

**The go with the (vanadium redox) flow  
EESAT 2004 Presentation**

Dr. John M. Hawkins  
Telepower Australia  
2/71 Rushdale St  
Knoxfield VIC 3180

[telepower@telepower.com.au](mailto:telepower@telepower.com.au)

[www.telepower.com.au](http://www.telepower.com.au)

# The go with the (vanadium-redox) flow

*or Subtitle*

*To Go with the Flow (or not)*

**John M. Hawkins**

Telepower Australia

Telepower Australia

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Flow batteries were the flavour of the month a few years ago, but the commercialisation of virtually all flow batteries has stalled.

In the case of the vanadium-redox technology outside Japan, lack of progress has more to do with speculative share market characteristics rather than any particular technical impediment. I am happy to take questions on this aspect later, but for now, I want to talk about technical aspects of the vanadium-redox technology itself, not talk about the technicals of the corporate mess behind the technology.

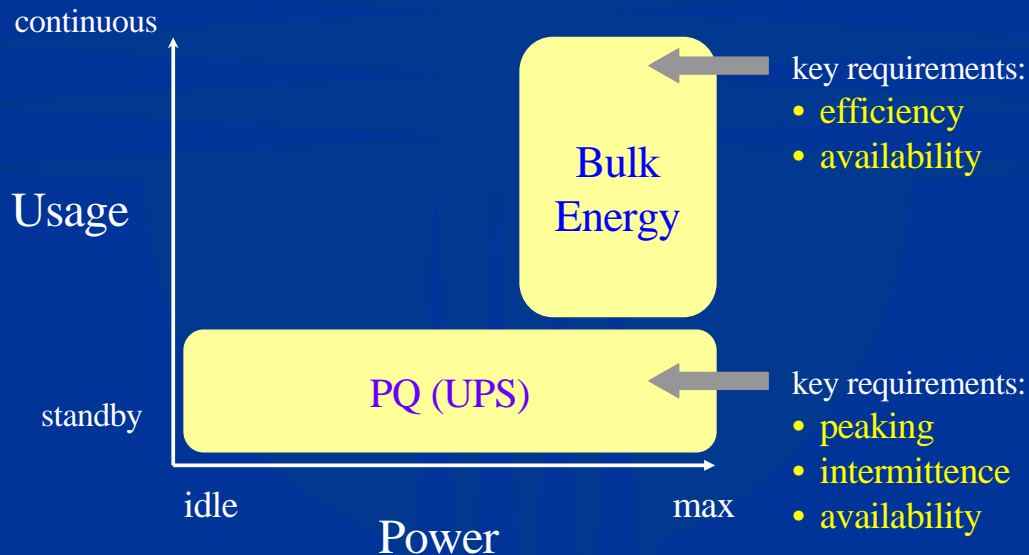
# Flow Batteries

- **Technology outside User experience**
- **What you need to know?**
  - Technical design options
  - Performance compromises
  - Operational obligations
- **Generic technical aspects**
  - Focus on Vanadium Redox (VRB)

Generally, flow battery technology is outside end user experience. In terms of batteries as large energy storage elements, the End-user's are probably, at best, limited to some sort of experience with lead-acid or NiCd batteries. While I am going to talk about the vanadium redox technology specifically, please recognise that much of the technical and engineering aspects of flow batteries are generic.

Where to start? There is a lot to know about flow batteries. As a system, a flow battery is a complex beast. Perhaps the best way to start this is to assume that the End-user will only adopt a flow battery if it meets application requirements.

