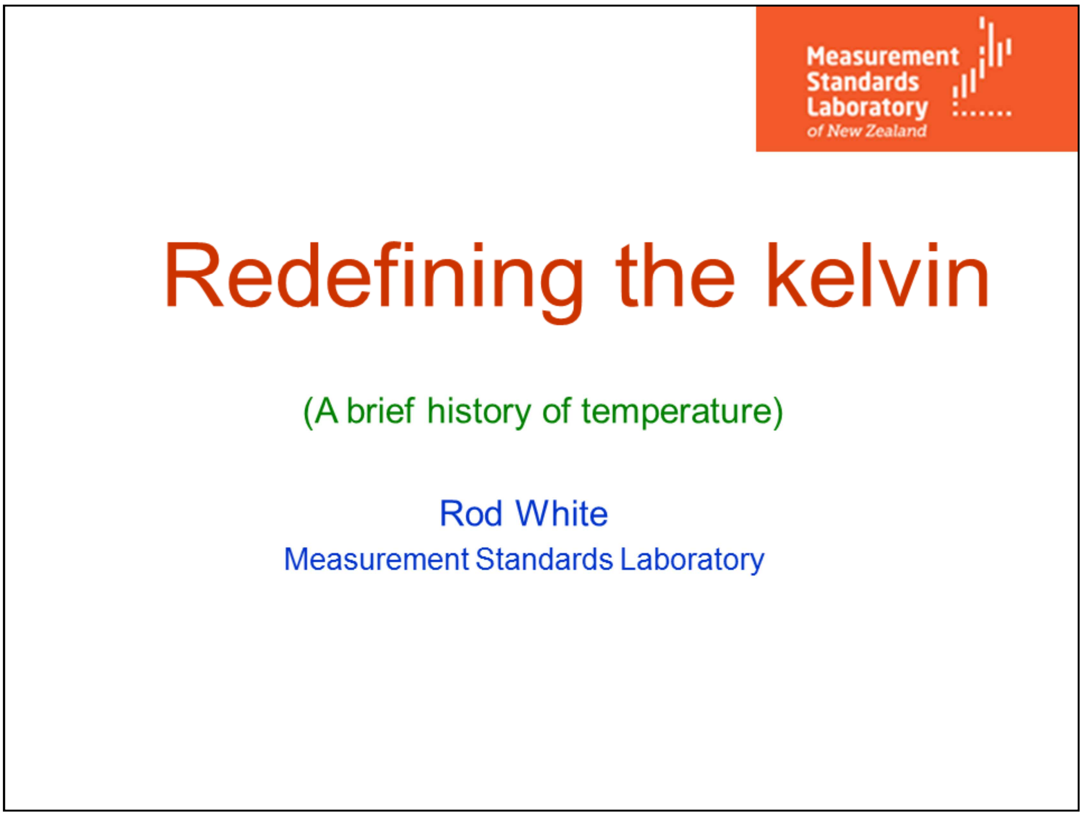


Measurement Standards Laboratory of New Zealand

Redefining the kelvin

(A brief history of temperature)

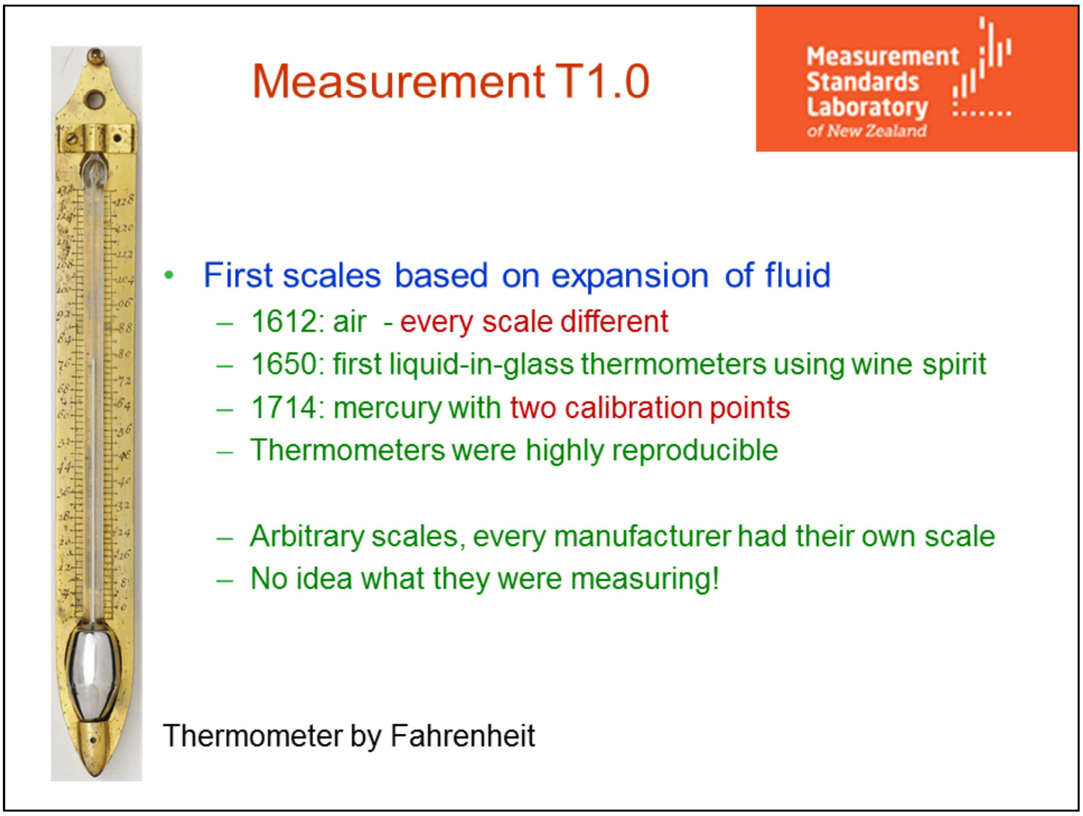
Rod White
Measurement Standards Laboratory

Thank you Gavin…..

Good morning everyone, and welcome again to MSLs World Metrology Day celebrations.

The aim of this talk is to explain the changes that will be made with the change in the definition of the kelvin, and the consequences. But as you will see, that’s not much, and certainly not enough to fill a 20 minute talk.

So I thought it would be better to explain why we are making the changes – so the talk is really a brief history of temperature.



