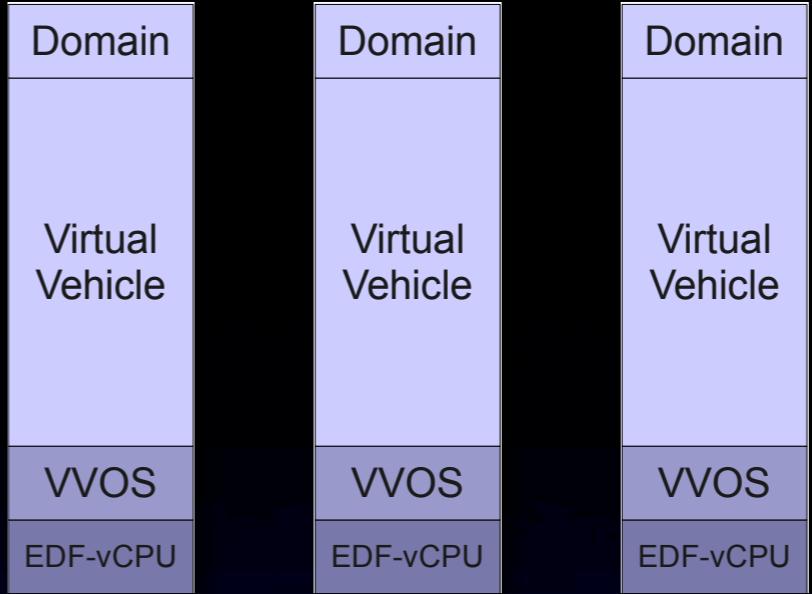
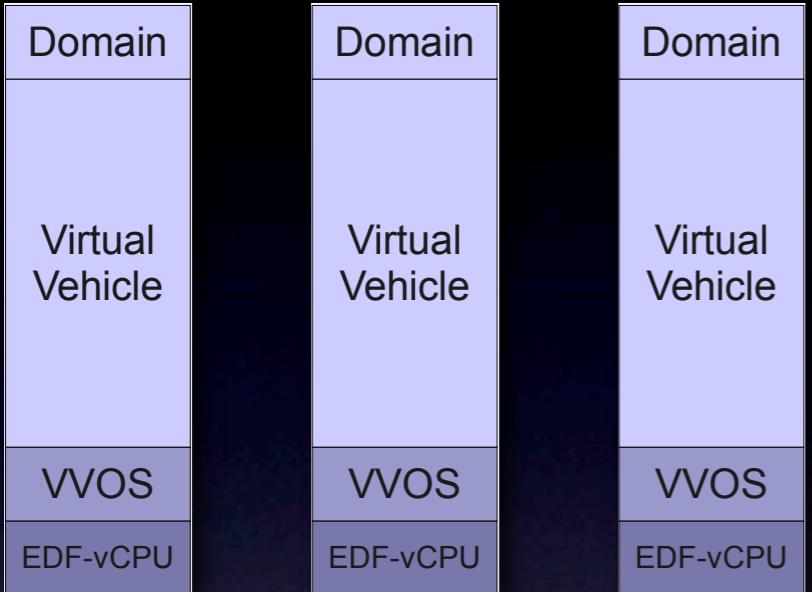
idealized

- IP address
- location
- capabilities
- motion



A Cyber-Physical Cloud [HotCloud 2010]

migration
=
flying



A Cyber-Physical Cloud [HotCloud 2010]

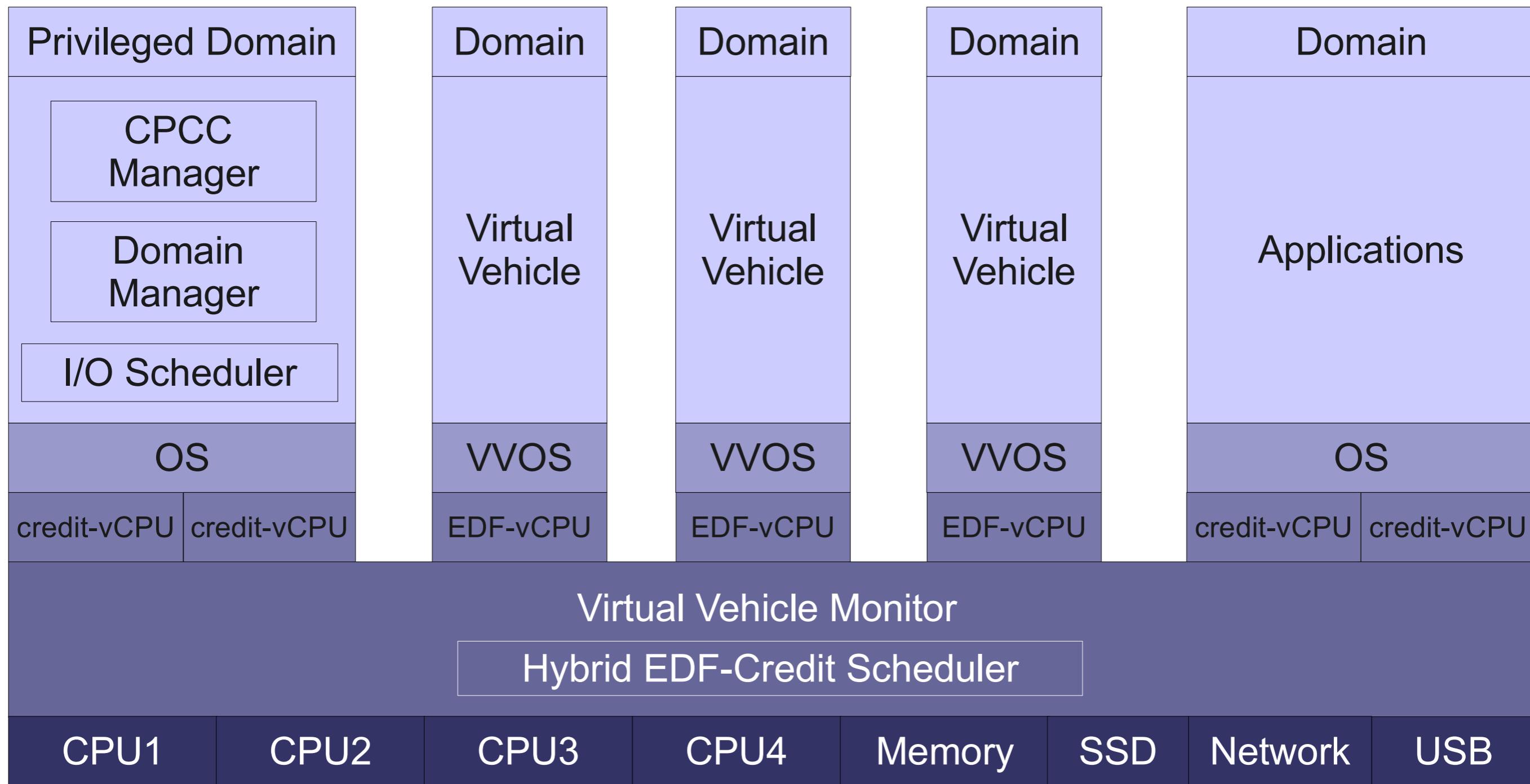
Goals

- Multi-provider (10s):
 - heterogeneous operations
- Multi-vehicle (100s):
 - heterogeneous systems
- Multi-task (1000s):
 - heterogeneous missions

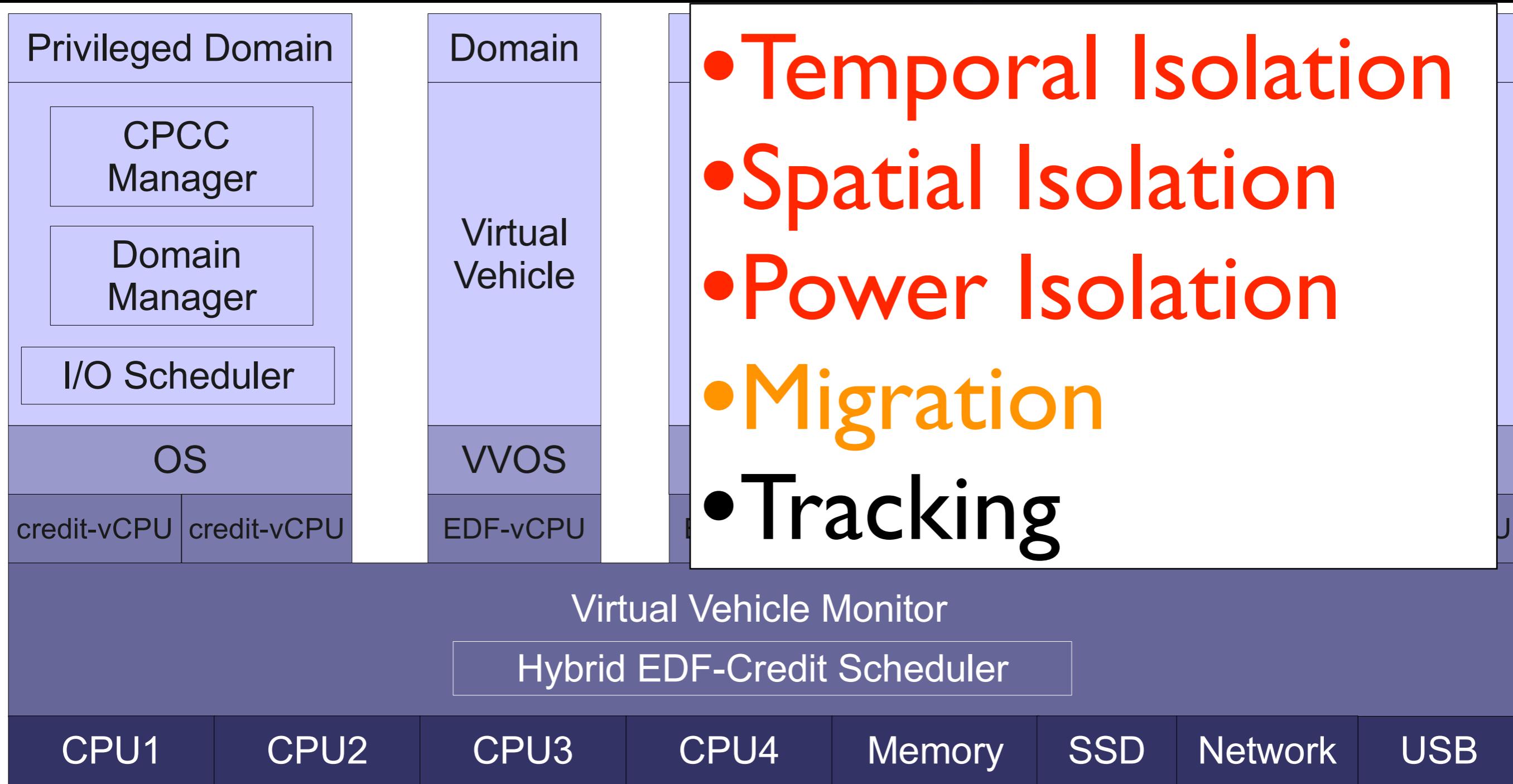
High-Level Challenges

- Virtualization **Infrastructure**
 - ▶ Salzburg
- Collaborative **Control**
 - ▶ Berkeley
- Programming **Language**
 - ▶ Berkeley, Salzburg

Virtualization Infrastructure



Virtualization Infrastructure



There is a
fundamental trade-off
between
quality and **cost**
of
time, space, power
isolation

Time

- **quality:** response time jitter
- **cost:** scheduling overhead

Time

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Space

- **quality:** fragmentation jitter
- **cost:** management overhead

Time

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Space

- **quality:** fragmentation jitter
- **cost:** management overhead

Power

- **quality:** power consumption jitter
- **cost:** total power consumption

Time

Variable-Bandwidth Servers (VBS)
[SIES09]

VBS Overhead Accounting
[RTAS10]

Space

Compact-fit
[USENIX ATC08]

Short-term Memory
[Submitted II]

Power

Power-aware VBS
[EMSOFT10]

The Power of Isolation
[Submitted II]

Time

- **per-process** lower/upper bounds
on response times [SIES09]

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The Power of Isolation

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Space

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The Power of Isolation
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- refresh needed rather than deallocate not-needed objects [Submitted II]
- save power while maintaining response times [EMSOFT10]
- per-process lower/upper bounds on power consumption [Submitted II]

Space

Power

The trade-off
between
isolation **quality** and **cost**
extends to
scalability
on **multicore** systems

Multicore

- many concurrent data structures **do not scale**,
e.g. a concurrent FIFO queue for scheduling