# Major applications



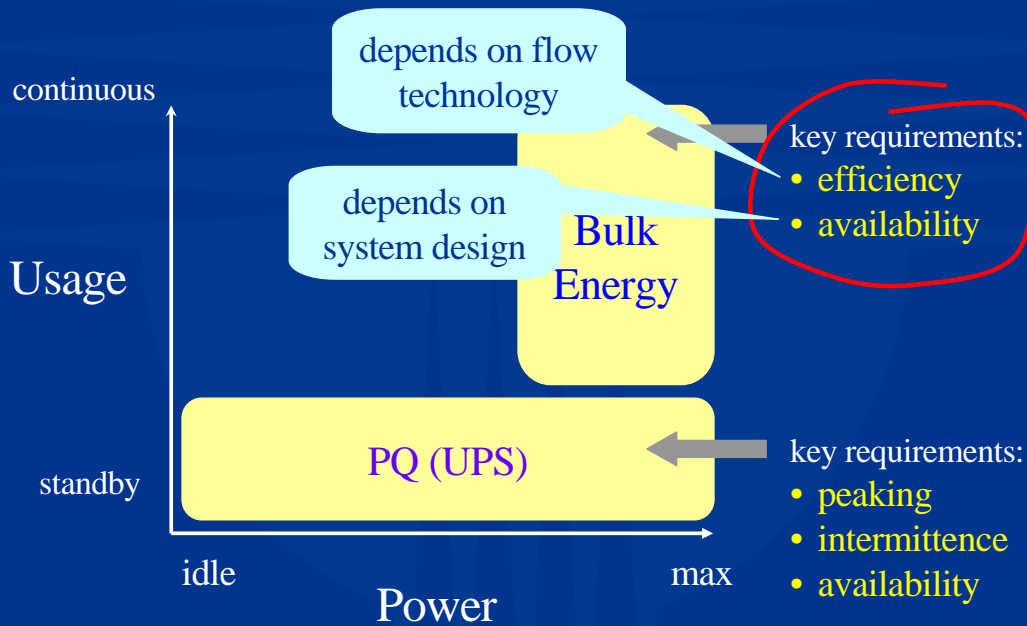
With a bit of license, we can represent the functional purpose of energy storage into areas related to system usage.

We can identify key requirements for each area.

For large bulk energy, such as load-leveling and arbitrage, we need storage with the characteristics of efficiency and availability.

For UPS and PQ type usage, efficiency is not as important as needing the storage to have peaking and the ability to operate with a high degree of intermittence, and of course, for UPS purposes the overriding requirement of very high availability.

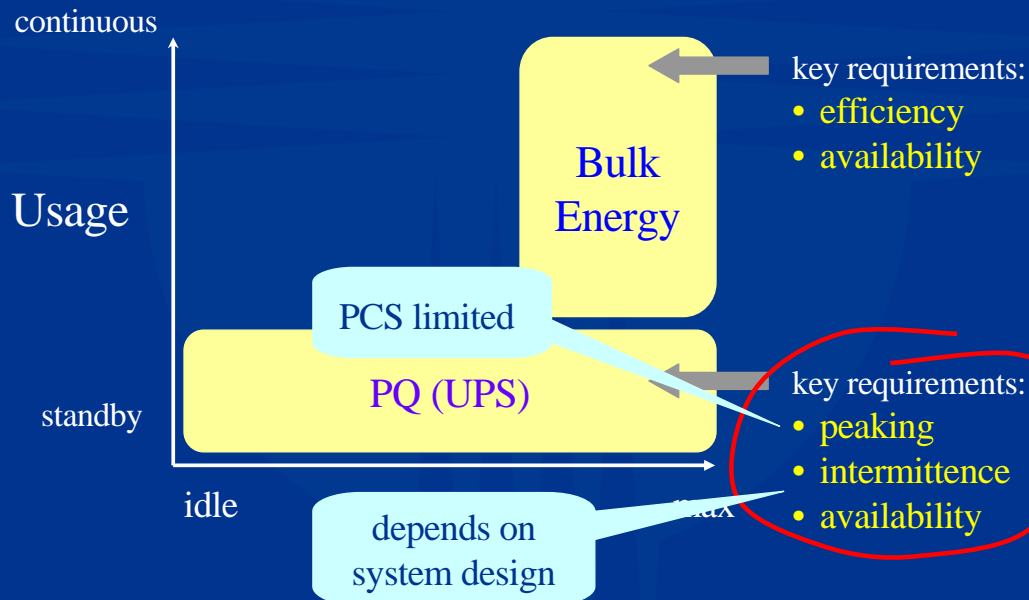
# Major applications



Now, if we overlay flow batteries onto this.

For bulk energy, efficiency is directly dependant on the flow technology and availability is very dependent on flow system design. That is, how we engineer the link and control between power and energy in the flow system. For example, for load leveling, we have to coincide the demand with the state of charge of the electrolyte.

# Major applications



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And for PQ type applications.

