Requirements:

Data Generator:
- We want to generate sensor data to be sent and stored.
- We should be able to generate random data or use a source CSV file

Object System:
- We want to make a generic system that can emit & receive data from multiple objects (e.g. car + toaster)
- Objects have a set of sensors with different data types and different send frequencies

Sensor System:
- We want to dynamically download and cache sensor information for a given object.
- The system will only download ~~new~~ sensor information.
- Each sensor will contain relevant data type and frequency info, along with identifiers.
- Additionally, sensors will come w/ transformation data that will let us convert raw voltage to an appropriate unit.

Channel System:
- Data for a given object will be sent through a channel. For example, a car will receive sensor data over CAN. Sensors will have a "channel decoding ID" that will help them get the appropriate data.

Transceiver System:
- We will have a generic UDP/TCP system that will give an object an interface to start telemetry sessions, receive sensor information, and receive messages (e.g. display a remote message on a driver's dash). The interface will also let objects send sensor data.

VFDCP:
- "Variable Frequency Data Compression Protocol".
- We will use UDP to send data at a variable frequency in a compressed format. Additionally, we will only send data if it has changed from it's previous value by some ϵ scaled by the sensor's min and max value.

Storage Sys.:
- We want to store (flash in HW terminology) sensor information so we don't waste "RTE" data fetching.
- We also want to store a local copy of a session's telemetry data for a "source of truth" as sending over UDP will cause loss, we can fetch full data from the HW.

VFDCP:

Definitions:

We have a set of sensors $S_1, S_2, \ldots, S_n$

Each sensor S_i has:
- A frequency f_i
- An id s_i
- A max value M_i
- A min value m_i

The function to determine a "substantial change" in the present value a sensor worthy of transmission is:

```
f(currentValue, prevValue, min, max, ε):
  range = the absolute value of the range between min, max
  minChange = range * ε
  if(|currentValue - prevValue| > minChange)
    worth sending
  else not worth sending
```

A "frame" is a set of sensor data that will be sent at a given timestep.

The frame will have the following structure:

```
{
  sensor_ids;
  sensor_values;
}
```

The sensor_ids are an ordered list of small identifiers that allow us to decode an ordered list of unevenly sized sensor values inside sensor values.

The frame will only contain sensor values if the sensor's frequency lines up with the given timestep AND the sensor's value has significantly changed.

VFDCP Goals:
- Reduce cost of data transmission by only sending data that we need.
- Tradeoff reliability for speed of packets.

We decode VFDCP frames with a copy of the sensor list on the receiver.

VFDCP tradeoffs and potential problems:

- Complicated...
- Reliability - Sending over UDP will cause loss and potentially out of order data.
- Generic typing - all in C will make this tricky, but for the simulator, we have C++, should try to use C syntax.

VFDCP benefits:

- Huge cost savings in the average case.
- Efficient.

Let's take the SR-21 FSAE vehicle for example:

40+ sensors ($S_1, S_2, \ldots, S_{90}$), each with a different freq. f_i, each with different value sizes (double, float, byte).

Without VFDCP:

- We have a max frequency $f_{max} = 60$
- We have a min frequency $f_{min} = 1$
- We send data at 60 Hz with the most recent value of each sensor
- Our data per second is:

Average

$$\left(60\tfrac{1}{s} \times 8 \text{ bytes}\right) + \left(60\tfrac{1}{s} \times 40 \text{ sensors} \times 4 \text{ bytes/sensor}\right)$$

UDP header — Amount of sensor data sent

$$= 480 \text{ Bps} + 9{,}600 \text{ Bps} = 10{,}080 \text{ Bps}$$

Our average session is 20 minutes:

$$= 10{,}080 \text{ Bps} \times 60 \text{ s/min} \times 20 \text{ min} = 12{,}096{,}000 \text{ bps}$$
$$= 11.54 \text{ MB}$$

We have about 200 hours of testing per season (600 sessions):

$$\approxeq 6.76 \text{ GB}$$

Our cost per MB is ~$0.03:

Cost per season = $207.72 → Yikes! We don't have this.

There was extra overhead for identifying sensors, which would bring the total to ~$300. (Extra data sent specifying sensor:value).

With VFDCP:

We have an average frequency of 5 Hz.

Many sensor values don't change often, let's assume, that on average, only 75% of sensor values need to be sent at their respective time range.

Doing the above calculations again:

Data per second:

$(60\frac{1}{s} \times 8 \text{ bytes}) + (60\frac{1}{s} \times 5 \text{ sensors} \times 4 \text{ bytes/sensor})$ ← Average number of values sent

UDP header

constraint

$+ (60\frac{1}{s} \times 10 \text{ bytes}) \times 0.75$ ← Sensor IDs (decode information) ↓ 1 byte per sensor (255 possible sensors)

$= (480 \text{ Bps} + 1{,}200 \text{ Bps} + 600 \text{ Bps}) \cdot \frac{3}{4} = 1710 \text{ Bps}$

Data per season:

$\cong 1.14$ GB

Cost per season:

$\cong \$35.22$ → Not bad, still expensive

Net improvement = $1 - (\$46.97/\$300) \approx 89\%$ ↗ Nice!