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Measurement T1.0

- First scales based on expansion of fluid
  - 1612: air - every scale different
  - 1650: first liquid-in-glass thermometers using wine spirit
  - 1714: mercury with two calibration points
  - Thermometers were highly reproducible

  - Arbitrary scales, every manufacturer had their own scale
  - No idea what they were measuring!

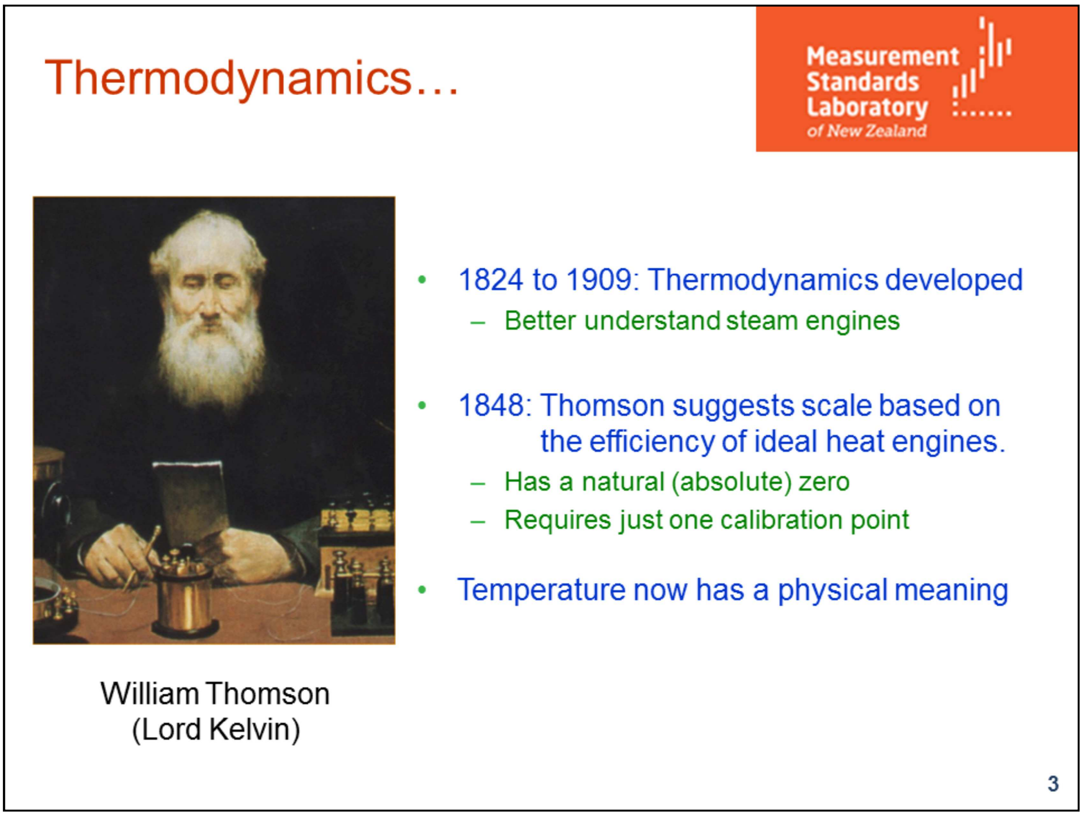
Thermometer by Fahrenheit

Mankind has been measuring length, volume, and weight for thousands of years. In contrast, instruments to measure temperature were developed quite recently.

The first thermometers were air thermometers, built around 1612. Quite rapidly, people discovered problems with the use of air as the temperature sensor, and developed more reproducible liquid and glass thermometers that used wine spirit. Not surprisingly, they discovered the problems with the variable composition of the fluid and the fluid wetting the bore. Even today, spirit thermometers are pretty awful. Really high quality, reproducible thermometers weren't available until they started using mercury. During the 1700s there were dozens of different makers of thermometers and most used their own proprietary scale. We still recognise the scales of Fahrenheit and Celsius today, in part because they made such good thermometers. They both used two reference points to put the scale on their thermometers. Fahrenheit had the reputation of making the best thermometers (See photo of Fahrenheit thermometer).

As we know, Celsius used the freezing and boiling point of water, and arbitrarily defined these points as zero and one-hundred degrees. Lets call this method T1.0. It marks the invention of the first genuinely useful temperature scale. Of course, Fahrenheit's and Celsius's arbitrary scales had a significant effect on the shape of our modern scales.

Its interesting that these guys did not know what they were measuring, and that problem was not completely resolved until the science of thermodynamics had fully developed, nearly 200 years later.



Thermodynamics…

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- 1824 to 1909: Thermodynamics developed
  - Better understand steam engines
- 1848: Thomson suggests scale based on the efficiency of ideal heat engines.
  - Has a natural (absolute) zero
  - Requires just one calibration point
- Temperature now has a physical meaning

William Thomson
(Lord Kelvin)