The peaking characteristic is generally limited by the Power conversion equipment, not the flow battery chemistry. In the case of the vanadium-redox, over-current peaking characteristic is good, but not that much different to virtually any battery. It is the input range and peak power capability of the power conversion device which is the functional determinant.

And for flow batteries, particularly the vanadium-redox, the ability to operate in intermittent mode, and display a very high level of availability is very dependant on the topology of the system.

Let's look at why?

# The go with the (vanadium-redox) flow

*Vanadium redox:-*



*Features:*

- Vanadium is sole active species
- Single (liquid) phase
- Energy is in electrolyte, not electrodes

*Limitations:*

- EMF *ca* 1.25V
- Energy Density *ca* 15-25 Wh/l
- Stability of V ions

Concentration  
dependent

The vanadium-redox technology is elegant (and) unique in that it is a single element redox couple, operating on the four valence states of vanadium. Its elegance is both its advantage and its Achilles' heel.

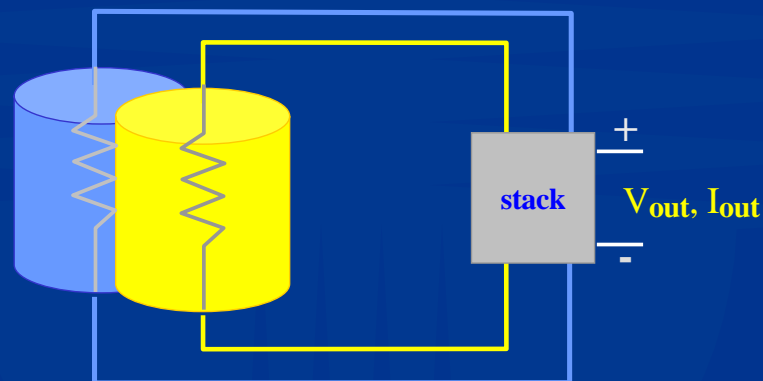
The single element, single phase system delivers chemical advantages that ultimately mean there is true decoupling of the power-energy nexus. The bang is only in the electrolyte, and this is its single biggest promise of the system, offering a broad range of system options.

The down side is that it has relatively modest energy density : *ca* 15 wh/l (in practice), and a relatively low practical electrochemical emf *ca* 1.25V.

And there are currently stability issues which dictate the operating temperature range and how high the energy density can be increased. These mean operational compromises in a practical system.

How do we approach these compromises.

## The go with the (vanadium-redox) flow



System losses: Pumping  
heat exchanges, etc  
shunt current

**Reduces efficiency**

depends on  $V_{out}$

If the technology were perfect, life would be simple.

We put the two electrolytes (the energy) into containers, and we pump the stuff to the stack, and we transfer electrical current from the stack. It's scalable in both power and energy dimension. Best thing since sliced bread!

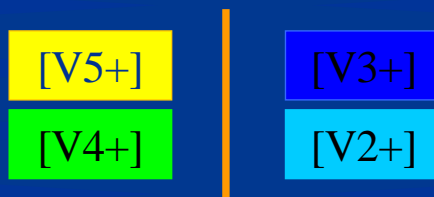
Sure, we have some losses, which we can't do much about, but we can keep to a few percent. But, as most of you already know, we have some other serious problems to worry about.

The electrolyte is conductive, so we have a continuous (non-faradaic) current drain, regardless of whether we are charging or discharging, through both electrolyte circuits. It's called shunt current for obvious reasons. It is a form of capacity loss, or self-discharge.

Bad part for us is that how much we lose depends on the output terminal voltage,  $V_{out}$ . (In fact, the power we lose is of-course proportional to the square of  $V_{out}$ ). And thus we have a source of reduced efficiency that doesn't apply to other battery storage technology such as NiCds, or lead-acid. We have ways to minimise shunt currents, and hence we start on our path of design compromises.