↳ Probably gonna be ~80% with overhead of fetching sensors

One more optimization...

We need to deal with byte padding.

```
struct x {
  char ci
  int  bi
};
```

This struct has 5 bytes of data, but 8 bytes of allocated memory! This is because data is stored in words (4 bytes).

The structure in memory looks like cXXXiiii. (Padding)

We have wasted data! How do we solve this?

Big endian

Approach 1:

We have a constraint of a library that destructures structs, not bytes in Python. Meaning we need to view data in words.

Our receiver can currently destructure any data inside words.

For example, say we have a = int, b = short, c = char

Best case: aaaabbcX

Worst case: bbXXaaaacXXX

Our receiver can handle both cases.

Intuitively, we can minimize padding by ordering data largest → smallest. We have a solution, at maximum, we will have 3 bytes of padding. Nice!

Approach 2:

We can send the exact number of bytes our data fits into by using a byte array. We will have to create our own byte parser in the python server.

This might make the C/C++ code easier though.

Is it worth the extra effort to save 3 bytes? Maybe at scale, but the dev time is not worth it right now.

Design

Primary Systems:
- Data Generator
- Object/Sensor System
- Transceiver System
- Channel System
- VFDCP System
- Storage System

System breakdown:

Data Generator:
- Sensor sync (need to know which sensors to generate data for)
- Random data generation
- Data gen from file
- Publishing to a channel

Channel System:
- Maintain current & previous values for sensors
- Allow subscription to particular sensor data
- Allow read for a particular sensor using an id

Object System:
- An object interacts with sensors, channels, and the transceiver and acts as a mediator.
- Templates to support an object like a car

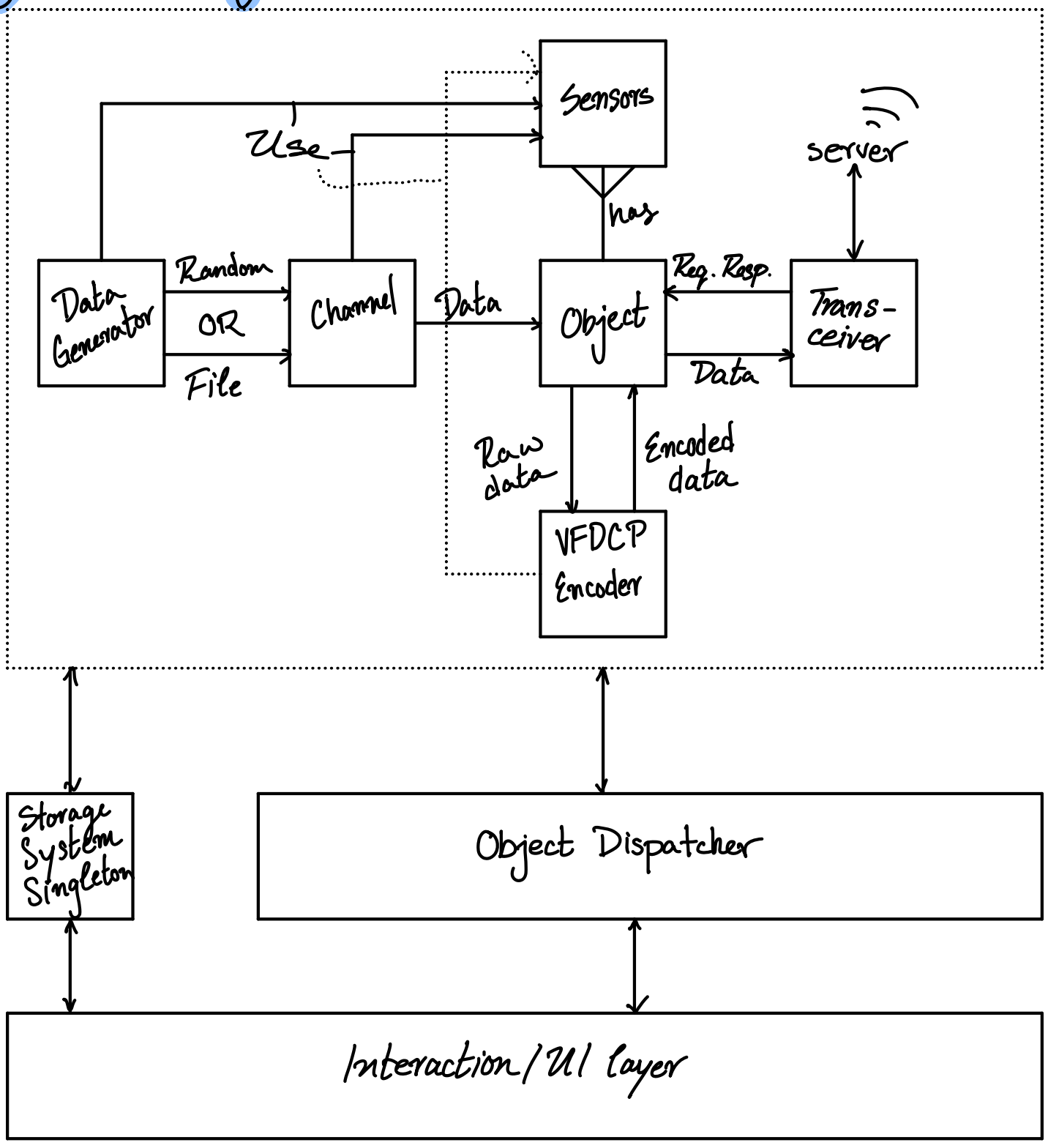
Sensor System:
- Objects retrieve their sensors through the transceiver and propagate them where needed
- Effectively stores and manages sensors.
- Reconciles updated sensors
- Stores sensor information locally using storage system

Storage System:
- Stores sensor information for a particular object via serial number
- Stores session data (object telemetry turned on then off) in csv format.