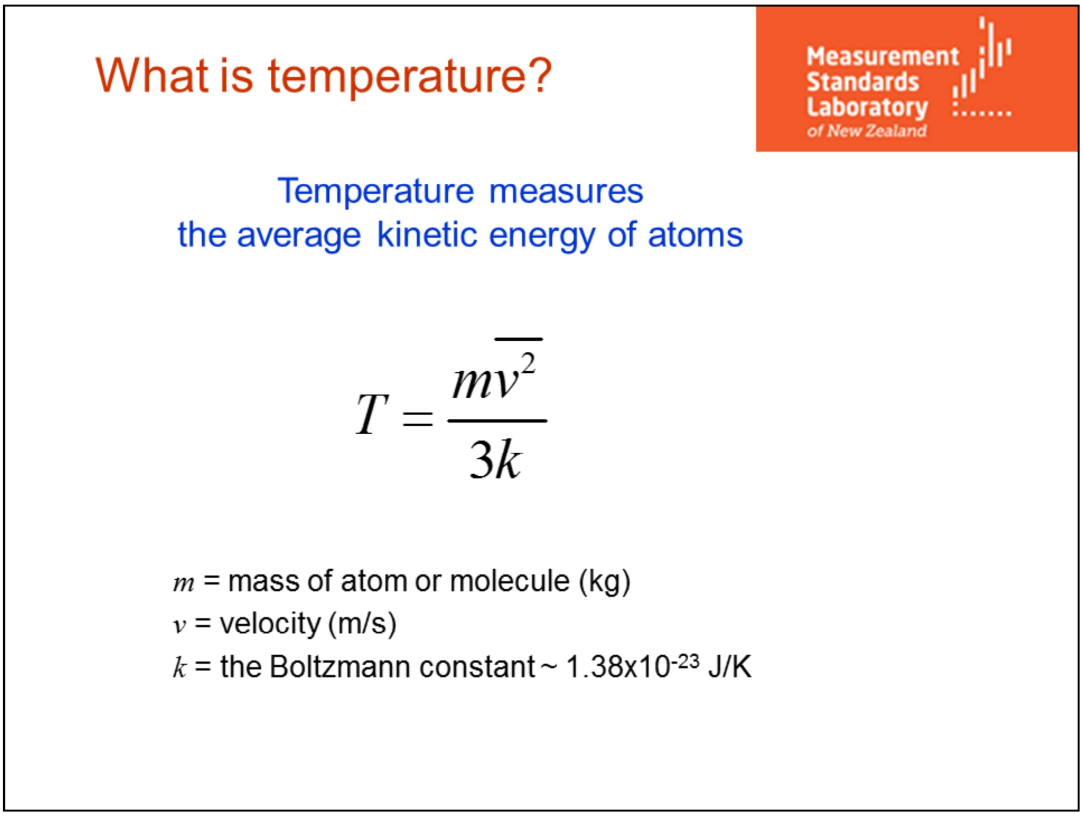
Real progress on the theoretical foundation of temperature was made only with the arrival of the industrial revolution, and the need for better understanding of steam engines.

William Thomson, later Lord Kelvin, exploited the concept of an ideal heat engine – a machine that would convert heat into mechanical work. He suggested two possible temperature scales. In later work with Joule, he conducted a number of experiments that led him to choose the temperature most like those in use at the time, and that is the scale we have today.

His scale has a couple of interesting features

- A natural or meaningful zero
- It requires a single calibration point.

Most importantly, he had an understanding of what temperature is. Given a heat engine operating between reservoirs at different temperatures, he could tell us the maximum efficiency of the engine.



What is temperature?

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Temperature measures
the average kinetic energy of atoms

$$T = \frac{m\overline{v^2}}{3k}$$

m = mass of atom or molecule (kg)
v = velocity (m/s)
k = the Boltzmann constant ~ 1.38x10^{-23} J/K

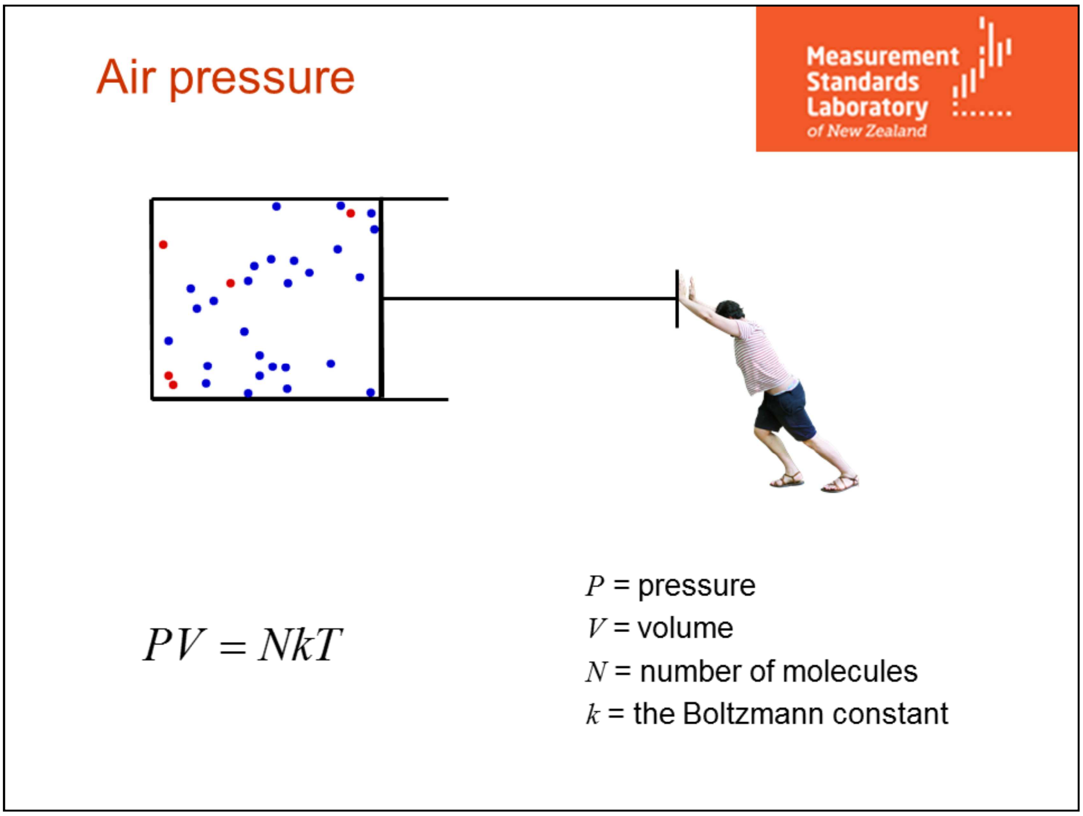
OK, so what does temperature mean – what is it?

Thermodynamics tells us that temperature is directly related to the average (translational) kinetic energy of (unbound) atoms and molecules.

Some of you might remember, from high-school science, that the kinetic energy of a moving object is half m v squared – you can see the “m v squared” terms here.

Of course the energy of atoms is extremely small, and if we want to scale those numbers up to match Celsius’s arbitrary scale, we have to divide it by a very small number – that’s the *k* here.

k is very small….