## The go with the (vanadium-redox) flow



*Requires*

- Equal ratio of concentrations
- Equal volumes per half



- Imbalance
  - Chemical
  - Volume

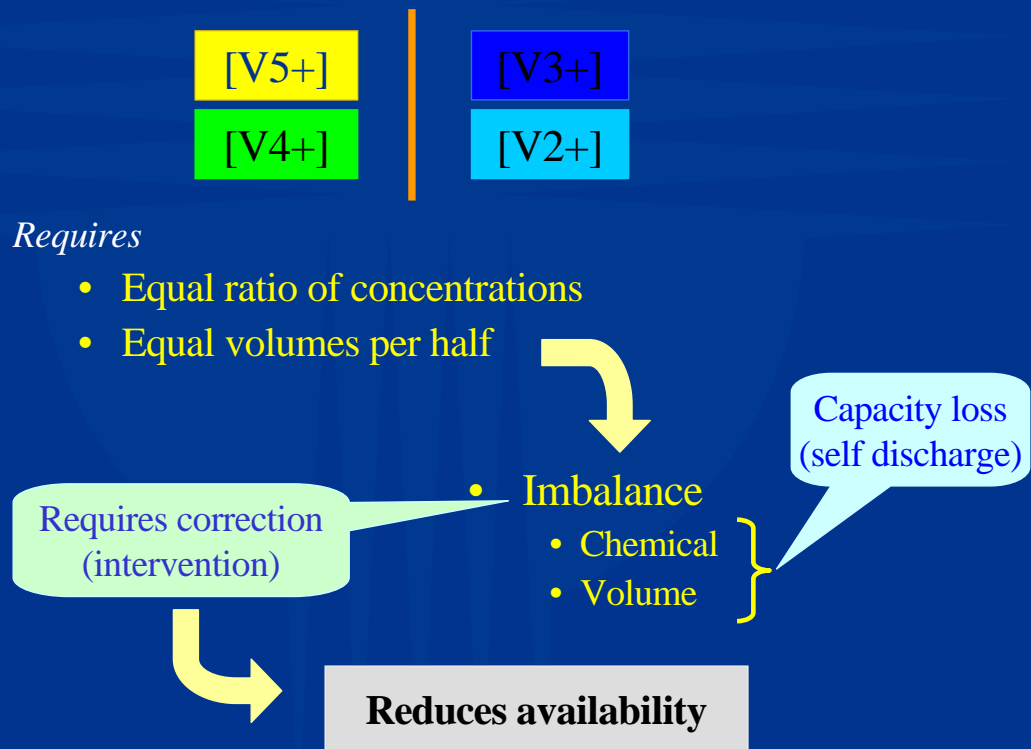
The second, and perhaps more difficult design compromise (and performance sacrifice) we have to consider arises from the very elegance of the single element, single liquid phase of the electrochemistry.

The two half cells of the electrochemistry work on ratios of the two different valence states.

Therefore, the vanadium flow systems, requires an equal ratio of concentrations. We need to maintain equal ratios on each side.

Now, this chemical-physical arrangement being what it is, the ion exchange membrane is less than perfect, in operation. We lose equivalence in the ratios, and we end up with what's known as imbalance. There are two types, the chemical imbalance being more of a problem than volumetric imbalance.

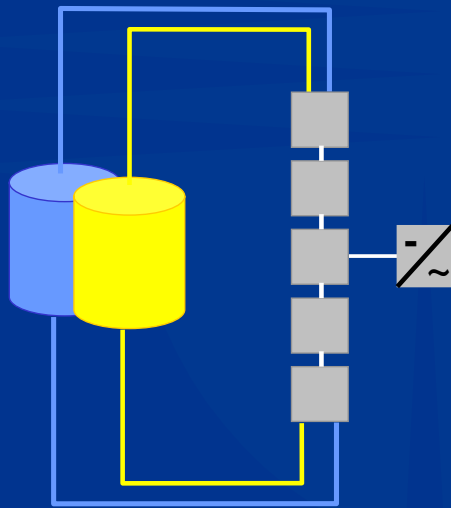
## The go with the (vanadium-redox) flow



Imbalance is a form of self-discharge, and results in capacity loss. It is insidious in that it is an ever reducing capacity loss unless it is corrected.

Correction requires intervention into the normal operation storage purpose of the battery (*i.e. a discharge followed by a charge*), and so contributes to reduced system availability. Insidiously, correction involves complete discharge of the electrolyte.

## The go with the (vanadium-redox) flow



*Electrolyte flow is parallel through stacks*

### Simplest topology

- Series-connect stacks
- Single electrolyte sources

### Advantages

- lowest cost BoS
- simple operation & control

### Disadvantages

- highest shunt-current losses
- highest self-discharge
- lowest efficiency
- highest unavailability for rebalance

So how are these problems real issues for the End-user? Doesn't the technology vendor fix all this? Well, yes and no. Because, as you have probably worked out, it's the application which tends to dictate which of these problems to optimise against.