Transceiver System:
- Receives/requests server data, including starting a session, asking for sensors/sensor diff, and other messages.
- Transmits sensor data with VFDCP over UDP

VFDCP System:
- Acts as an encoder by receiving current and previous sensor information, along w/ all sensor information.
- Return encoded byte array to be sent out.

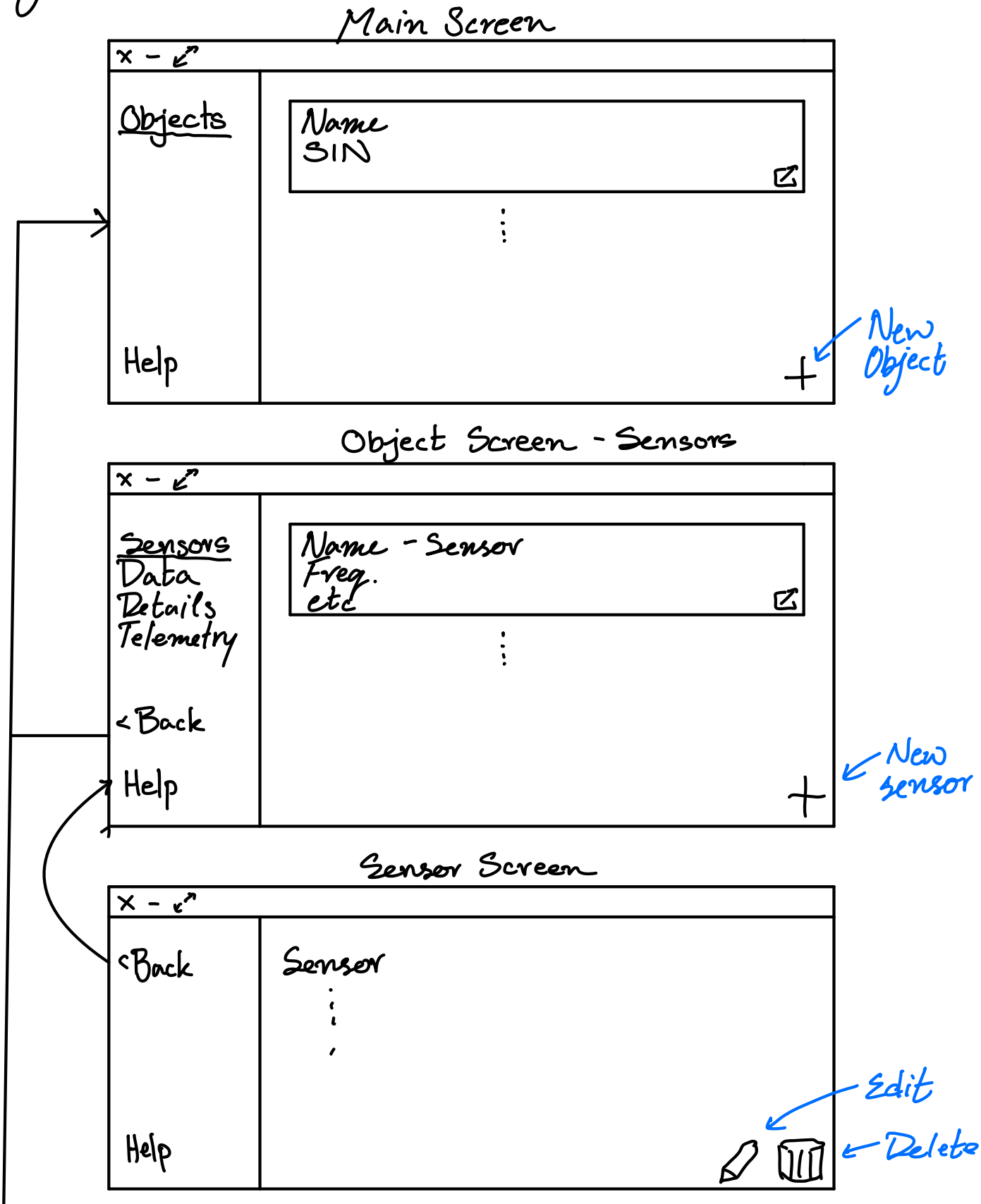