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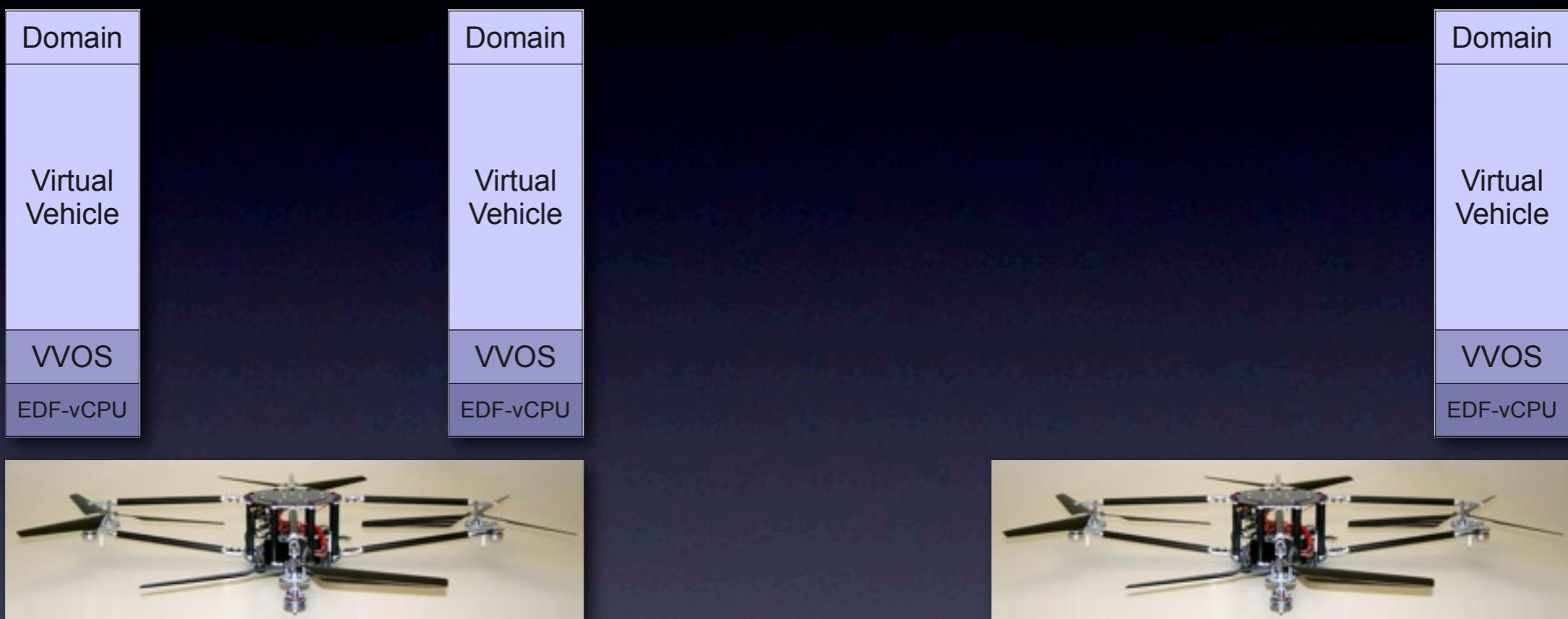
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Non-linearizable Computing Breaks the Scalability Barrier [Submitted]]

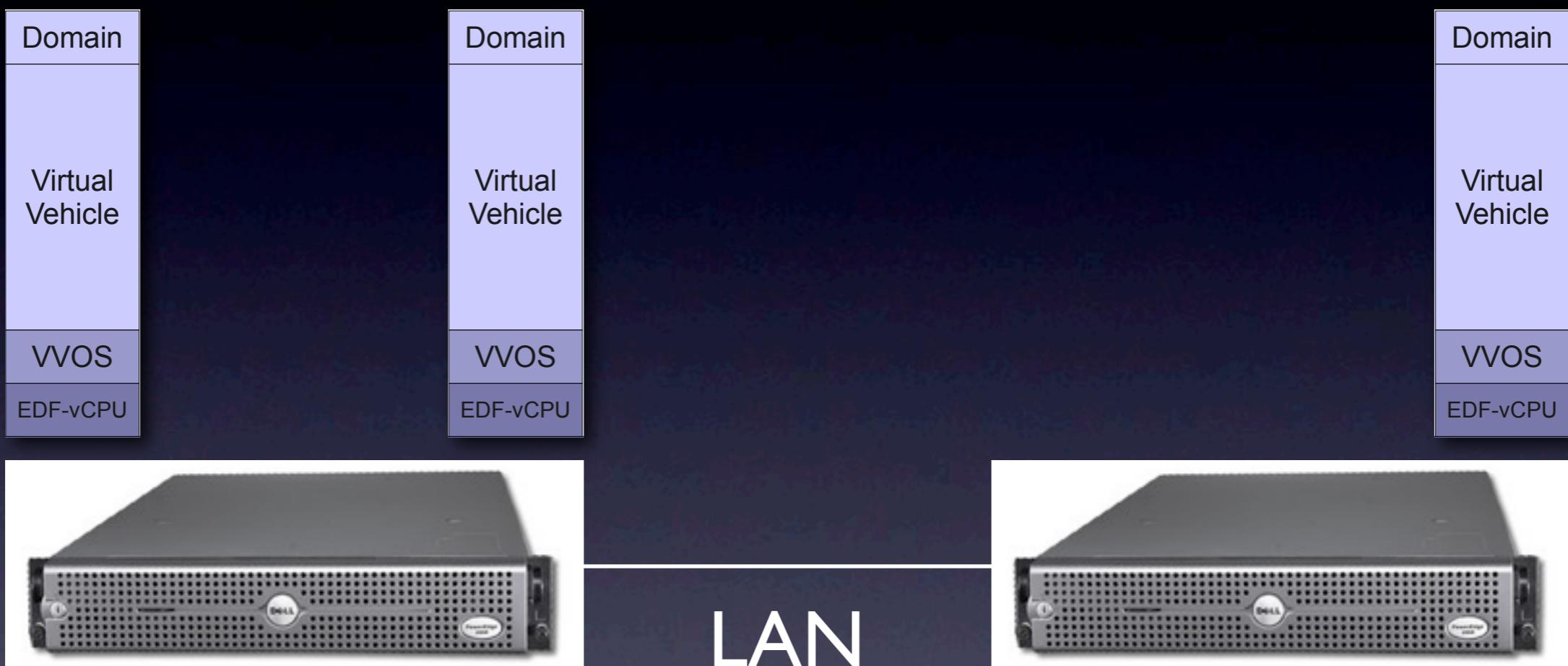
Virtual Vehicle Demo

by Florian Landolt and Andreas Rottmann



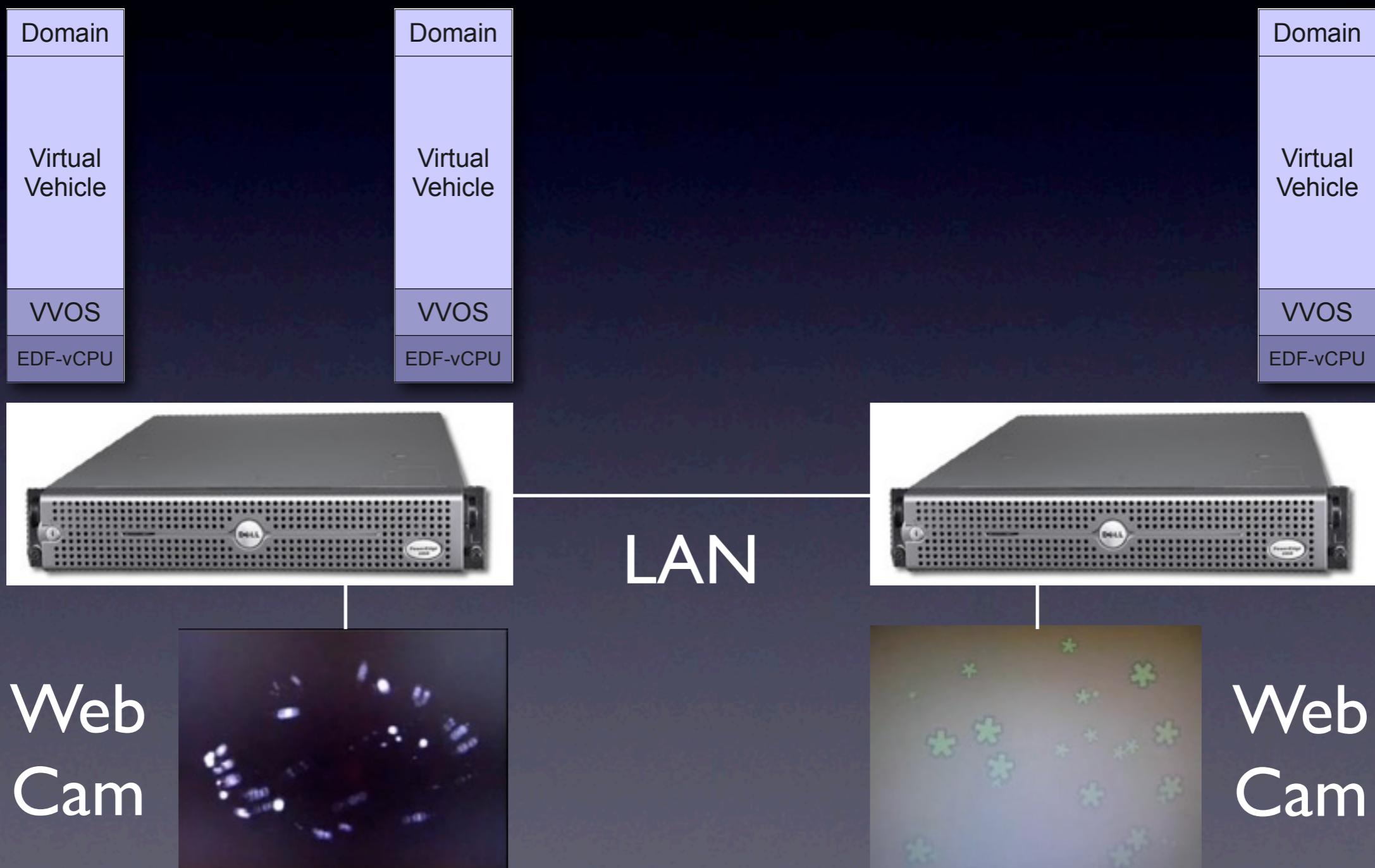
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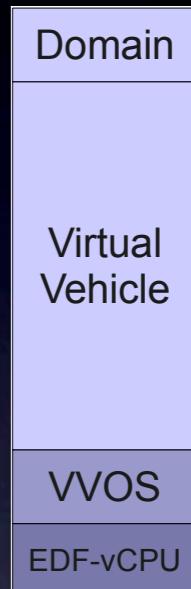
Virtual Vehicle Demo