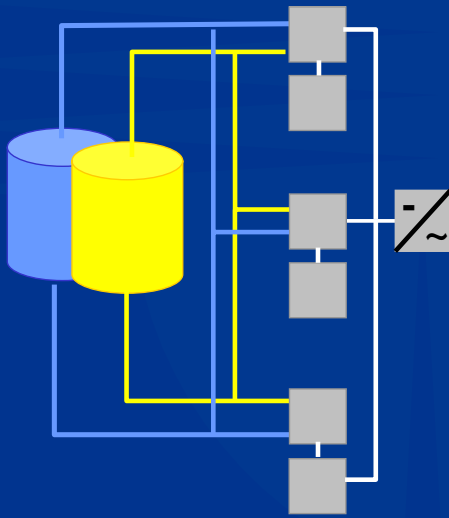
To see why, lets look at a few different design topologies.

The simplest system topology is a series connection of stacks to give us the voltage we need to satisfy the inverter input requirements. All the electrolyte housed in the two containers – one for each of the anolyte and the catholyte.

The advantage of this are lowest cost, and simplest operation – *i.e.* the promise of the technology

But you don't get anything for nothing, and the downside is the worst-case losses in terms of efficiency, that's because shunt currents are maximised, and the worst case in terms of availability in that rebalance, which involves fully discharging the battery, re-mixing all the electrolyte, and recharging, and the system is not available in a functional sense *i.e.* to provide energy, during this period.

## The go with the (vanadium-redox) flow



*Electrolyte flow is still parallel through stack groups*

### Simple series-parallel

- Series stacks grouped in parallel
- Single electrolyte sources

### Advantages

- reduced shunt-current losses
- improved efficiency
- simple operation & control

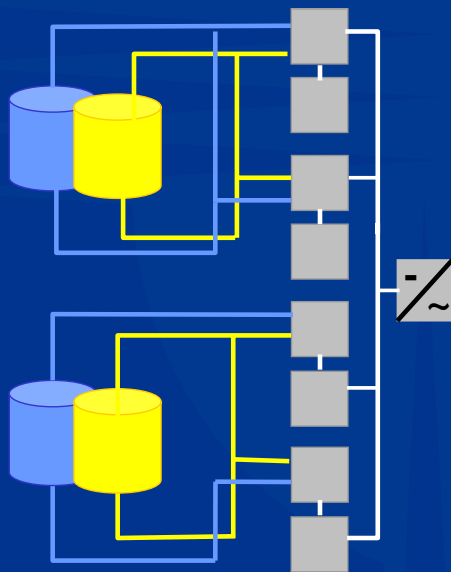
### Disadvantages

- higher piping costs
- highest unavailability for rebalance

We can improve this a bit, by introducing series-parallel combination of the stacks - still being supplied by only two common electrolyte sources. This allows us to alleviate the losses from shunt currents, yet still keeps the system relatively simple.

But the improvement is at the expense of more piping and valving, and we still have the cost to the system availability in terms of rebalance, and we haven't got that much flexibility in mode of operation.

## The go with the (vanadium-redox) flow



*Electrolyte flow is still parallel through stack groups*

### Parallel series-parallel

- Series stacks grouped in parallel
- Parallel electrolyte sources

### Advantages

- reduced unavailability for rebalance
- some operational flexibility (redundancy)

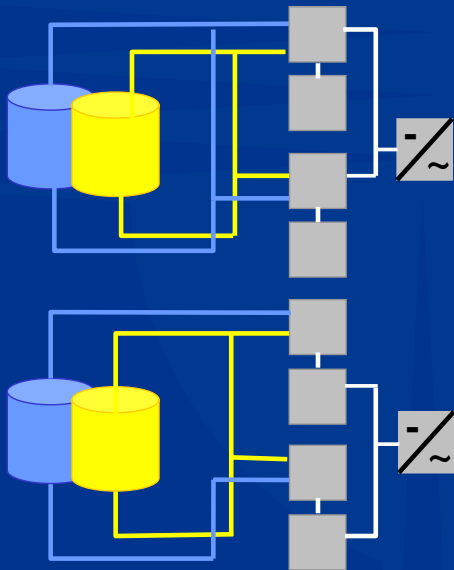
### Disadvantages

- higher piping & BoS costs
- more complicated operation & control

We can improve this yet a bit more, by introducing independent parallel electrolyte sources to supply the parallel groups of stacks. In doing so, we get to keep the improvement in lowering shunt-current losses, and we now have some flexibility in quarantining the imbalance effects on the availability since we have some functional redundancy, and greater flexibility in modes of operation.