High-level Design

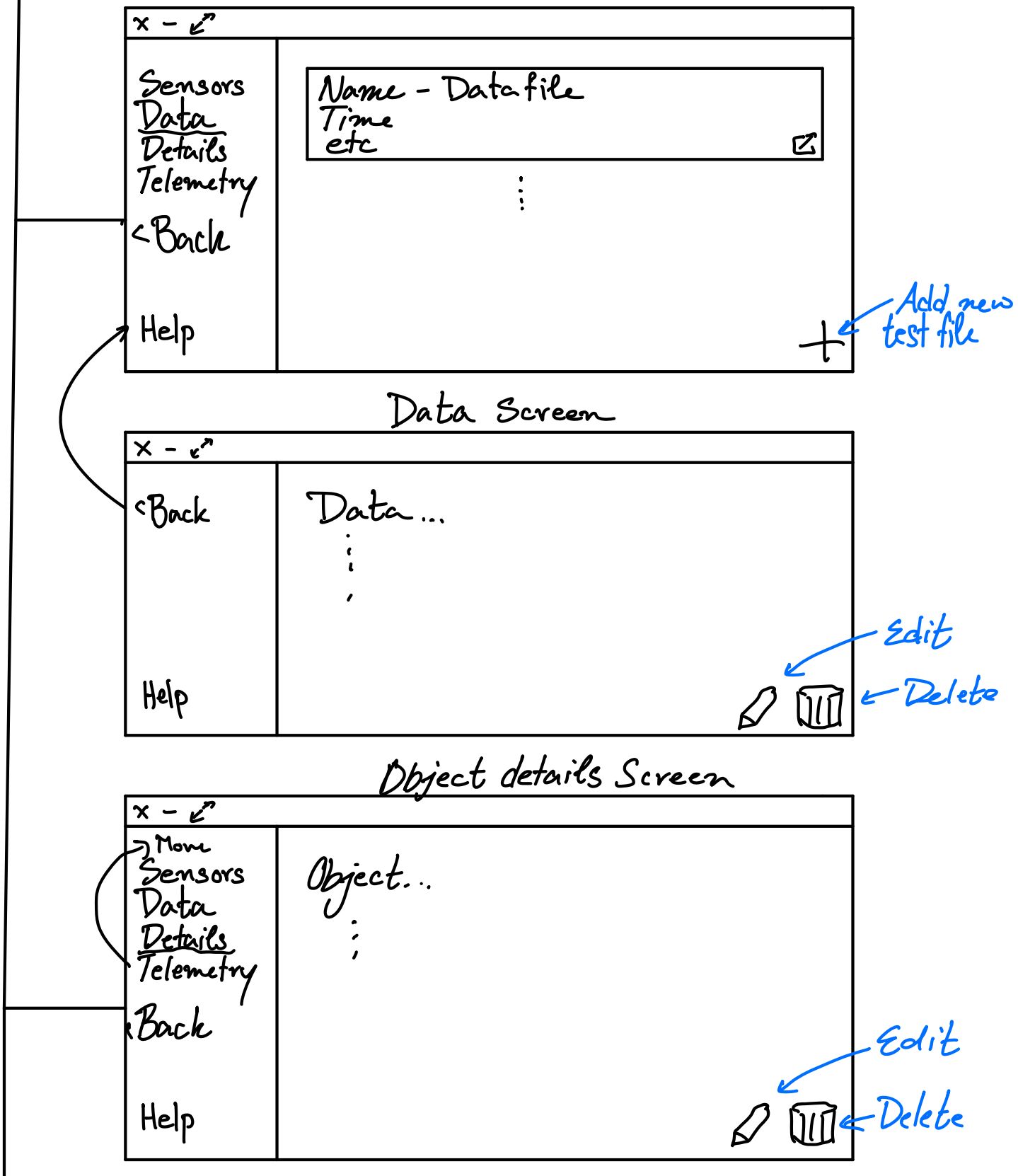


Interaction / UI Layer

We want to interact with the system in an easy to use matter. We also want to run multiple objects simultaneously, the system as a whole is a multiobject telemetry simulator.

Using Qt, we can make some UI:

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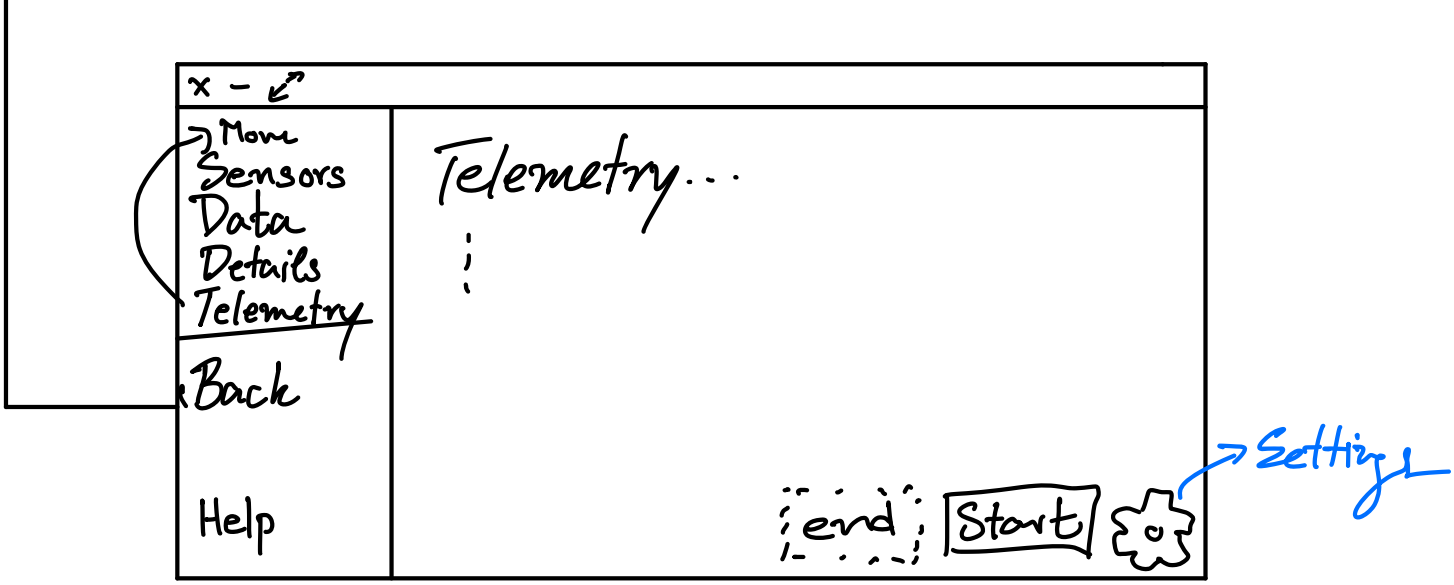