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Laptop



LAN

Web
Cam



Web
Cam



Laptop



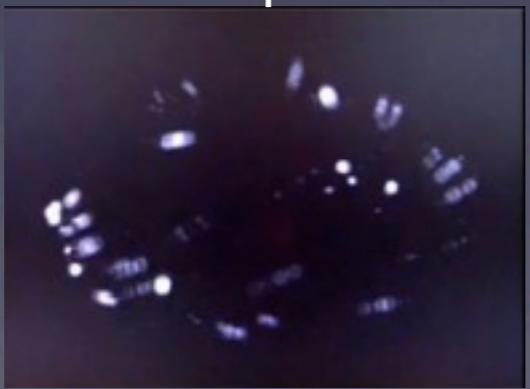
Multicast



LAN



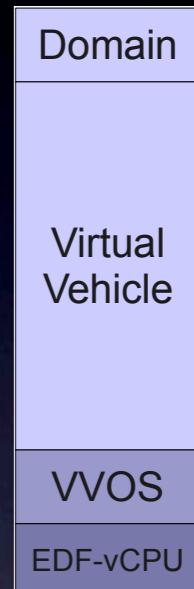
Web
Cam



Web
Cam



Laptop



Migration



LAN

Web
Cam



Web
Cam

Laptop



Web Cam



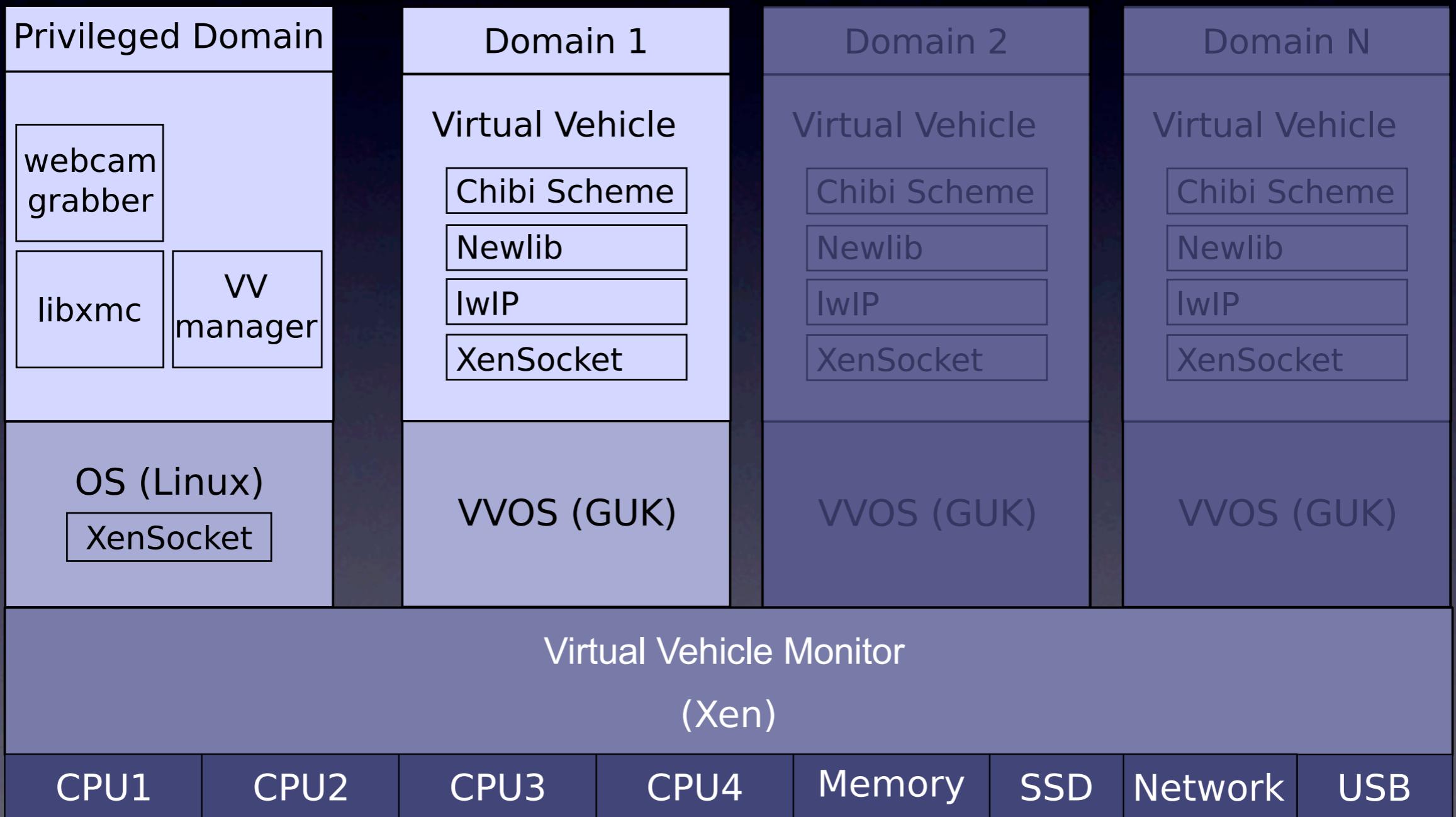
LAN



Web Cam

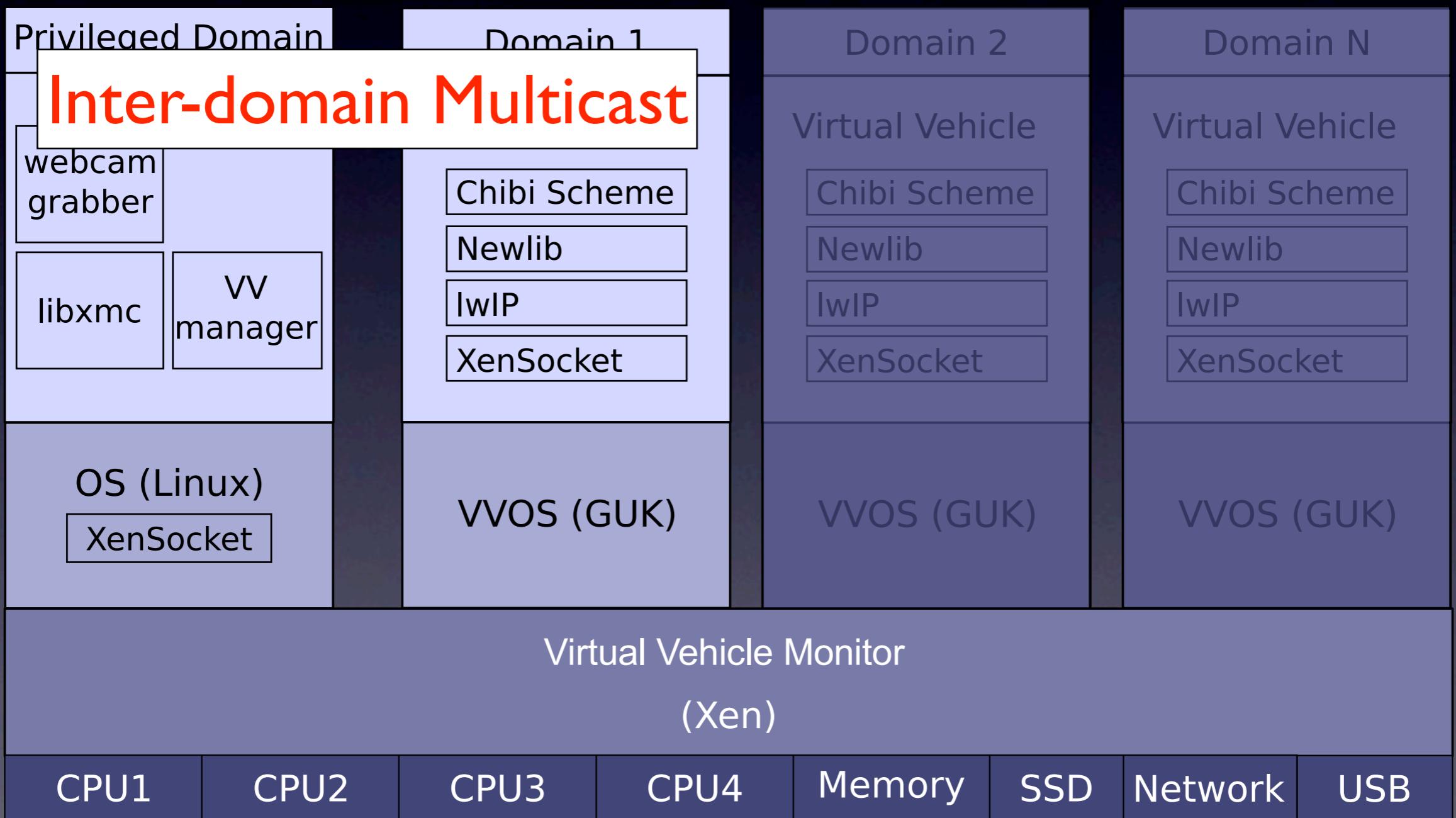
Virtual Vehicle Monitor

(Xen, XenSockets, GUK, lwIP, Newlib, Chibi Scheme)