Air pressure

$$PV = NkT$$

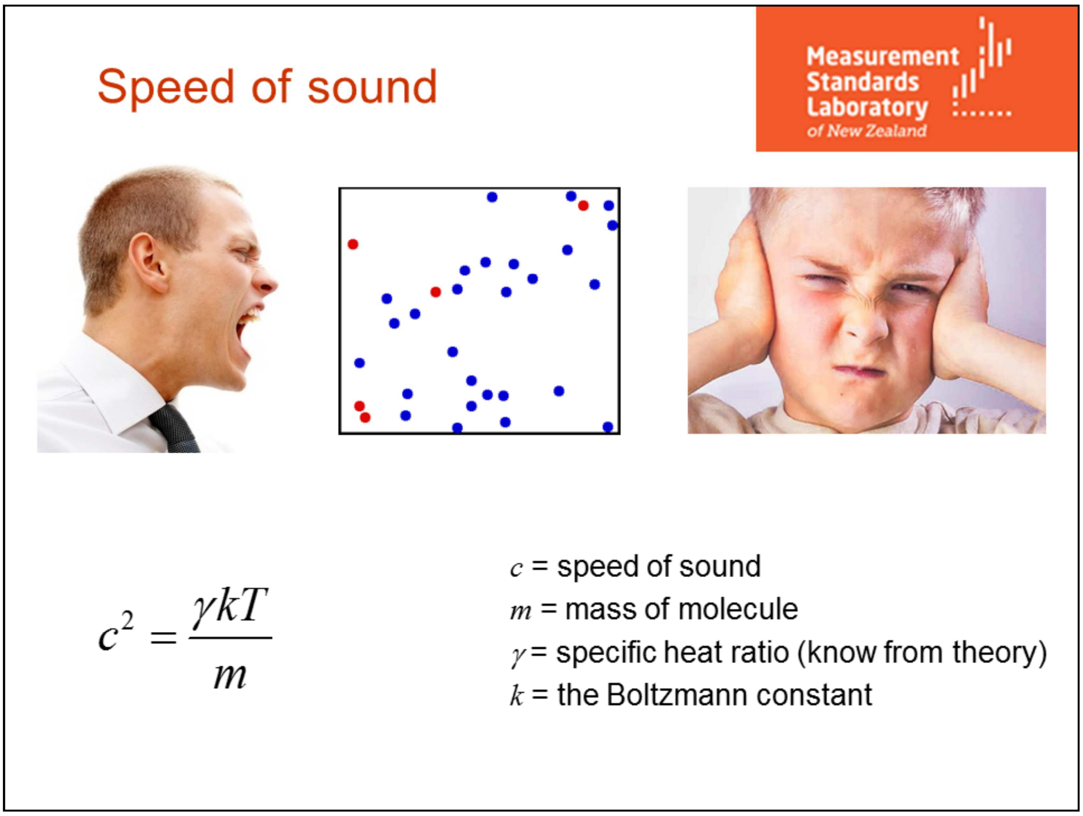
P = pressure
V = volume
N = number of molecules
k = the Boltzmann constant

Thermodynamics can also tell us how temperature relates to other quantities.

If we have *N* molecules trapped in a volume *V*, then the pressure is proportional to temperature.

You might remember this equation from high-school too, its called the ideal gas law.

We have about a dozen or so equations that relate temperature to other quantities - they are called equations of state.



Speed of sound

$$c^2 = \frac{\gamma k T}{m}$$

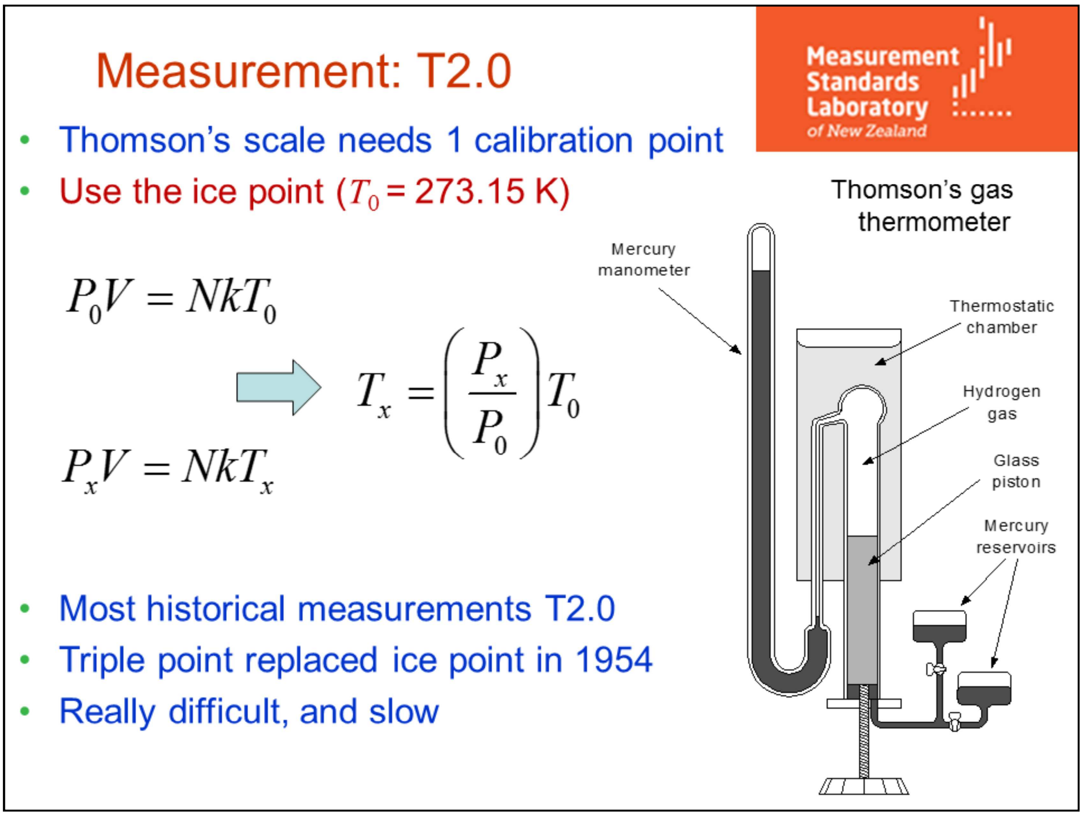
c = speed of sound
m = mass of molecule
γ = specific heat ratio (know from theory)
k = the Boltzmann constant

Here is another equation of state. This one deals with the speed of sound, given the symbol *c*.

Suppose we have a sound generated here (mad dad), it propagates across the airspace and is detected here.

The speed of the sound propagation turns out to be related to the temperature of the gas. In fact, the speed of sound is directly proportional to the average speed of the molecules, which should not be a surprise.

OK, so we have all these equations of state, can we use them to measure temperature?