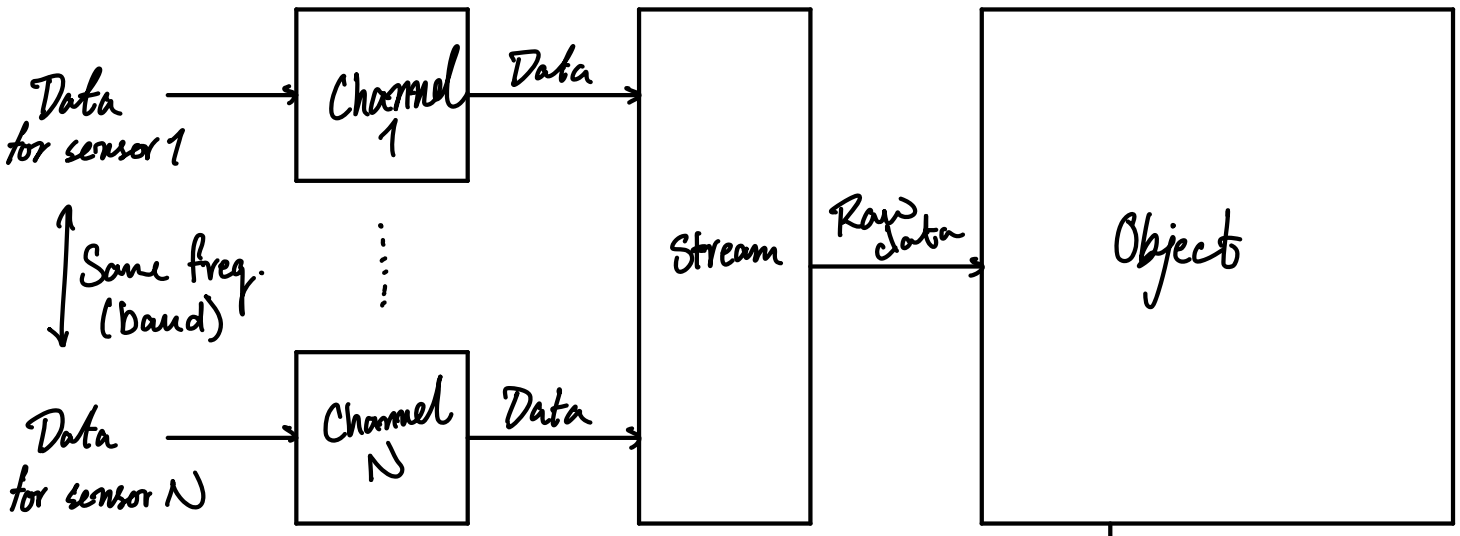
UI is meh, proper mockups should be made. Needs to be easy and convenient to use.

I realized we need to fetch objects from our API, we will need a higher level receiver to get top level data.

In the end, we don't want to store anything locally, all should be stored on the server. For testing purposes, we will have local stores of data.

Low-Level Design - Base functionality to start with.

Each channel has a strategy to get data & its own data type



Channel values update at different frequencies, each have different data types.

Each channel needs to be created with unknown types & data.
→ Factory Pattern (kinda, just more making types)

Each channel must implement a strategy to read data

→ Random
→ From file
→ Others (future)