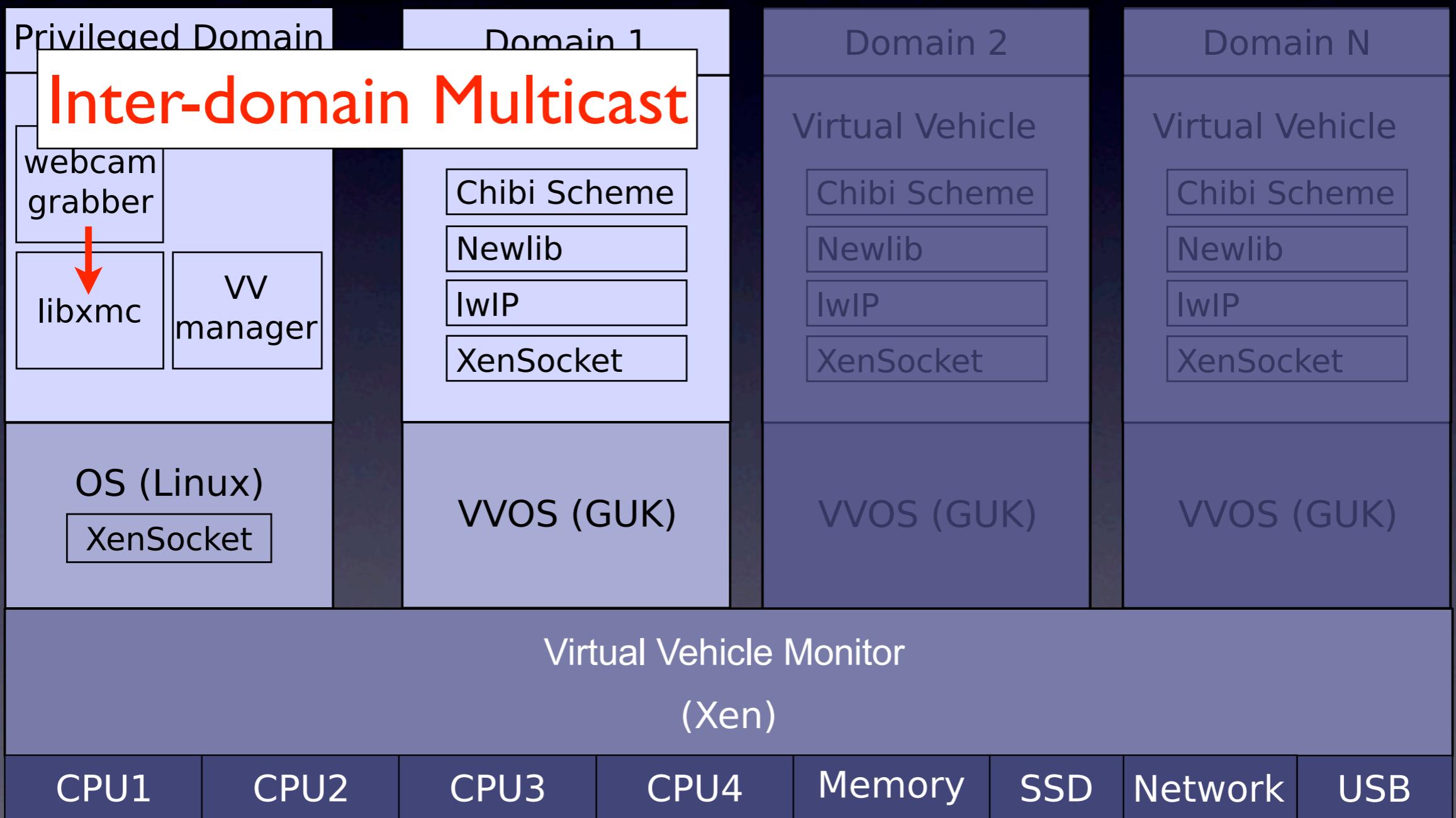
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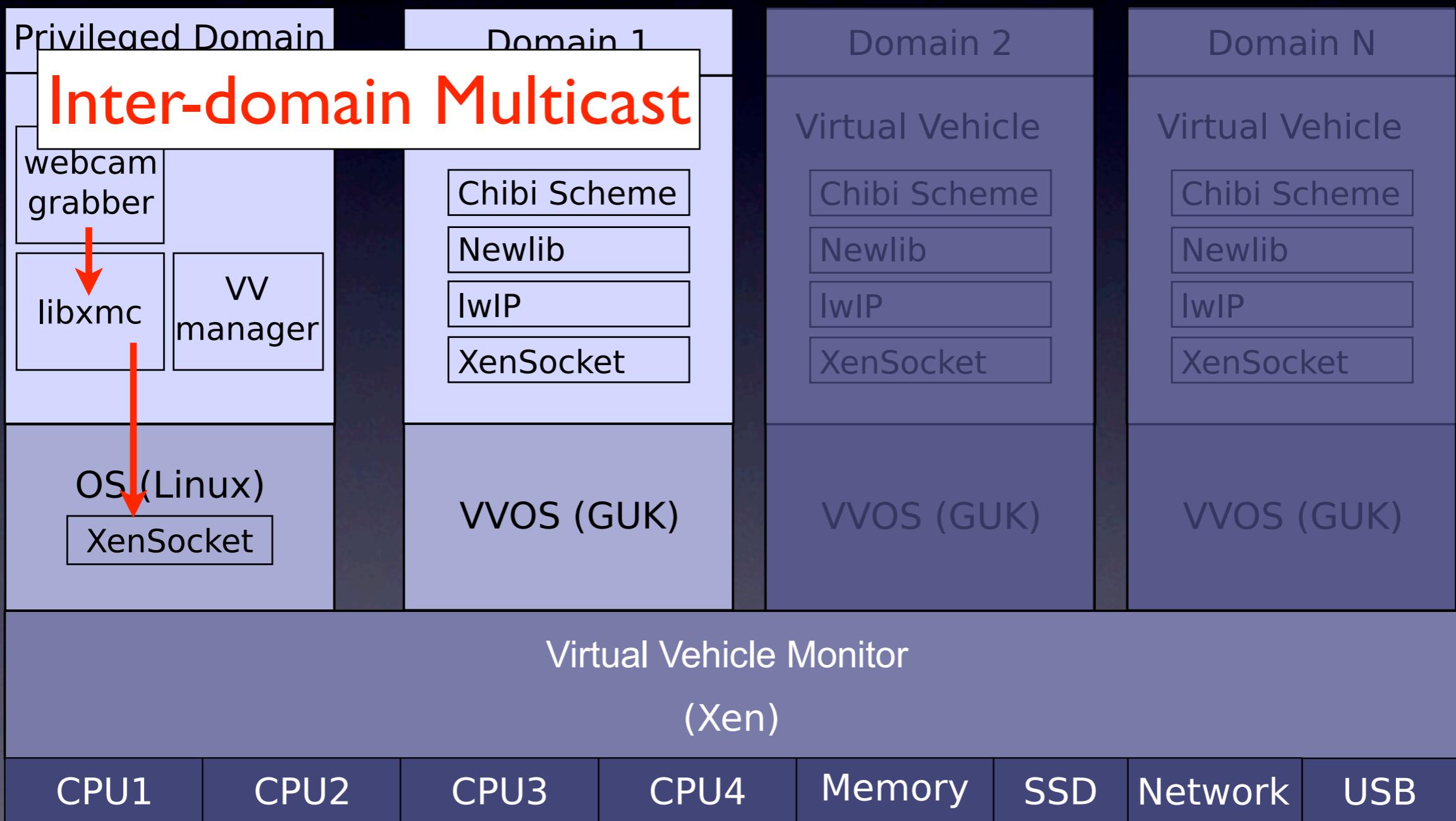
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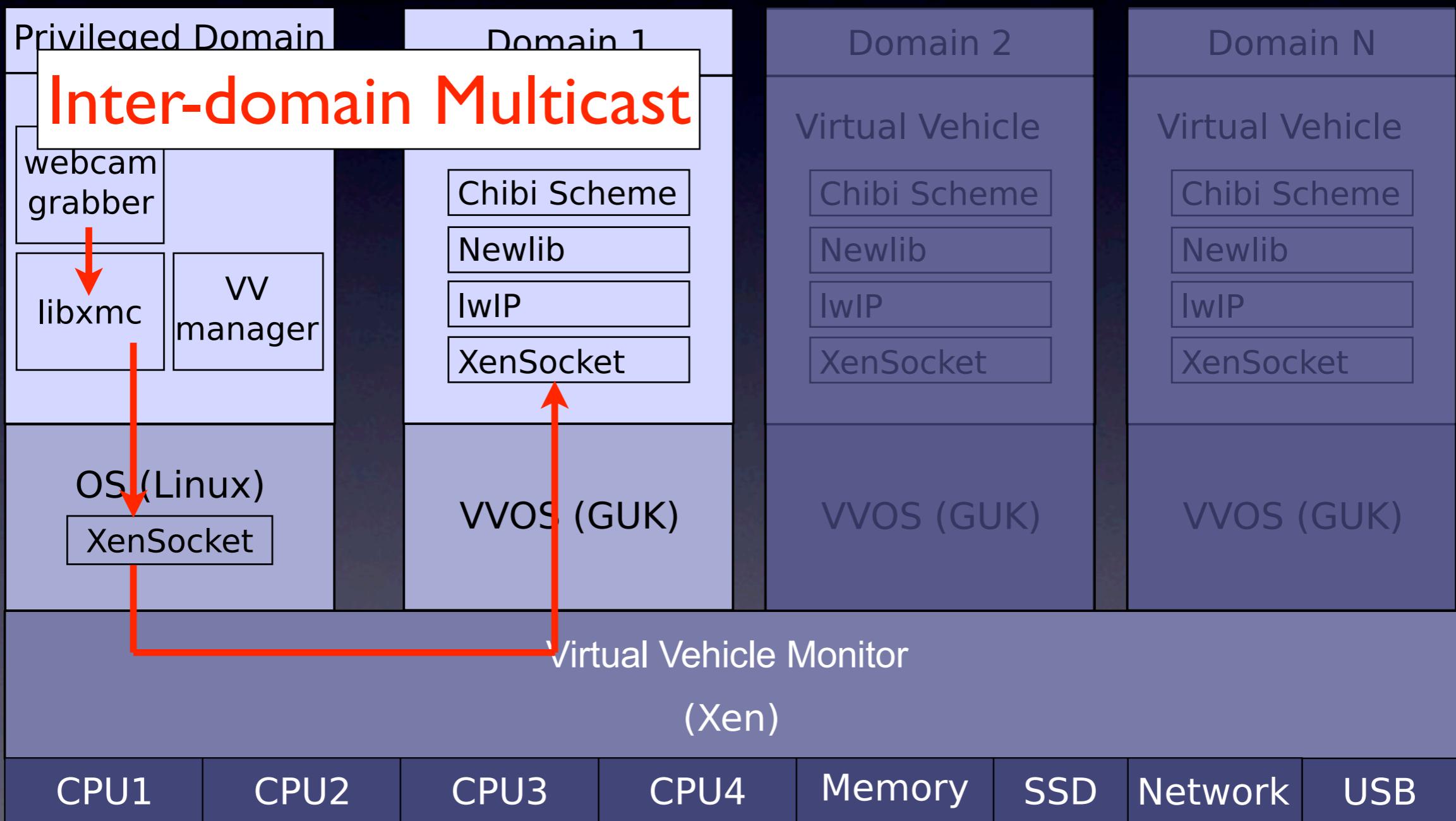
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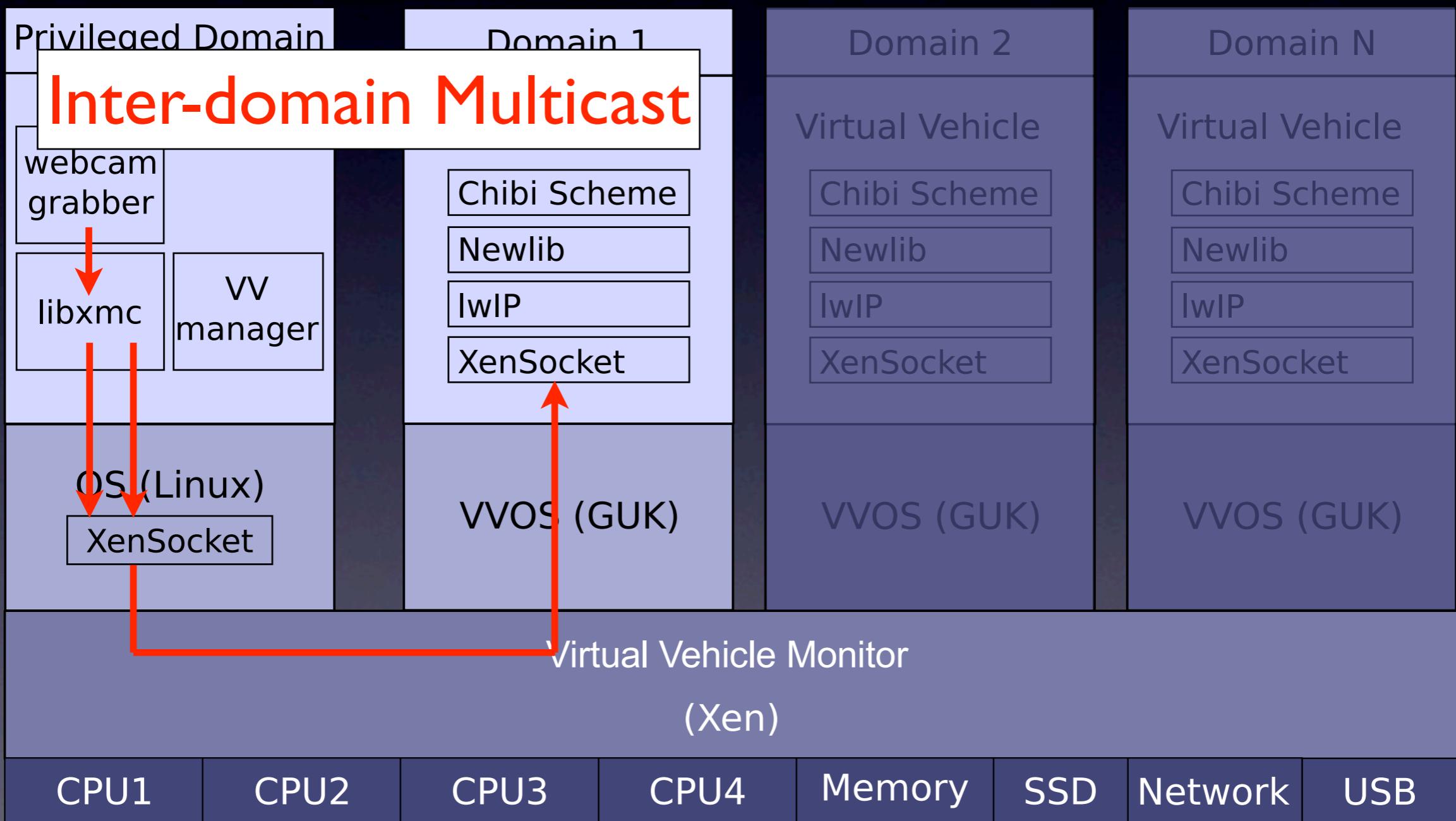