Measurement: T2.0

- Thomson's scale needs 1 calibration point
- Use the ice point ($T_0 = 273.15$ K)

$$P_0 V = NkT_0$$

$$\Rightarrow \quad T_x = \left(\frac{P_x}{P_0}\right) T_0$$

$$P_x V = NkT_x$$

- Most historical measurements T2.0
- Triple point replaced ice point in 1954
- Really difficult, and slow

Thomson's gas thermometer

Yes we can. In fact, this is exactly what Kelvin did using the ideal gas law. The instrument is called a constant-volume gas thermometer.

The measurement involved two experimental steps

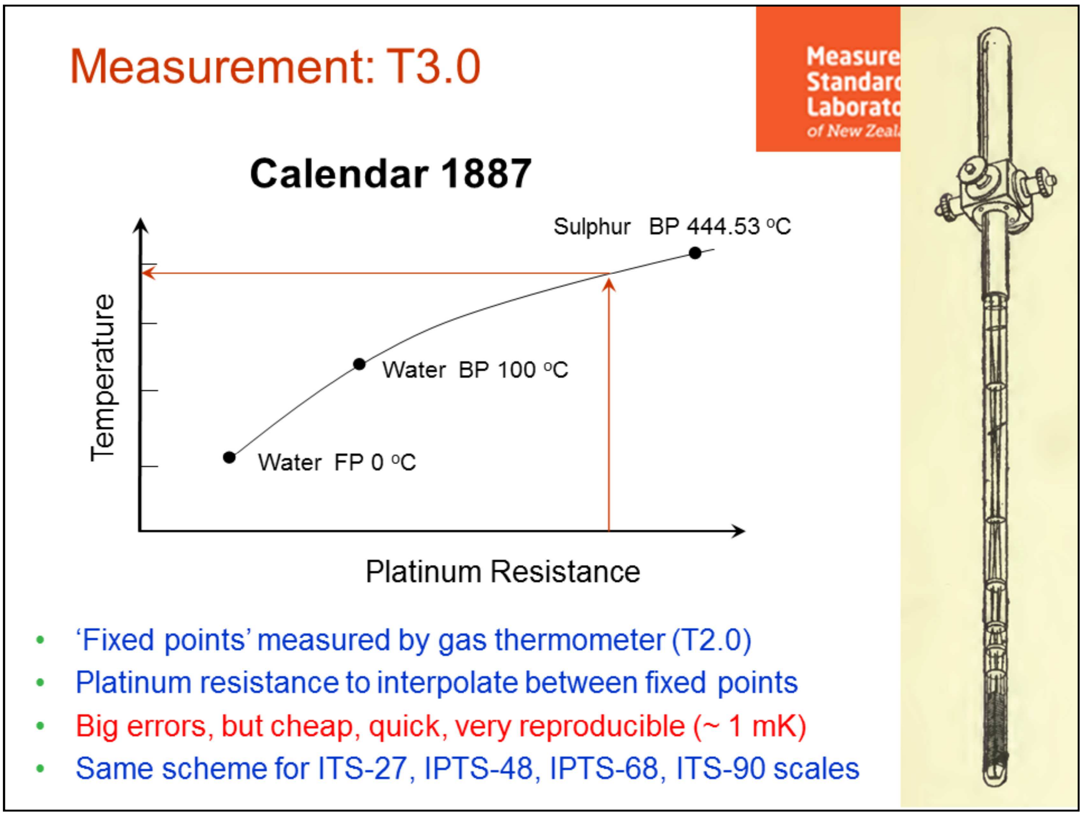
First: take a fixed volume with a fixed number of molecules or atoms and measure the gas pressure at the reference pressure (here, the ice point).

Second: take the same volume and number of molecules and measure the pressure at the unknown temperature.

Then using the equations, calculate the temperature as the ratio of the pressures multiplied by the reference temperature. Note how this has the same form as other measurements expressed in SI units:

measured temperature = a number x reference temperature

Of course it's not that simple – there are lots of problems. Most notably, the ideal gas law is an awful description of the real behaviour of gasses, and a lot of subsidiary measurements and corrections are required. Measuring temperature this way is a very difficult and slow process. But most historical thermodynamic temperature measurements were done in exactly this way.



Measurement: T3.0

Calendar 1887

- ‘Fixed points’ measured by gas thermometer (T2.0)
- Platinum resistance to interpolate between fixed points
- Big errors, but cheap, quick, very reproducible (~ 1 mK)
- Same scheme for ITS-27, IPTS-48, IPTS-68, ITS-90 scales

The constant volume gas thermometer was so difficult and slow to use that people kept looking for better thermometers. In 1887, Calendar developed the platinum resistance thermometer, and that turned out to be one of the best thermometers ever. There is a picture of one on the right hand side, and MSL is lucky enough to have a couple of thermometers built according to Calendar’s design in our museum.

He suggested using the thermometer to interpolate between defined temperatures:

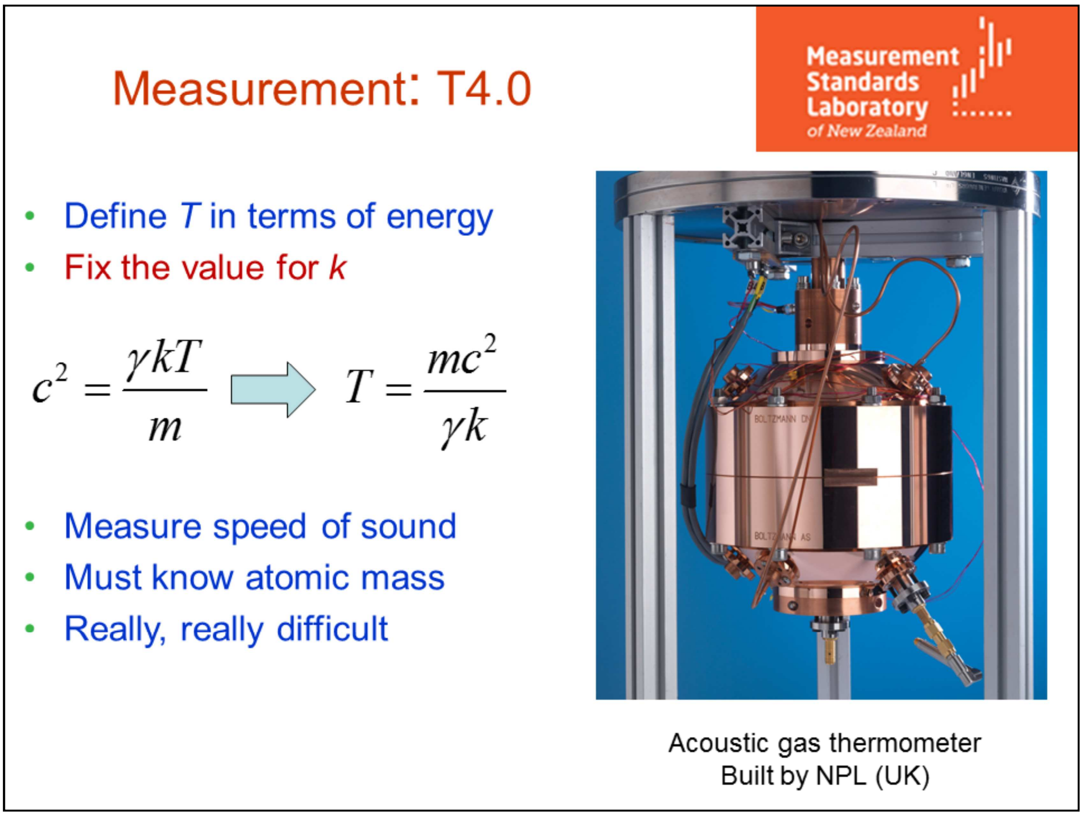
Freezing point of water = 0 °C, which he took to be a defined value

Boiling point of water = 100 °C, also a defined value

Boiling point sulphur = 444.5 °C, which was measured using a constant volume gas thermometer like Kelvin’s.

Then when you measure the resistance at an unknown temperature you can map the resistance back to the temperature. Now this temperature scale has has horrible errors, mostly due to due errors in the gas thermometry, but the resistance measurements were very cheap and quick and amazingly, repeatable to about 1 mK.

We have used the same scheme for out temperature scales ever since, but each time the scale is revised we have more accurate temperatures, more fixed points, cover a wider temperature range. We can think of the ITS-90 scale as T3.5.



Measurement: T4.0

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- Define *T* in terms of energy
- Fix the value for *k*

$$c^2 = \frac{\gamma k T}{m} \Rightarrow T = \frac{mc^2}{\gamma k}$$

- Measure speed of sound
- Must know atomic mass
- Really, really difficult

Acoustic gas thermometer
Built by NPL (UK)

Now, in the meantime we continue to try to make better thermometers.

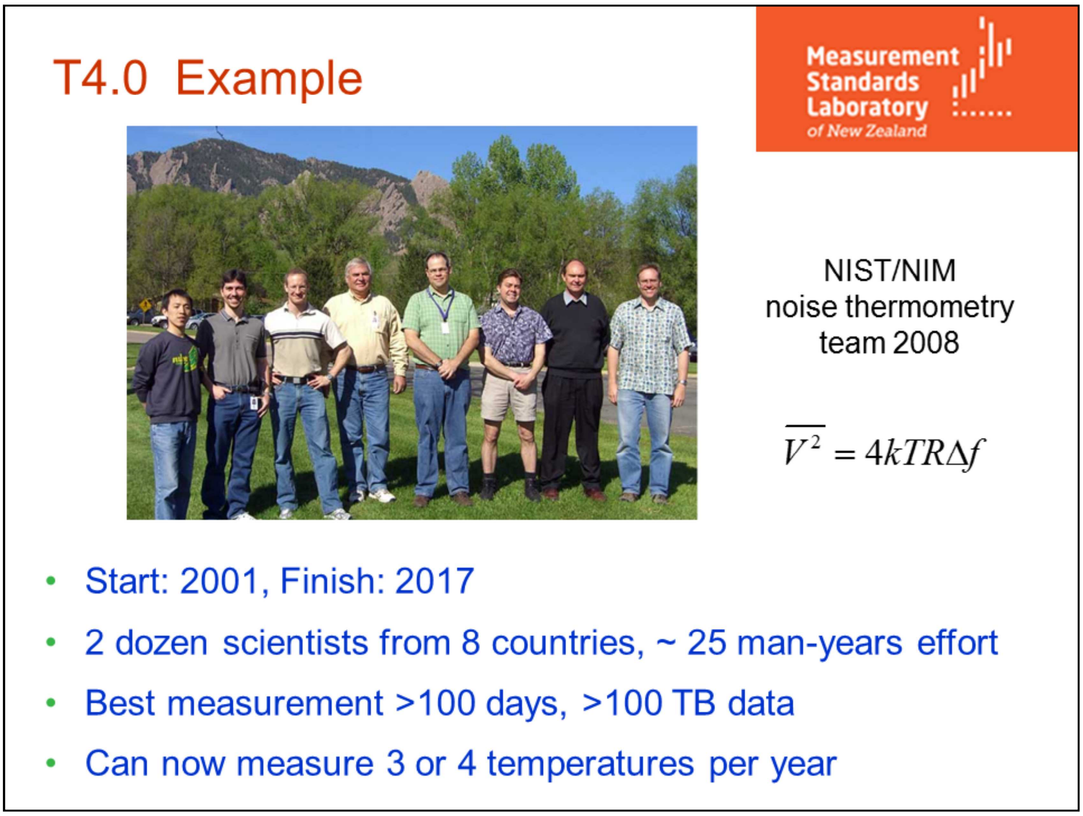
Another possibility is to measure temperature directly using the equations of state. If you remember one of the earlier slides, we related temperature to energy, so why don't we measure temperature in terms of energy? We can, but that means we must fix the value for Boltzmann's constant. Lets look at an example using the equation of state for the speed of sound.

If we rearrange the equation, and express temperature in terms of the other quantities, we find we can measure the temperature in terms of

- Measurements of the speed of sound, *c*
- Measurements of the mass of the atom or molecules, *m*
- Knowledge of the specific heat ratio, which we know from theory
- And the value of Boltzmann's constant, *k*, which we fix.

This instrument that measures temperature this way is called an acoustic gas thermometer, and here is a photo of the beautiful copper one built at NPL (UK). They have been using it to measure *k* by using it at the triple point of water.

So we can measure temperature this way, but it's difficult, really, really difficult.