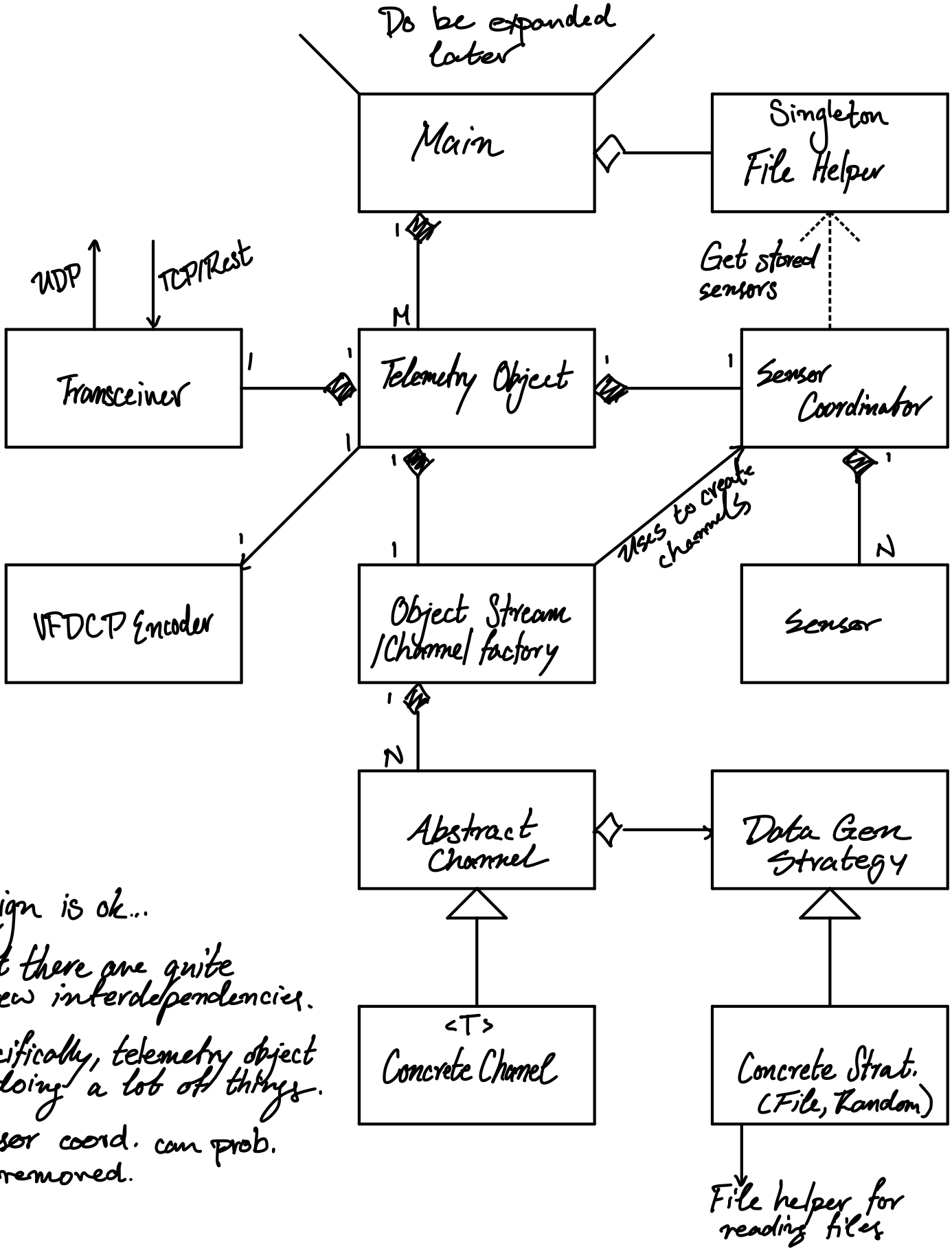
Strategy Pattern!

The object observes the stream, but there is only one, no need for observer pattern.

Template method might be useful for constructing data, but seems overkill.

Adapter might be helpful for incompatible datagen strategies to the context, but doesn't seem necessary.

UML-ish



Design is ok...

But there are quite a few interdependencies.

Specifically, telemetry object is doing a lot of things.

Sensor coord. can prob. be removed.

Let's design the flow

→ Main creates a new object to start a telemetry session for.

→ Object makes request to server to start a new telemetry session

→ On failure or success, notify main & destroy/persist

→ On session start:

  → Check if we have sensor data stored

    → If yes, load the sensors, then request data from the server w/ the most recent update time of all sensors, then only get the sensors that are updated.

  → If no sensors, fetch all from server

  → Store the updated sensor list.

→ After synchronizing sensor info, we create a stream and generate all channels for each sensor w/ appropriate types & frequencies.

→ Channels start generating data and begin sending them through the stream

→ The stream publishes data to the object at the max frequency of all channels.

→ The object determines, at this timestep, which sensors should be sent?

→ The list of abstract data types for this timestep, along w/ sensor id & type information is sent to the encoder which returns a byte array.

→ The object publishes the byte array to the transceiver to be sent off to the server via UDP.

→ The stream ends, terminate the stream, but keep the object & sensor around in case we want another session

→ Terminate application

We want to support multiple objects streaming at the same time. Since each object will basically have an infinite loop while streaming, the object will block.

We should create each telemetry session on a new thread so multiple objects can run uninterrupted.

Additionally, each sensor channel reads data asynchronously. We don't want each channel to update the stream one by one, otherwise frequencies will not be correct. The stream may have a buffer that stores the present & most recent data value, each channel may modify the buffer w/ a mutex This seems like a ton of overhead at scale, but each channel needs to run async..., else we might block waiting for data, especially reading from a file.

Could use std::async for running these channels, or have stream iterate through channels & only get them to generate new values on read.