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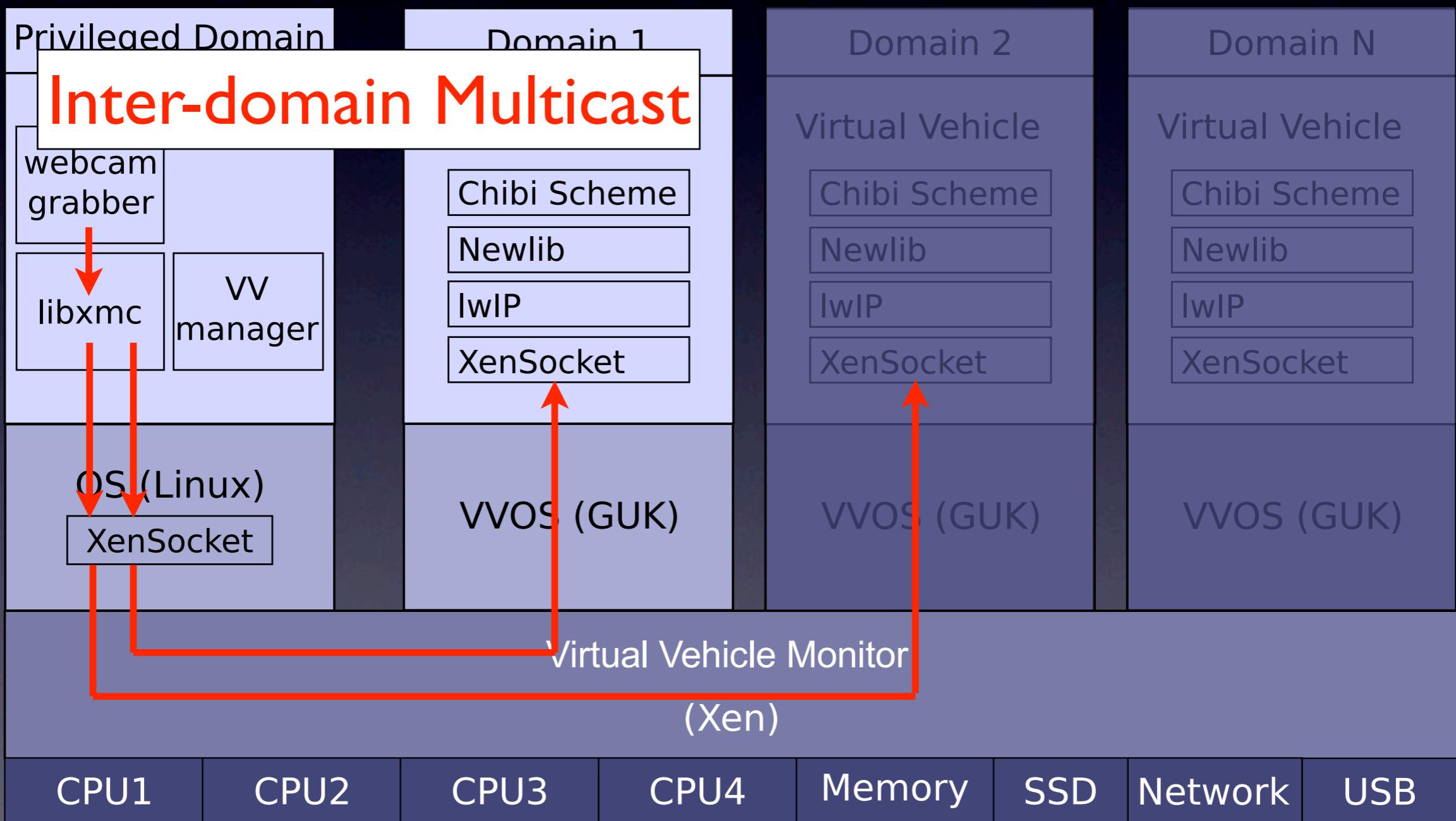
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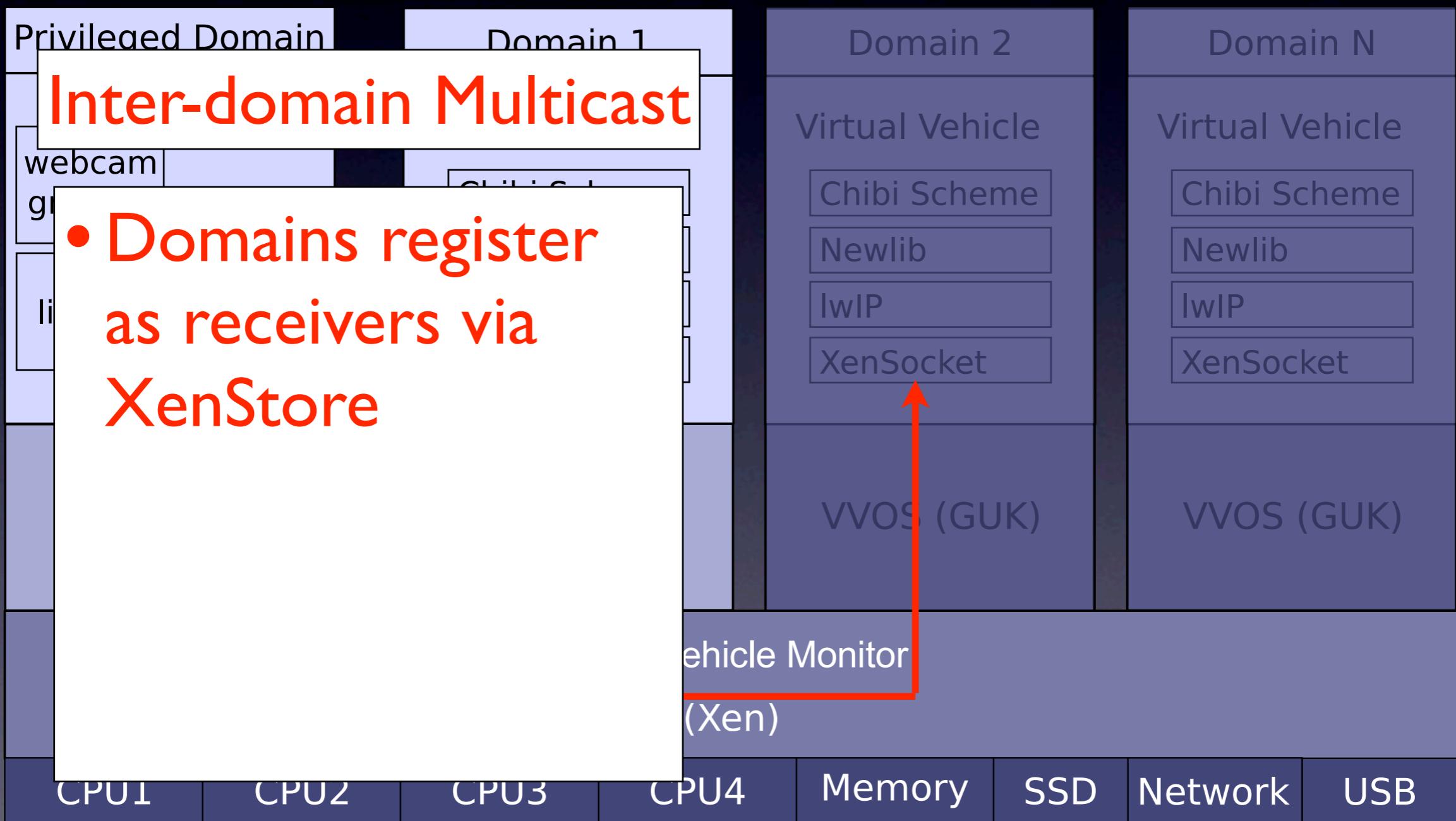
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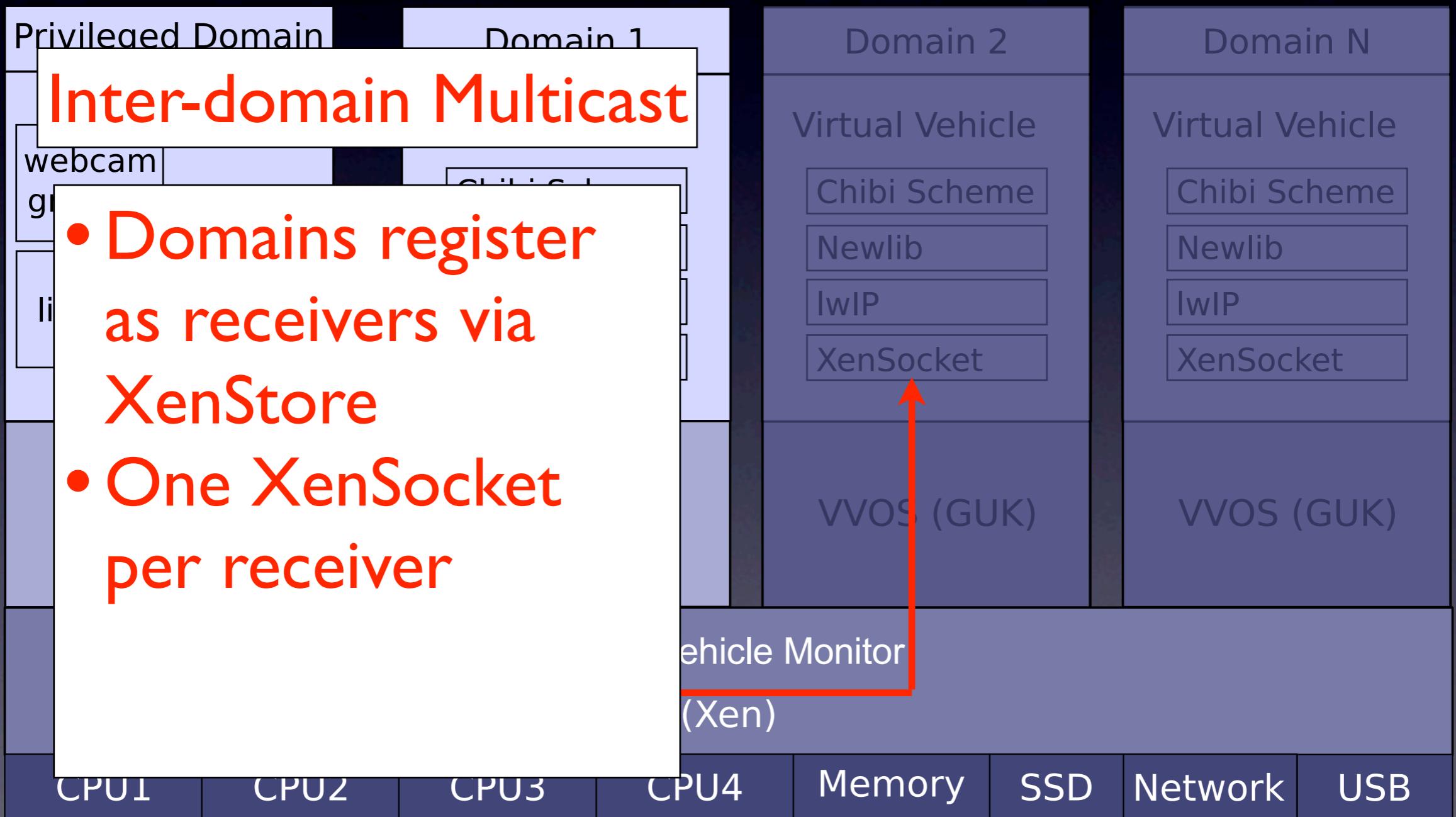
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- Domains register as receivers via XenStore