But, with every increasing reminder of the paraphrased second law of thermodynamics, “that you don’t get anything for nothing”, we have increased balance of system costs, and increased complexity in operational (automated) control requirements.

## The go with the (vanadium-redox) flow



*Electrolyte flow is still parallel through stack groups*

### Parallel series-parallel

- Series stacks grouped in parallel
- Parallel electrolyte sources

### Advantages

- reduced unavailability for rebalance
- some operational flexibility (redundancy)

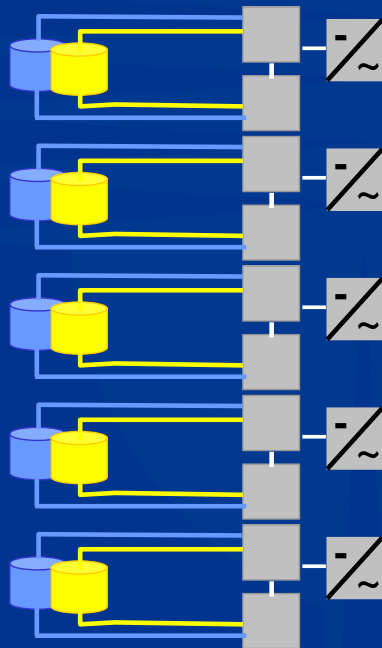
### Disadvantages

- higher & PCS costs
- more complicated operation & control

If we have concerns about redundancy and flexibility, we can simply add variation of the theme, and have independent sub-systems all the way through to the AC side.

I think you can probably see where this is going. To fully exploit the technology in a functional sense, we really have to add even more complexity, and align our independent sub-systems at the storage, stack and converter level.

## The go with the (vanadium-redox) flow



*Electrolyte flow is still parallel through each stack group*

Most complex topology

- Parallel stack/electrolyte units
- parallel dc-ac or dc-ac PCS

Advantages

- Functional redundancy
- most reduced unavailability
- maximum operational flexibility (modes)

Disadvantages

- highest costs
- complex operation & control

The real advantage of this flexibility is to allow maximum opportunity to reduce availability downtime by quarantining rebalance requirements to each sub-system as they arise, without necessarily affecting the operation of the other sub-systems. It's all about flexibility, functional redundancy – can never lose service with this topology...

Of course, down side is that this design is the most costly of the implementations.....

## The go with the (vanadium-redox) flow

<i>Efficiency deficiencies to manage</i>	<i>Operator Options</i>
I <sup>2</sup> R & electrochemical	no (inherent)
pumping	yes - electrolyte distribution
thermal	yes
shunt current	maybe
loss of balance	no (inherent)
rebalance	yes
mode of operation	yes

So, lets summarise the issues with the vanadium-redox technology....

In terms of needing to address efficiency (energy losses), we have the following deficiency issues to manage ..., and the corresponding operator options are ....

Message is that it comes down to what the User wants and needs.



## The go with the (vanadium-redox) flow

<i>Availability deficiencies to manage</i>	<i>Operator Options</i>
pumping response (for PQ)	maybe
volume rebalance	yes
chemical rebalance	maybe
system redundancy	yes (design & cost)
single point of failure	yes (design & cost)
mode of operation	yes
downtime (unavailability)	yes (design complexity)

In terms of needing to address system availability, we have the following deficiency issues to manage ..., and the corresponding operator options are ....

Again, the message is that it comes down to what the User wants and needs, and overriding what the User is prepared to pay for – given alternative or existing technologies.

## The go with the (vanadium-redox) flow

*To go with the vanadium redox flow (or not)*



It is a hard call

So, life isn't simple, and flow batteries in general, and the vanadium redox in particular, may not be the best thing since sliced bread!