On the car, CAN runs on a fixed baud, but each sensor updates at a different. We can write to CAN(stream) from a channel at the specified sensor frequency.

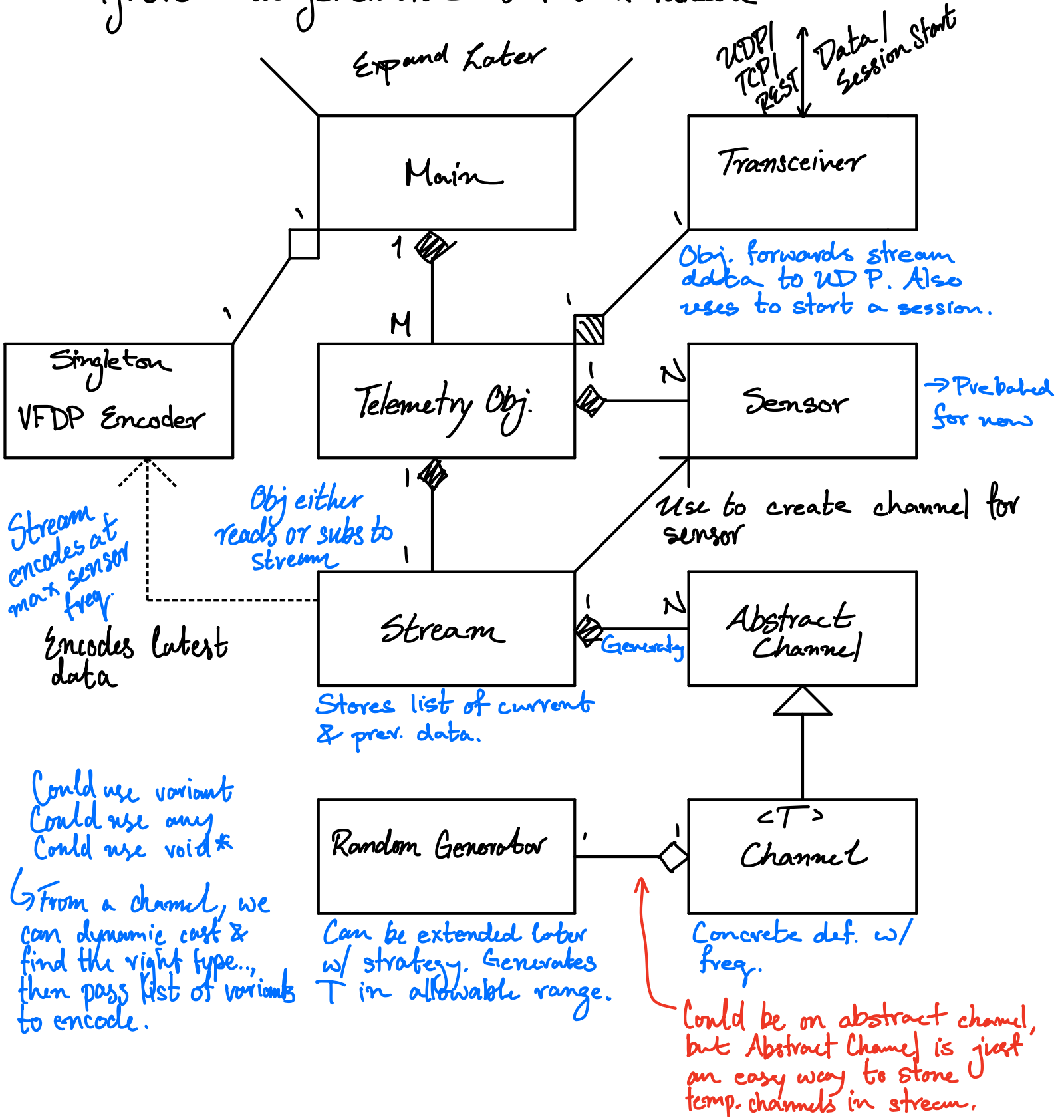
Yikes. We don't want to spawn hundreds of threads... But how do we get a channel to generate data at the right frequency? We could have the stream explicitely read each channel & pass a timestamp, if the channel's freq. lines up, we can update the value → no threads.

Let's make the stream responsible for giving us the data we need right now. Not technically how the hardware actually works, but reduces the complexity. We could consider it as the reading module.

Keep it simple, stupid

Let's get something working...

- → Ignore file system (no storing of data)
- → Ignore fetching sensors (just use testing)
- → Ignore data generation other than random



Ok..., I think we can make something work. Details will emerge, come back & draw out implementation.

Frequency Forward Data Transmission

We have some constraints:
- We can run at a max tick rate of 1000 Hz (1 ms)
- Some sensor frequencies don't divide evenly (e.g. $1000/3 = 333.\overline{33}$)

We need to find a way to decide when a sensor should be appended to our send buffer AND when to actually send the buffer.

Example:

We have 4 sensors - A, B, C, D

Each sensor has a different frequency:

A: 5 Hz, B: 4 Hz, C: 3 Hz, D: 1 Hz

With a continuous timestep

$$\text{Send?} = \left(\text{timestamp} \,/\, \frac{\text{Max.f}}{\text{Min.f}}\right) == \emptyset$$

Ok... but our timesteps are discrete:

$$\text{Send?} = \left(\text{timestamp} \,\%\, \frac{\text{Max.f}}{\text{Min.f}}\right) == \emptyset$$

This would only work for all Min.f that divides evenly into Max.f, and we run the timestamp at max.f.