T4.0 Example

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NIST/NIM
noise thermometry
team 2008

$$\overline{V^2} = 4kTR\Delta f$$

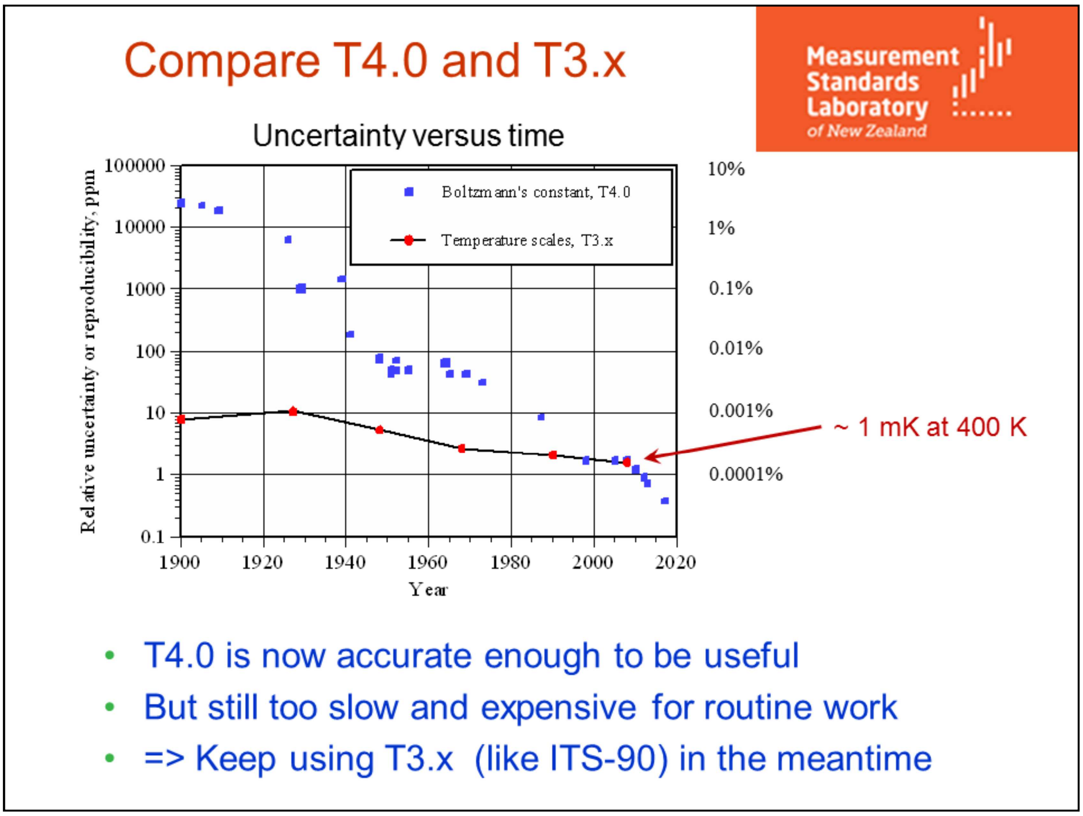
- Start: 2001, Finish: 2017
- 2 dozen scientists from 8 countries, ~ 25 man-years effort
- Best measurement >100 days, >100 TB data
- Can now measure 3 or 4 temperatures per year

So Just how difficult are T4.0 measurements? I've had the privilege of working with a team based in the USA and China using a different equation of state and a thermometer called a Johnson noise thermometer, which uses the electrical noise generated by a resistor. We also used it to measure Boltzmann's constant.

As you can see, the project has been running for more than 15 years, has involved more than 2 dozen people from at least 8 countries, and I guess has taken more than 25 man years of effort in total.

We completed our best measurement last year, which took more than 100 days. We sampled data at 8 MS/sec, and gathered more than 100 TB of data. That's 1500 audio CDs worth every day - 150,000 in total.

Of course, now that we have done all this research, we can measure temperatures much faster – maybe three or four measurements per year.



Compare T4.0 and T3.x

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Uncertainty versus time

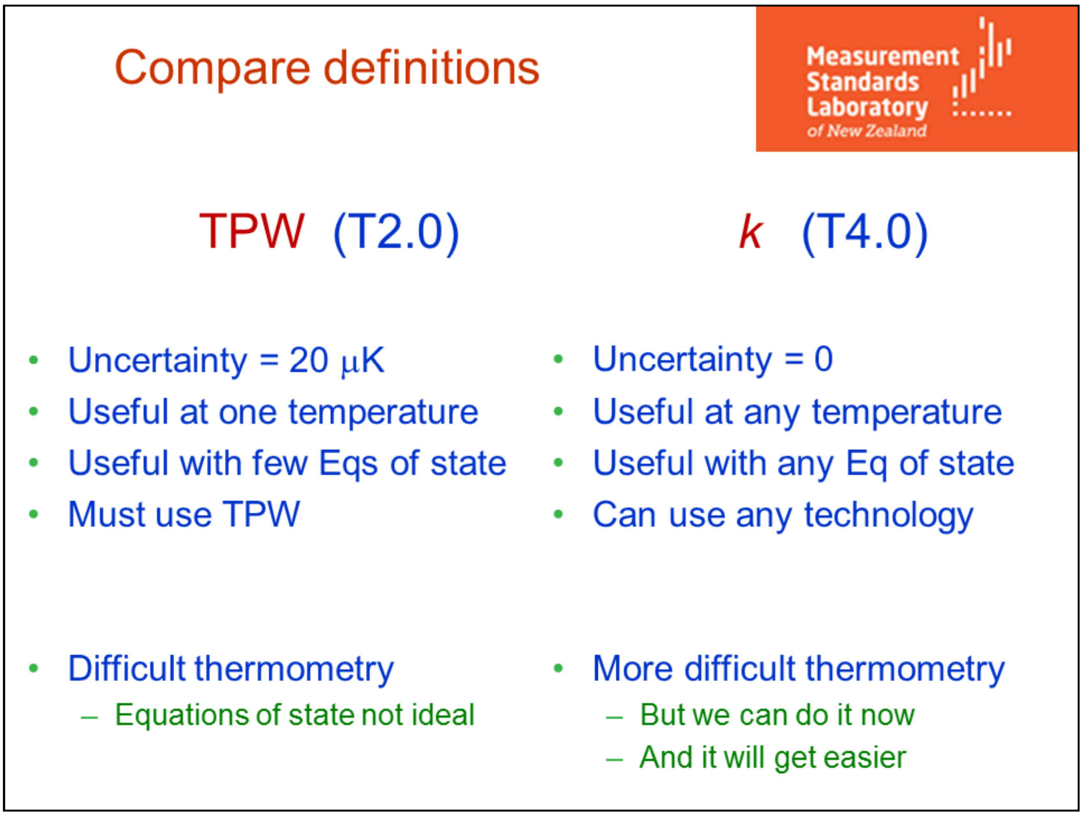
- T4.0 is now accurate enough to be useful
- But still too slow and expensive for routine work
- => Keep using T3.x (like ITS-90) in the meantime

This graph plots the uncertainty in our measurements versus time – from 1900 to the present, for two sets of measurements. Note the uncertainties given in % on the right hand side, and parts per million on the left hand side.