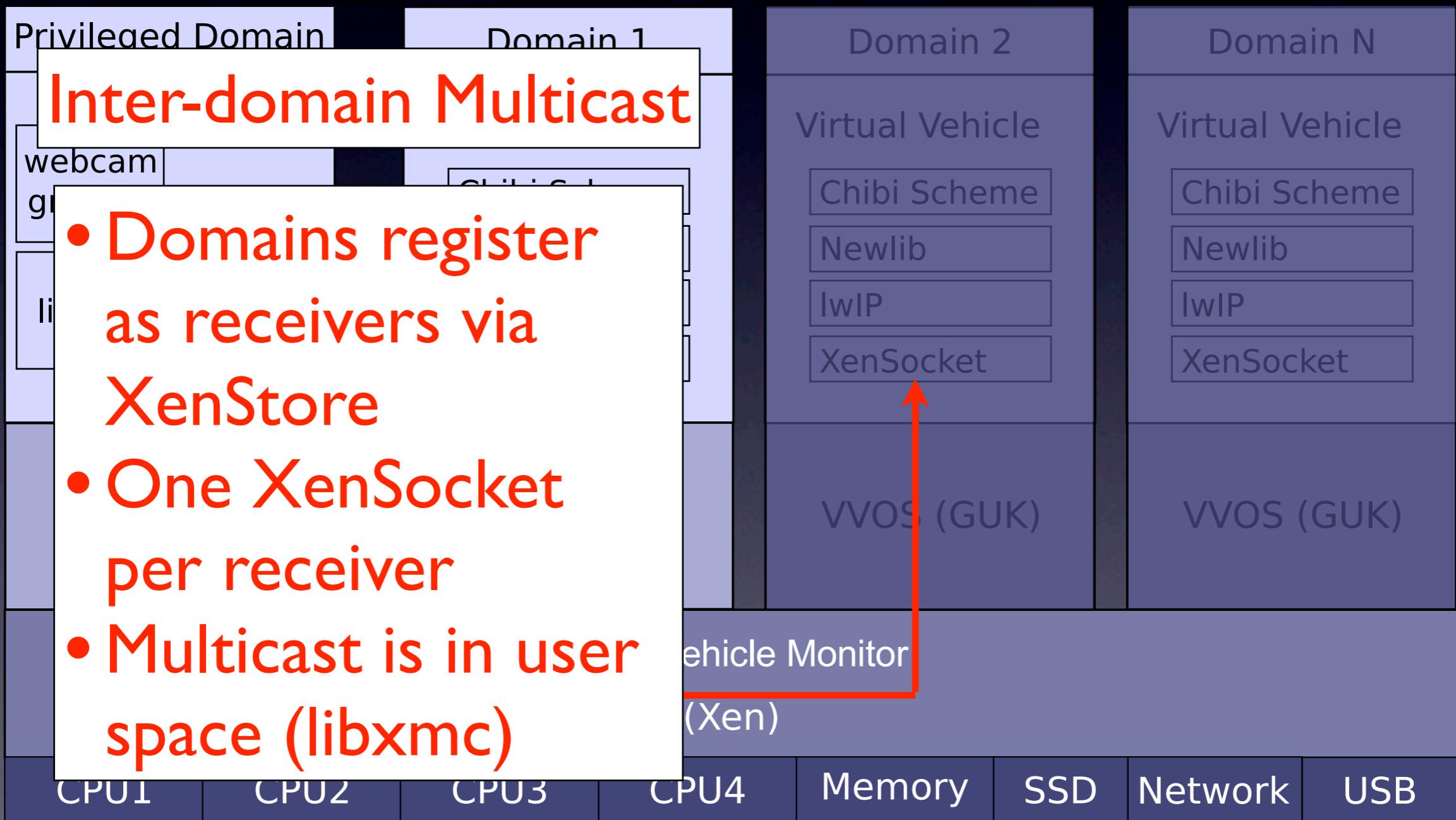
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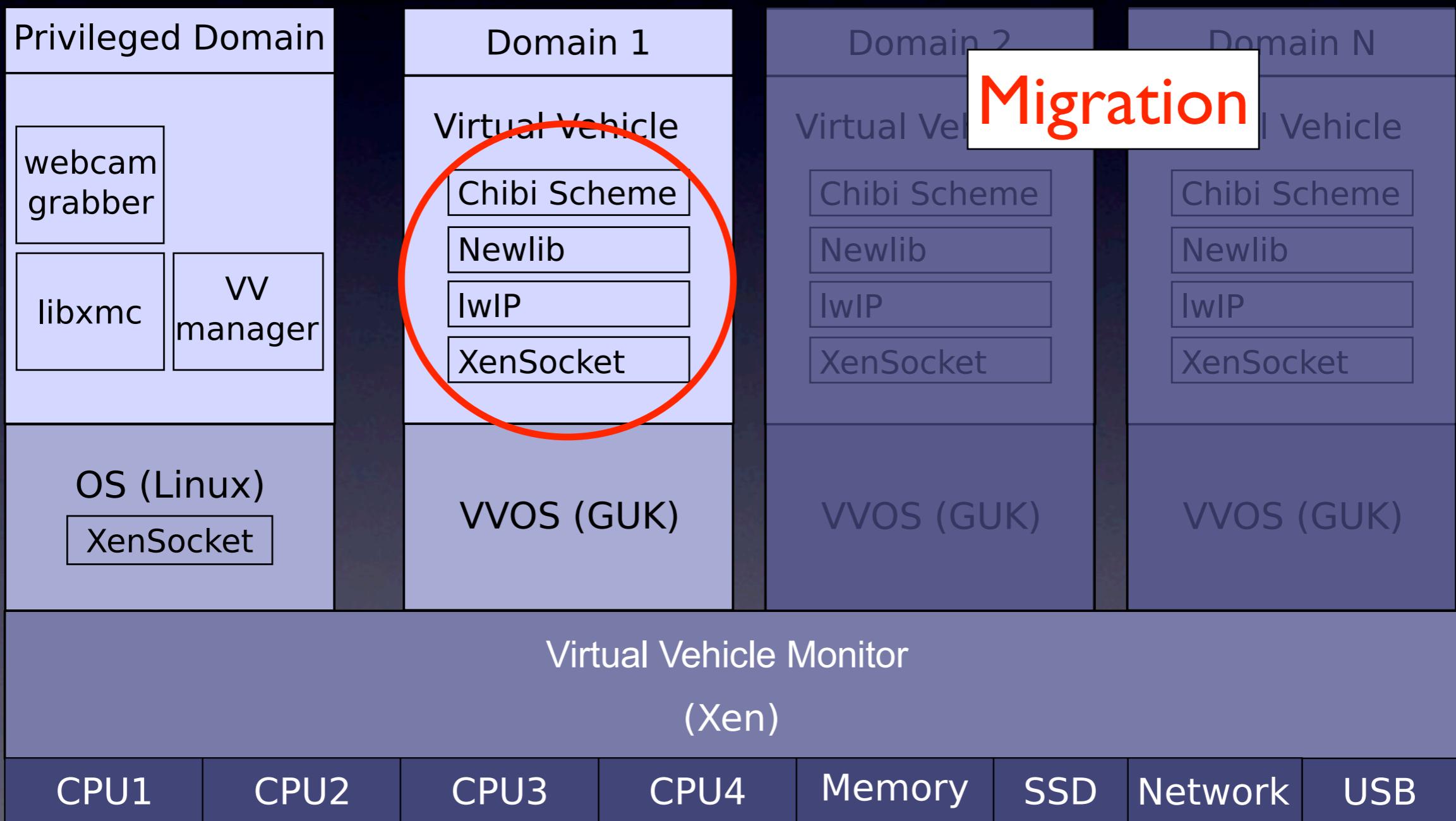
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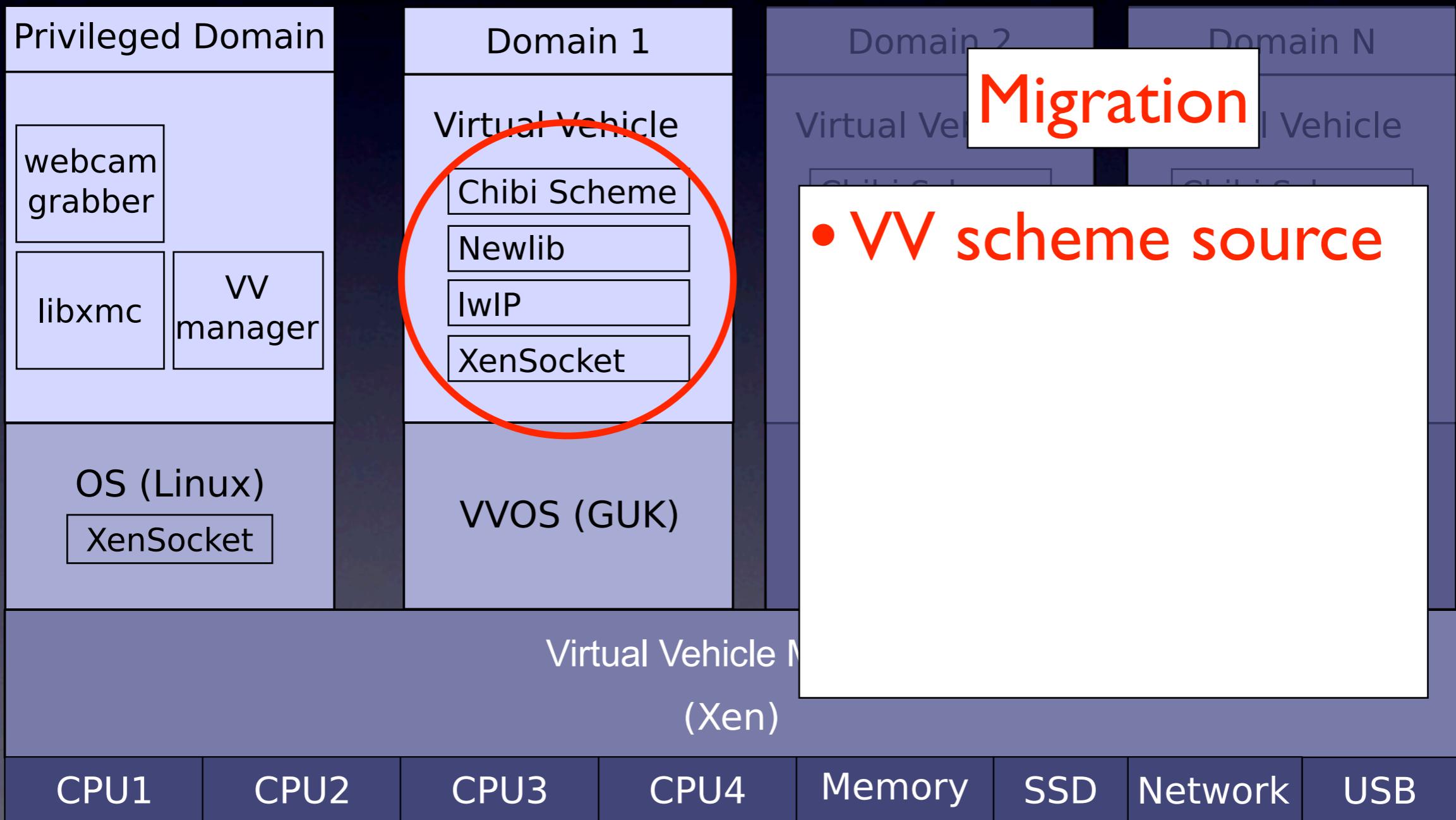
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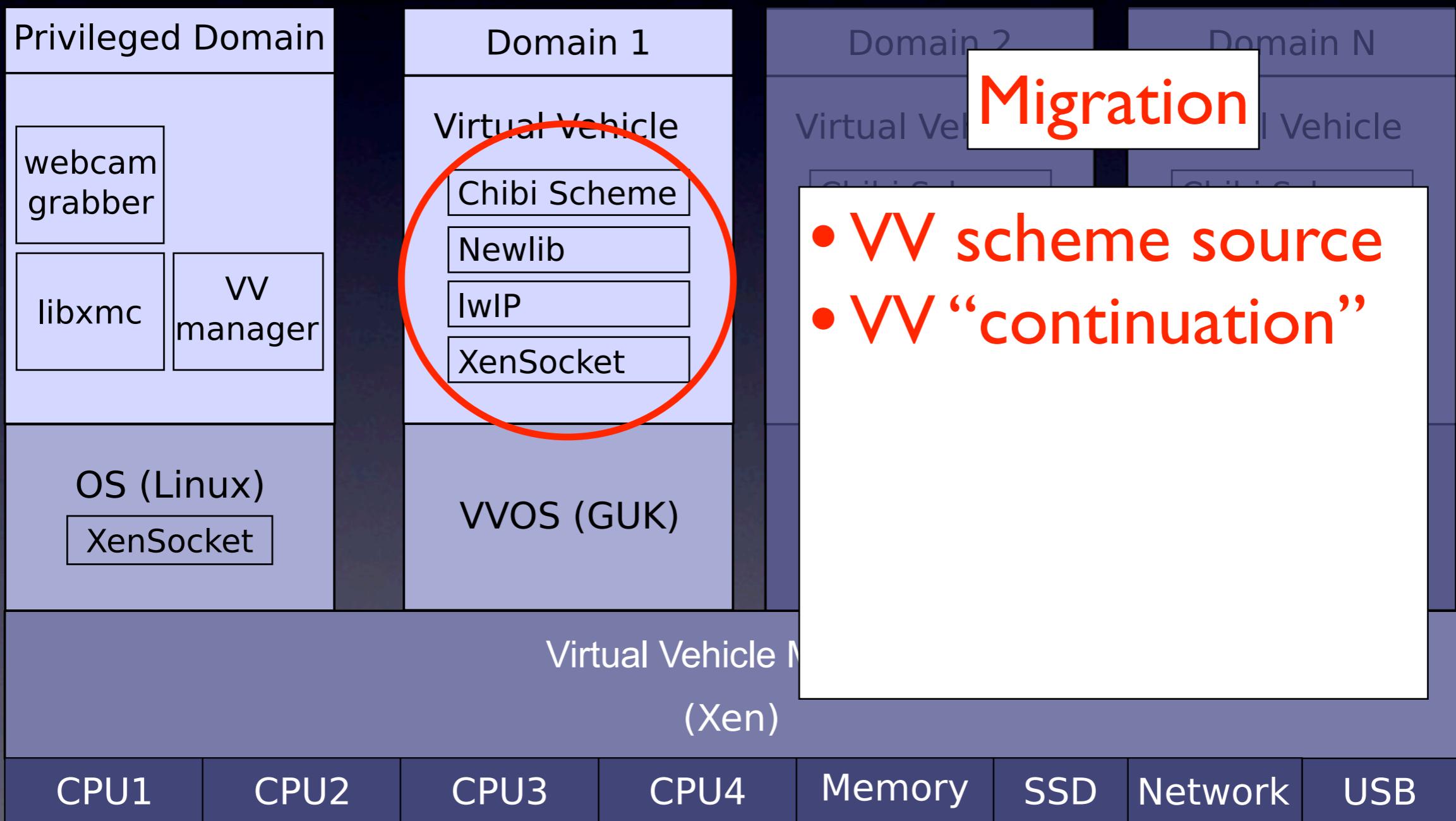
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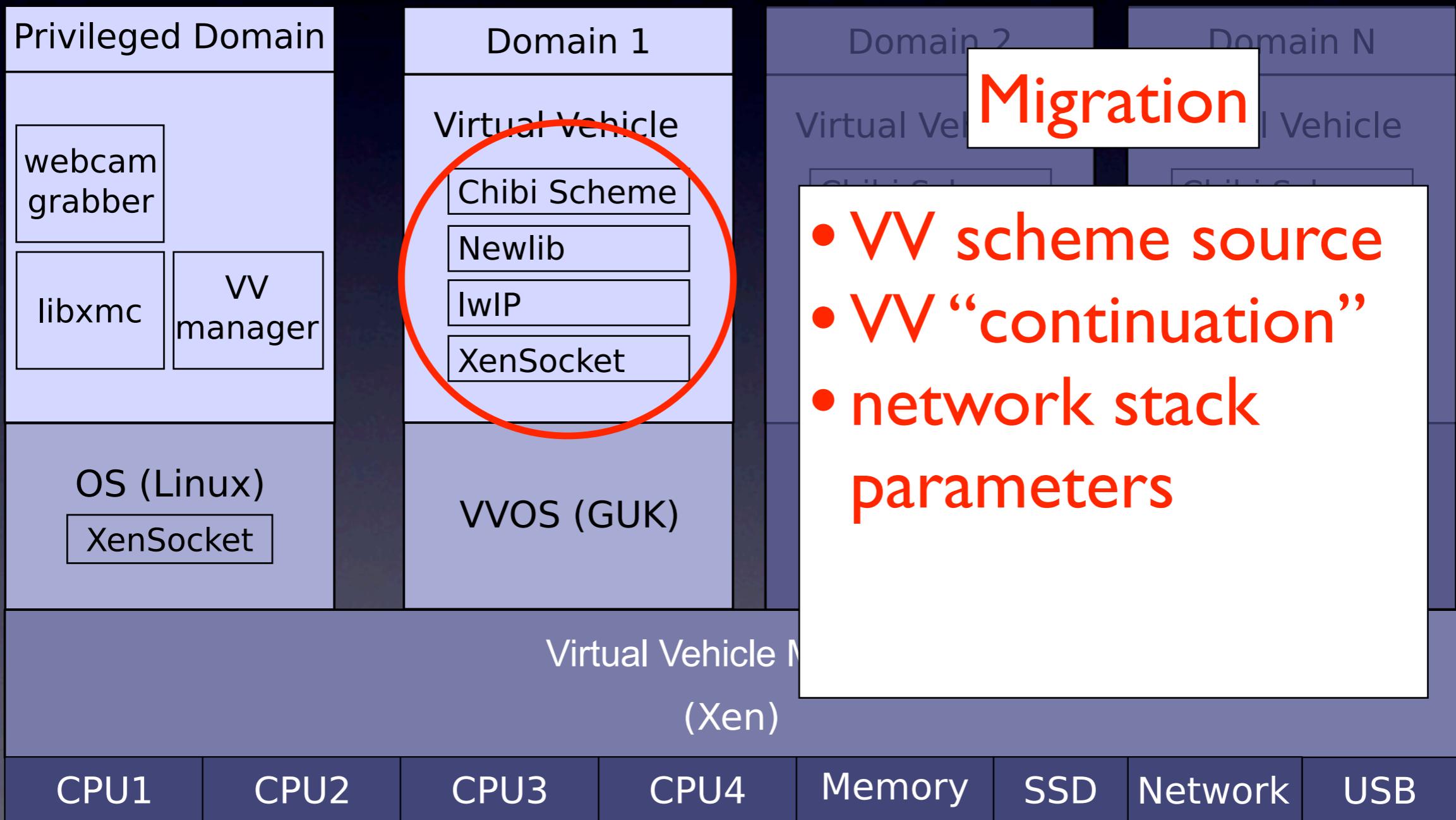
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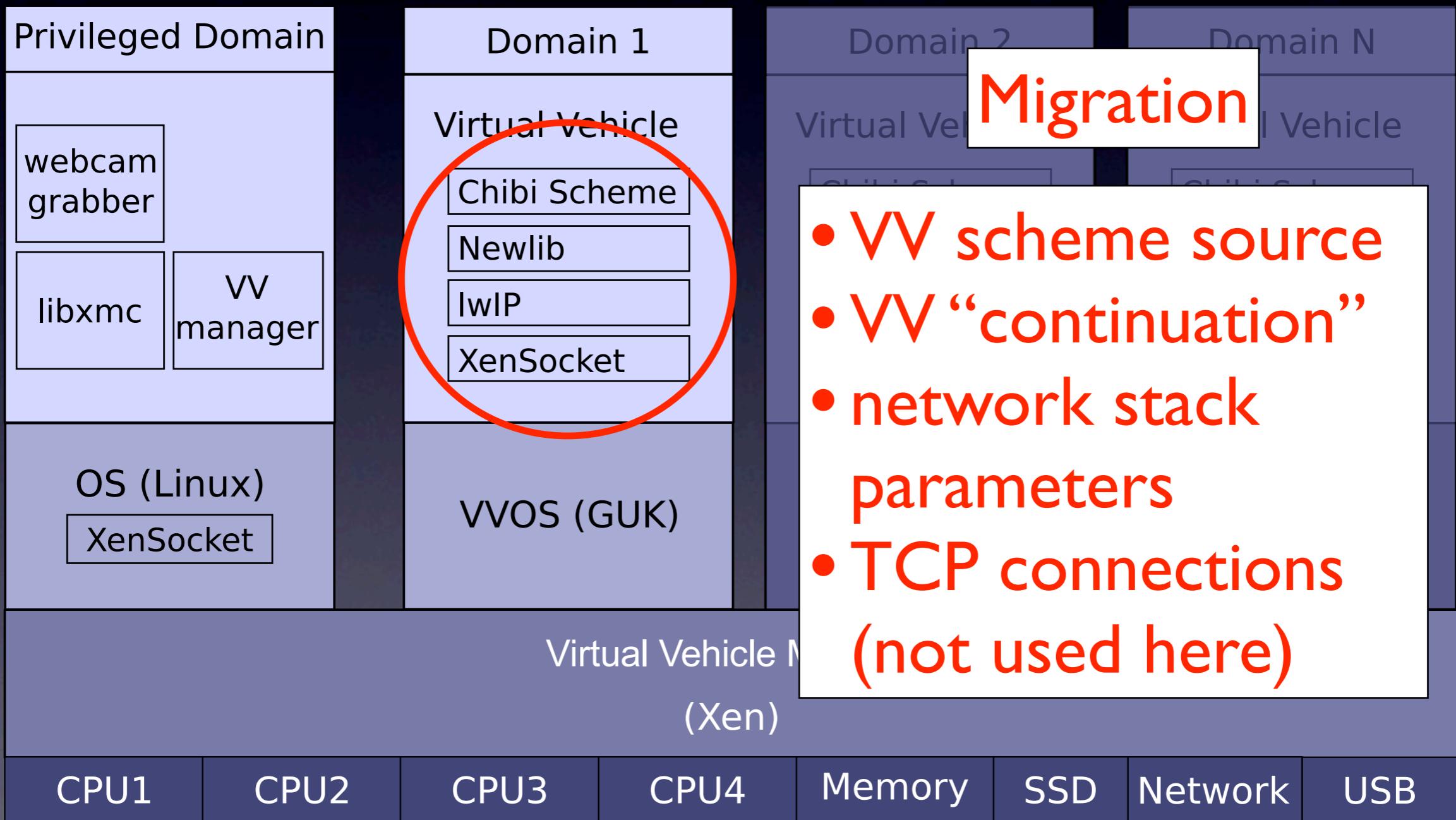
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3 VVs on 2 Servers