At 1000 Hz, we could send data when in lines up:

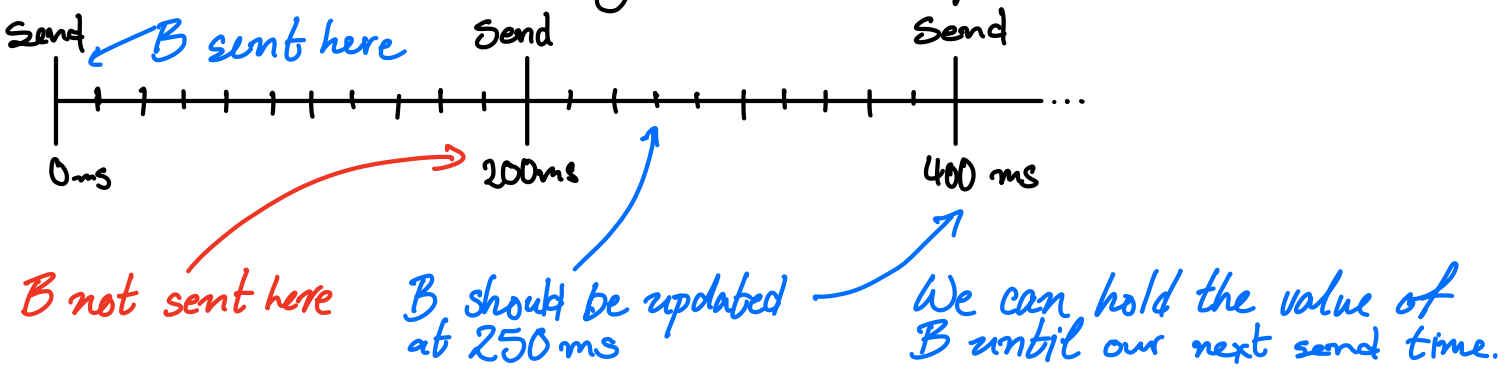
$$\text{Send?} = (\text{timestamp} \,\%\, \lfloor 1000/\text{freq}. \rfloor)$$

But, we just significantly increased our data transmission costs, and the send frequency is much higher.

We only want to send data at the highest sensor freq.

How? Let's think of our "send times" as intervals running at the highest sensor frequency, while running our timestamp() at 1000 Hz.

For example, suppose our highest sensor frequency is 5 Hz.



Suppose we have another sensor B, with frequency 4 Hz.

Viola! We only send data at our max frequency.

We basically queue up values we want to send until the next "send time".

Pseudocode:

```
Create a array Q
Timestamp t = 0
Every 1 ms:
  For each sensor s:
    divisor = round(1000/frequency of s)   # Hz
    If t % divisor == 0:
      Push current value of s to Q
  min_divisor = round(1000/max frequency of sensors)
  If t % min_divisor == 0:
    Send values in Q, clear Q
```

Storage

For now, let's store sensor data in txt csv format.

Each thing will have:

- Exactly one file with sensors for the thing
- Many files with telemetry session data for each thing

In the future, we will store sensor data in binary format to reduce size and emulate how hardware does it.

The sensor file format will be:

name, id , type, frequency, channel_id, u_calib, l_calib, \
u_bound, l_bound u_ → upper, l_ → lower

With following rows corresponding to values/sensor instances.

NOTE: Sensor names are guaranteed to be unique.

The name of the file will be thingID_sensors.txt

The telemetry session data format will be:

timestamp, [sensor name 1], [sensor name 2], ...

Following rows will provide sensor data at each timestep

We do not use sensor ids as sensor names are unique, why not use the sensor name as the id? Because that would break VFDCP. Also, we want sensor names since data on hardware is stored on an SD card, ids are not human readable!

The filename will be thingID_date_data.txt

For now, we will use thing's name for ID as we have not synced with the database.

Sensor Diff

Since we want to keep our data costs small, we don't fetch sensors from the database on every startup.

If we have sensors stored on disk, we don't need to fetch ALL sensors, just those that changed, then update disk.

If we have no sensors stored, we can fetch all sensors, then store.

For example

Hardware		Database	
Sensor	Last Update	Sensor	Last Update
A	1	× A	4
B	2	B	2
C	3	× C	5
		× D	6

We see that A and C need to be synchronized, we also see there is a new sensor D.

How can we get A, C, D? We can use the largest last update value on the hardware!

Pseudocode: (On server)

```
Largest_last_update -> sent from hardware
Create an empty list of sensors S
For every sensor s in the database for a thing:
  If s.last_update > largest_last_update:
    Append s to S
Send S back to the hardware.
```

Pseudocode: (Hardware)

```
S = read sensors from disk
L = most recent update time from S
If no sensors:
  S = Fetch all sensors from server
else:
  S' = Fetch sensor diff with L for the thing
  S = Replace all s in S with s' in S' if matching ids,
      append all s' not in S
Write S to disk
```