Virtual volumes are mapped to physical volumes on two servers.

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3 VVs on 2 Servers

flandolt@big-iron1: ~

```
xentop - 18:20:14 Xen 4.0.0-rc9
7 domains: 1 running, 5 blocked, 1 paused, 0 crashed, 0 dying, 0 shutdown
Mem: 3992300k total, 3787012k used, 205288k free CPUs: 4 @ 2000MHz
NAME STATE CPU(sec) CPU(%) MEM(k) MEM(%) MAXMEM(k) MAXMEM(%) V
Domain-0 ----r 86328 46.0 3741852 93.7 no limit n/a
tramp-1 --b--- 0 0.3 31744 0.8 32768 0.8
tramp-3 --b--- 0 16.1 31744 0.8 32768 0.8
tramp-4 --b--- 0 0.0 31744 0.8 32768 0.8
tramp-5 --b--- 0 0.0 31744 0.8 32768 0.8
tramp-6 --b--- 0 0.0 31744 0.8 32768 0.8
tramp-7 ----p- 0 0.0 31744 0.8 32768 0.8
```

Delay Networks vBds Mem VCPUs Repeat header Sort order Quit

flandolt@big-iron1: ~

```
top - 18:20:14 up 50 days, 2:38, 12 users, load average: 0.14, 0.06
Tasks: 190 total, 3 running, 184 sleeping, 3 stopped, 0 zombie
Cpu(s): 2.1%us, 1.6%sy, 0.0%ni, 96.0%id, 0.0%wa, 0.0%hi, 0.2%si
Mem: 3665672k total, 3588908k used, 76764k free, 315488k buff
Swap: 3903752k total, 0k used, 3903752k free, 1883756k cach
PID USER PR NI VIRT RES SHR S %CPU %MEM TIME+ COMMAND
6773 root 20 0 52656 11m 3136 S 8 0.3 0:00.25 xm
4311 root 20 0 231m 18m 2252 S 5 0.5 46:40.89 xend
28568 root 20 0 117m 9.9m 4220 S 5 0.3 135:42.45 Xorg
4302 root 20 0 8628 1132 624 R 4 0.0 1:16.80 xenstored
1531 flandolt 20 0 31300 1848 1484 S 1 0.1 0:03.26 bouboule
28909 flandolt 20 0 19212 1480 1072 R 1 0.0 0:59.00 top
```

flandolt@big-iron1: ~

flandolt@big-iron1: /home/rotty/src/guk-new/tramp

```
got line: Using config file "/tmp/trampd-cfg.sYnU2R".
got line: Started domain tramp-6 (id=199)
vm-pool: enqueued domain 199
Client 192.168.1.171:4098 accepted...
vm-pool: dequeued domain 196
Initiating state transfer with domain 196
vm-pool: creating new domain: name=tramp-7, ip=192.168.1.206
xm create -p /tmp/trampd-cfg.5FqDQ1
Waiting for domain 196 to become ready for state transfer
Copying state (3365 bytes) to domain 196...
Copying done.
Client 192.168.1.171:4098 done.
got line: main tool
got line: Using config File "/tmp/trampd-cfg.5FqDQ1".
got line: Started domain tramp-7 (id=200)
vm-pool: enqueued domain 200
```

flandolt@big-iron1: /home/rotty/src/guk-new/tramp

```
got line: Started domain tramp-4 (id=134)
vm-pool: enqueued domain 134
Client 127.0.0.1:38129 accepted...
vm-pool: dequeued domain 131
Initiating state transfer with domain 131
vm-pool: creating new domain: name=tramp-5, ip=192.168.1.204
xm create -p /tmp/trampd-cfg.II4gIR
Waiting for domain 131 to become ready for state transfer
Copying state (3298 bytes) to domain 131...
Copying done.
Client 127.0.0.1:38129 done.
got line: main tool
got line: Using config File "/tmp/trampd-cfg.II4gIR".
got line: Started domain tramp-5 (id=135)
vm-pool: enqueued domain 135
Client 192.168.1.171:4097 accepted...
vm-pool: dequeued domain 132
Initiating state transfer with domain 132
vm-pool: creating new domain: name=tramp-6, ip=192.168.1.205
xm create -p /tmp/trampd-cfg.MFJug0
Waiting for domain 132 to become ready for state transfer
Copying state (3440 bytes) to domain 132...
Copying done.
Client 192.168.1.171:4097 done.
```

flandolt@big-iron3: /home/rotty/src/guk-new/tramp

```
got line: Started domain tramp-4 (id=134)
vm-pool: enqueued domain 134
Client 127.0.0.1:38129 accepted...
vm-pool: dequeued domain 131
Initiating state transfer with domain 131
vm-pool: creating new domain: name=tramp-5, ip=192.168.1.204
xm create -p /tmp/trampd-cfg.II4gIR
Waiting for domain 131 to become ready for state transfer
Copying state (3298 bytes) to domain 131...
Copying done.
Client 127.0.0.1:38129 done.
got line: main tool
got line: Using config File "/tmp/trampd-cfg.II4gIR".
got line: Started domain tramp-5 (id=135)
vm-pool: enqueued domain 135
Client 192.168.1.171:4097 accepted...
vm-pool: dequeued domain 132
Initiating state transfer with domain 132
vm-pool: creating new domain: name=tramp-6, ip=192.168.1.205
xm create -p /tmp/trampd-cfg.MFJug0
Waiting for domain 132 to become ready for state transfer
Copying state (3440 bytes) to domain 132...
Copying done.
Client 192.168.1.171:4097 done.
```

flandolt@big-iron3: /home/rotty/src/guk-new/tramp

```
got line: Started domain tramp-4 (id=134)
vm-pool: enqueued domain 134
Client 127.0.0.1:38129 accepted...
vm-pool: dequeued domain 131
Initiating state transfer with domain 131
vm-pool: creating new domain: name=tramp-5, ip=192.168.1.204
xm create -p /tmp/trampd-cfg.II4gIR
Waiting for domain 131 to become ready for state transfer
Copying state (3298 bytes) to domain 131...
Copying done.
Client 127.0.0.1:38129 done.
got line: main tool
got line: Using config File "/tmp/trampd-cfg.II4gIR".
got line: Started domain tramp-5 (id=135)
vm-pool: enqueued domain 135
Client 192.168.1.171:4097 accepted...
vm-pool: dequeued domain 132
Initiating state transfer with domain 132
vm-pool: creating new domain: name=tramp-6, ip=192.168.1.205
xm create -p /tmp/trampd-cfg.MFJug0
Waiting for domain 132 to become ready for state transfer
Copying state (3440 bytes) to domain 132...
Copying done.
Client 192.168.1.171:4097 done.
```

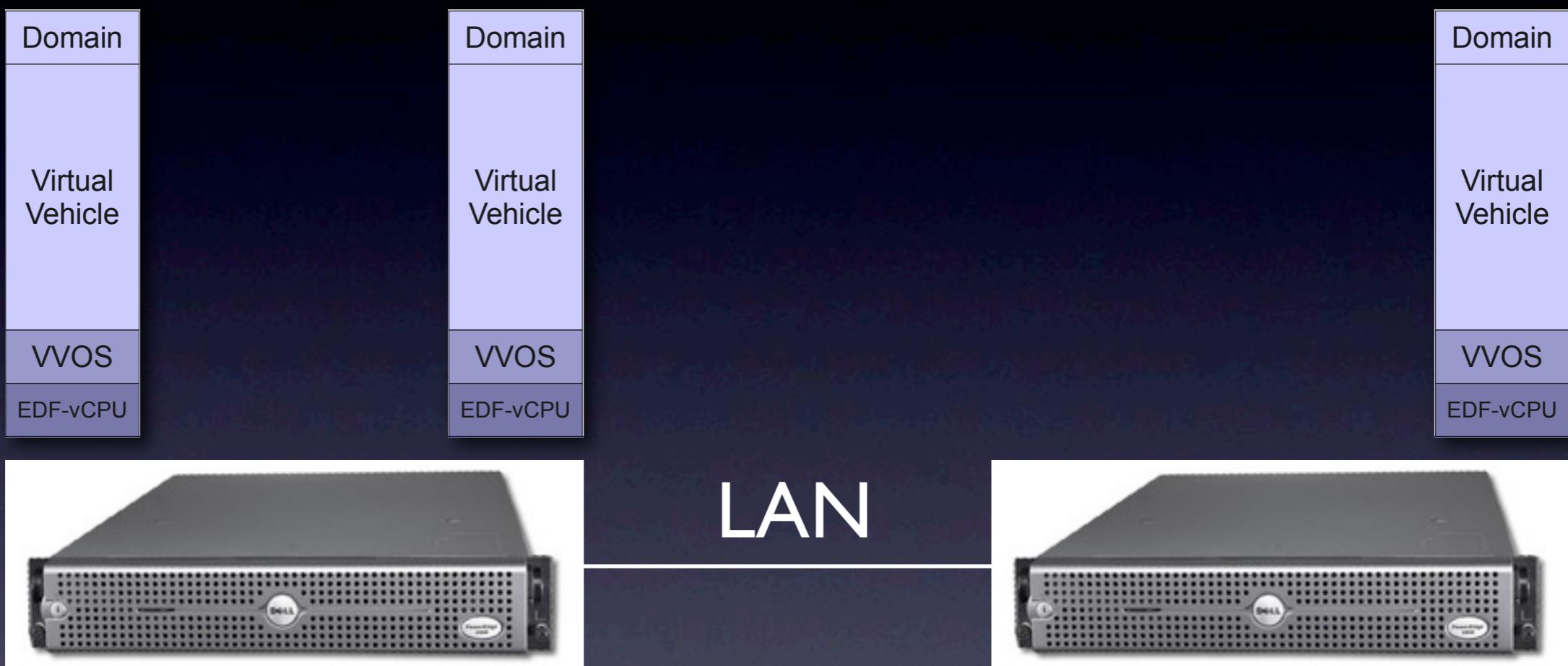
flandolt@big-iron3: /home/rotty/src/guk-new/tramp

```
got line: Started domain tramp-4 (id=134)
vm-pool: enqueued domain 134
Client 127.0.0.1:38129 accepted...
vm-pool: dequeued domain 131
Initiating state transfer with domain 131
vm-pool: creating new domain: name=tramp-5, ip=192.168.1.204
xm create -p /tmp/trampd-cfg.II4gIR
Waiting for domain 131 to become ready for state transfer
Copying state (3298 bytes) to domain 131...
Copying done.
Client 127.0.0.1:38129 done.
got line: main tool
got line: Using config File "/tmp/trampd-cfg.II4gIR".
got line: Started domain tramp-5 (id=135)
vm-pool: enqueued domain 135
Client 192.168.1.171:4097 accepted...
vm-pool: dequeued domain 132
Initiating state transfer with domain 132
vm-pool: creating new domain: name=tramp-6, ip=192.168.1.205
xm create -p /tmp/trampd-cfg.MFJug0
Waiting for domain 132 to become ready for state transfer
Copying state (3440 bytes) to domain 132...
Copying done.
Client 192.168.1.171:4097 done.
```

Migrating from machine 2 to 1

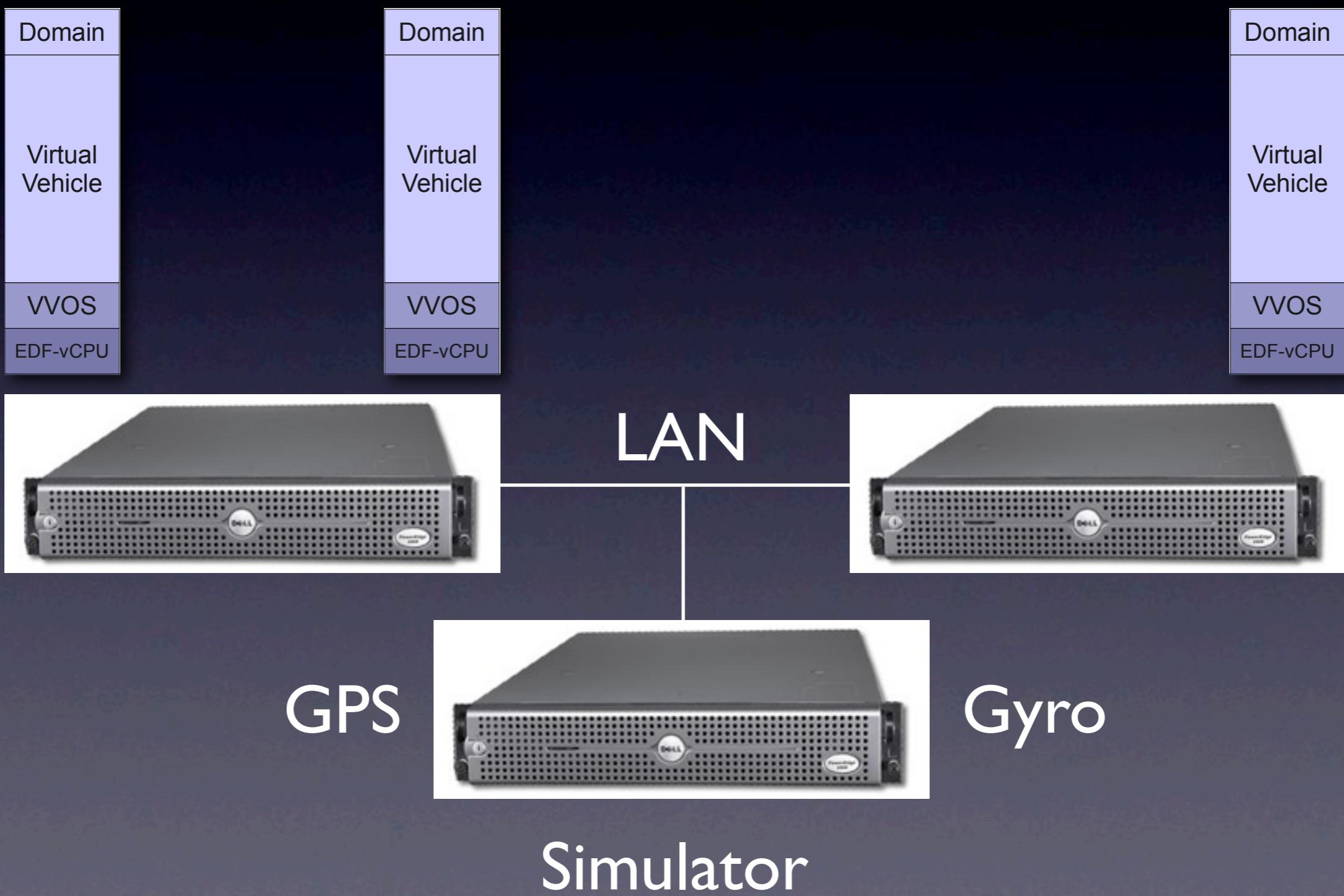
Future Work

(Simulating Motion, Flying Real Vehicles)



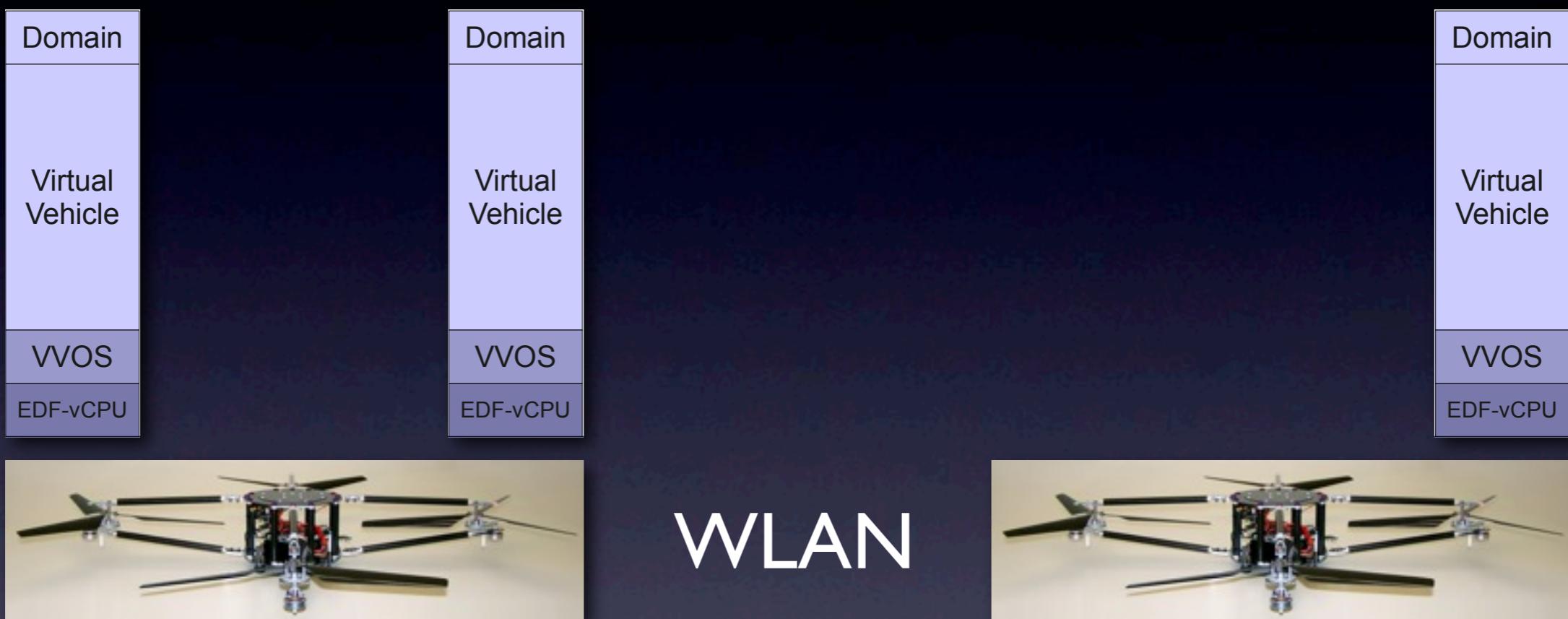
Future Work

(Simulating Motion, Flying Real Vehicles)



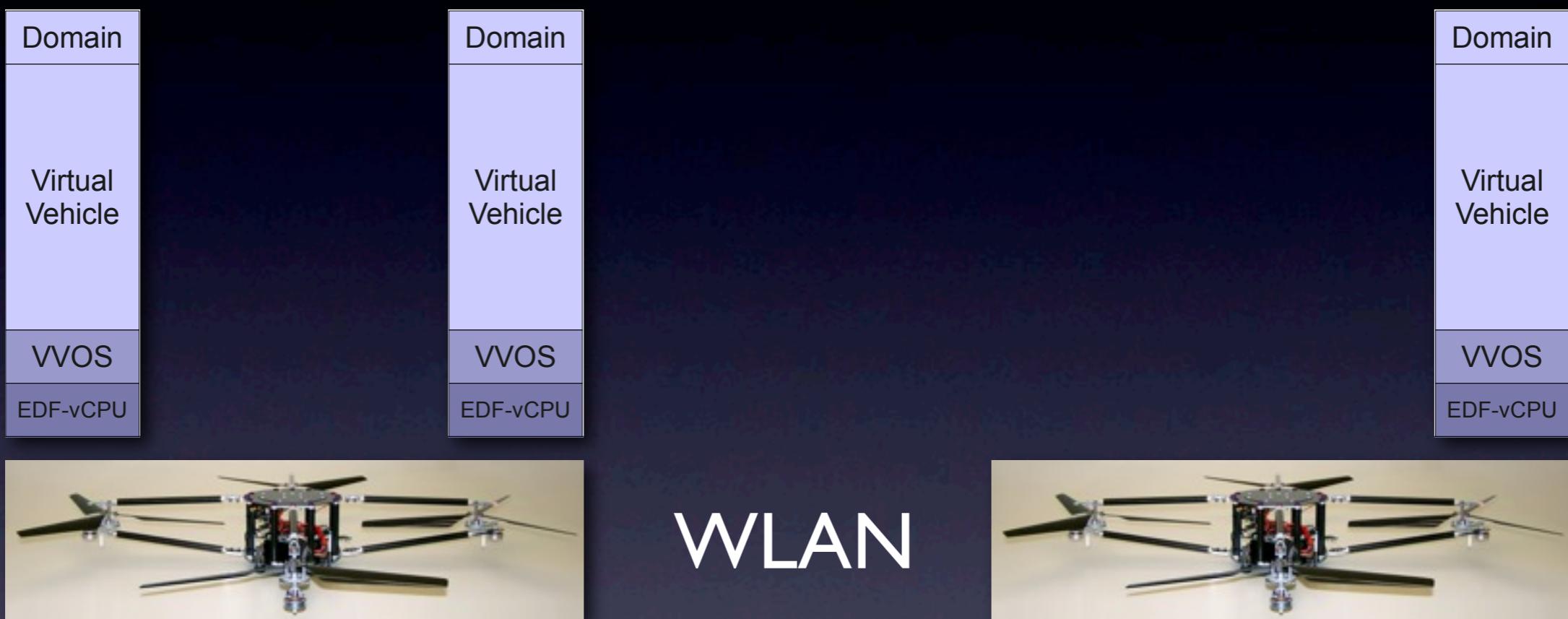
Future Work

(Simulating Motion, Flying Real Vehicles)



Future Work

(Simulating Motion, Flying Real Vehicles)

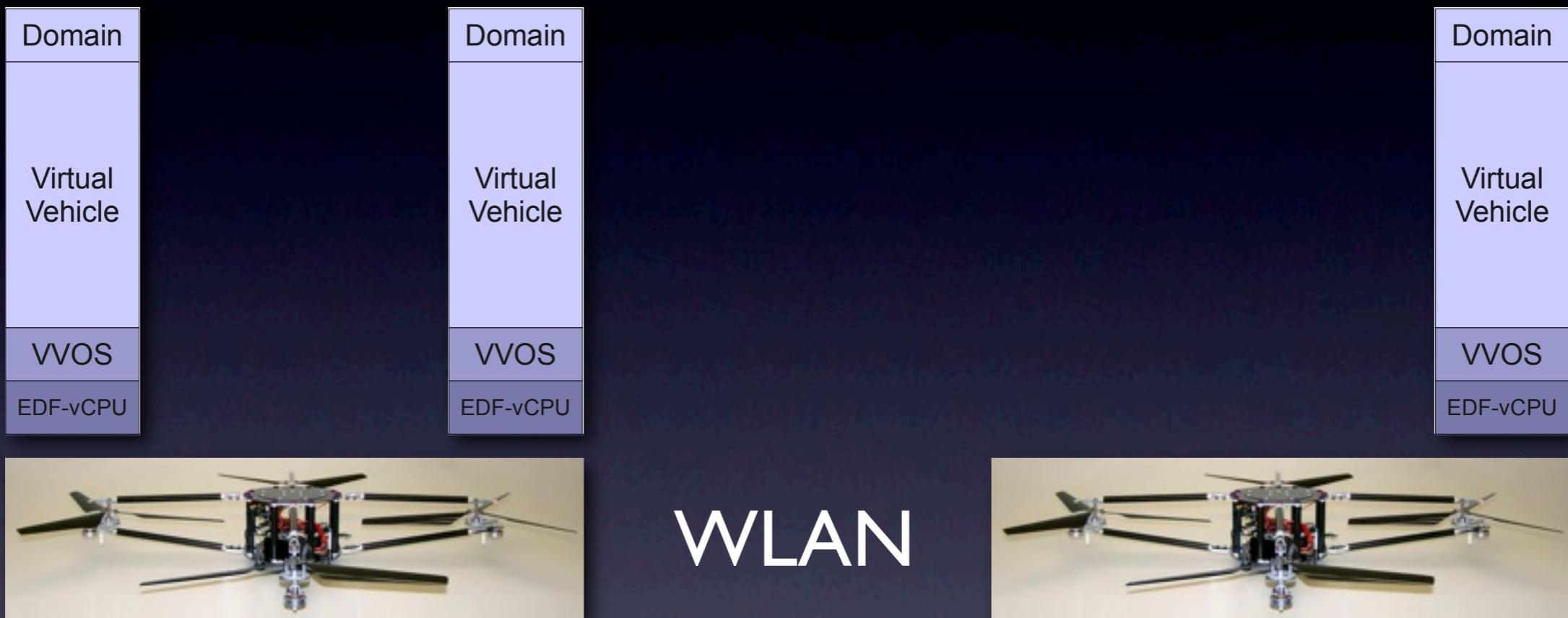


WLAN

- **read-only, scheduled real vehicle flight plans:**

Future Work

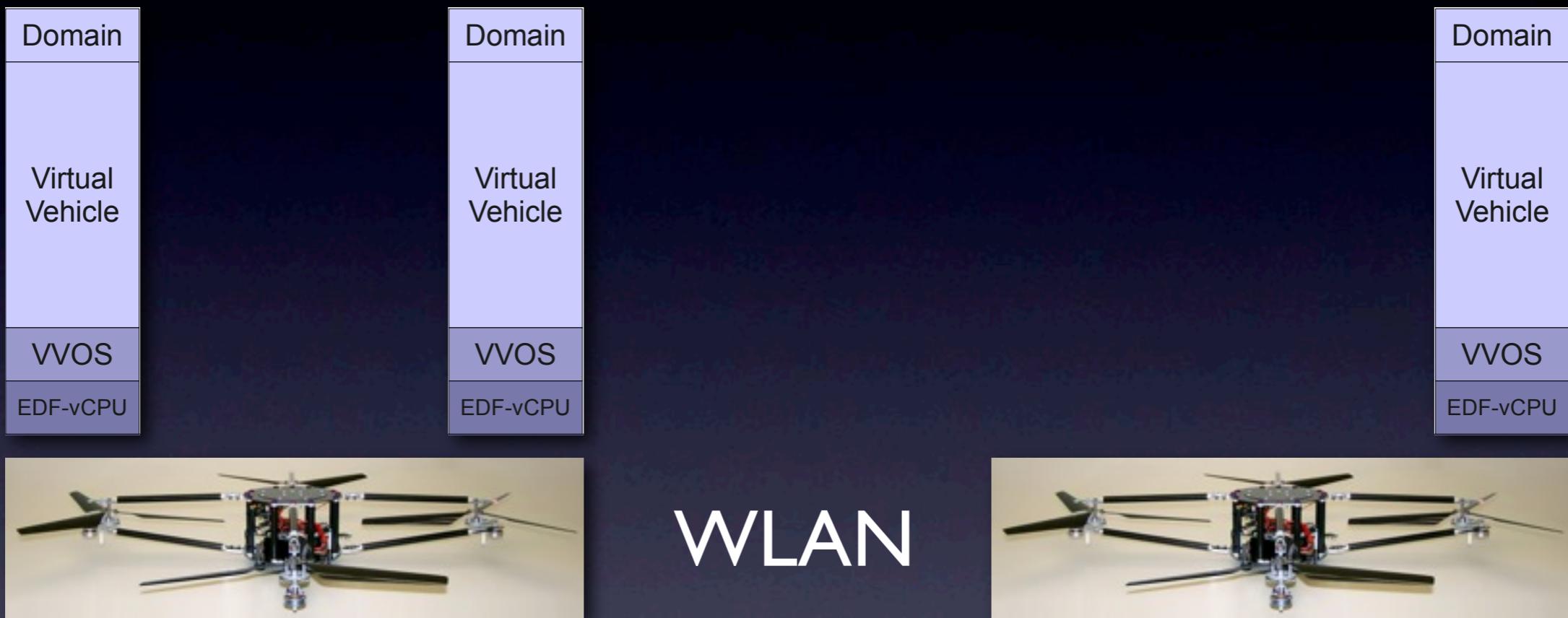
(Simulating Motion, Flying Real Vehicles)



- **read-only, scheduled real vehicle flight plans:**
 - ▶ **virtual-to-real** vehicle allocation problem

Future Work

(Simulating Motion, Flying Real Vehicles)



- **read-only**, scheduled real vehicle flight plans:
 - ▶ **virtual-to-real** vehicle allocation problem
- **read-write**, on demand real vehicle flight plans:

Future Work

(Simulating Motion, Flying Real Vehicles)



WLAN

- **read-only**, scheduled real vehicle flight plans:
 - ▶ **virtual-to-real** vehicle allocation problem
- **read-write**, on demand real vehicle flight plans:
 - ▶ **real-to-virtual** vehicle allocation problem



Thank you

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