The set of measurements indicated by the red dots is for the measurements made using our practical temperature scales (T3.X). If you remember, these are based on Calendar's scheme with the platinum resistance thermometer. From the left, the first dot is the uncertainty in Calendar's scale when it was adopted by the BIPM to replace mercury thermometers in 1900. The next is the ITS-27, the first international temperature scale introduced in 1927. The next three are the scale revisions made in 1948,1968, and 1990. The final red dot is our assessment of the accuracy of ITS-90 made in a big study in 2008. It corresponds to an uncertainty of about 1 mK at 400 K.

The blue dots plot our measurements of Boltzmann's constant, all made using T4.0 methods. You can see, that until the last decade, we could not measure *k* very well, certainly not well enough to replace the platinum wire scales. Only now is the accuracy of a T4.0 method better than the platinum wire scheme of Calendar.

But they are still too slow to be useful. Three or four measurements per year is no way to run a commercial business. So for foreseeable future, we must continue to use the platinum wire scales like ITS-90.



Compare definitions

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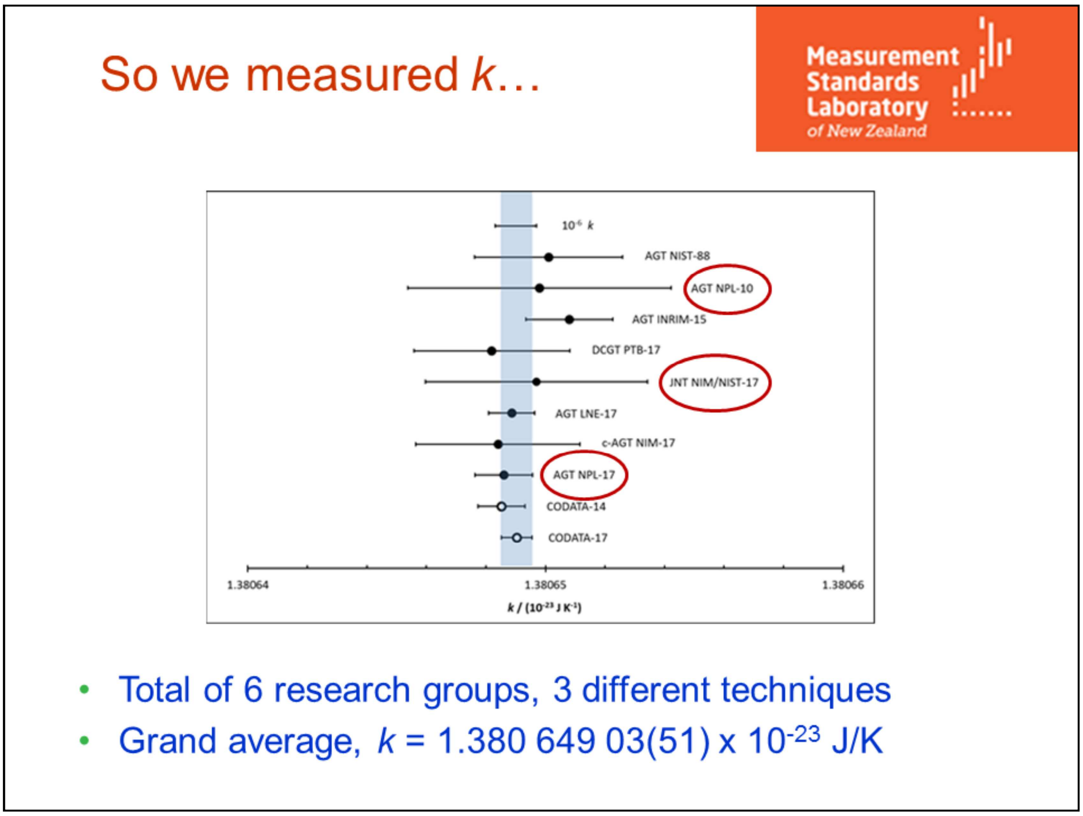
TPW (T2.0)	*k* (T4.0)
Uncertainty = 20 μK	Uncertainty = 0
Useful at one temperature	Useful at any temperature
Useful with few Eqs of state	Useful with any Eq of state
Must use TPW	Can use any technology
Difficult thermometry – Equations of state not ideal	More difficult thermometry – But we can do it now – And it will get easier

So now that we can make accurate measurements of *k,* it is also worthwhile considering the way we define the kelvin. At the moment is based on the triple point of water, but as of 20th May next year, we will fix the value of k instead. There are some problems with the triple point of water. Firstly it does not have zero uncertainty in practice, because we are stuck with 18th century bucket chemistry techniques – distilled water in a glass cell. There are a bunch of small technical problems with this technology that limit the uncertainty to about 20 uK (which is actually pretty good).

But the TPW is only useful at one temperature, 273.16K. If we want to apply that definition at another temperature, we have to use the equations of state and T2.0 thermometers. That means using equations that are mostly approximations. Worse, many of our equations of state simply don't work well at the TPW.

On the other hand, if we fixed the value of Boltzmann constant most of these problems go away. The uncertainty in the definition is zero, the definition can be used at any temperature, using any equation of state, and using any technology we like. The new definition is future proof.

The downside - the cost of using *k* to define the kelvin, is that T4.0 thermometry is more difficult than T2.0 thermometry. But as the previous slide showed, we can do it know, and it will get easier.



So we measured *k*…

- Total of 6 research groups, 3 different techniques
- Grand average, $k = 1.380\,649\,03(51) \times 10^{-23}$ J/K

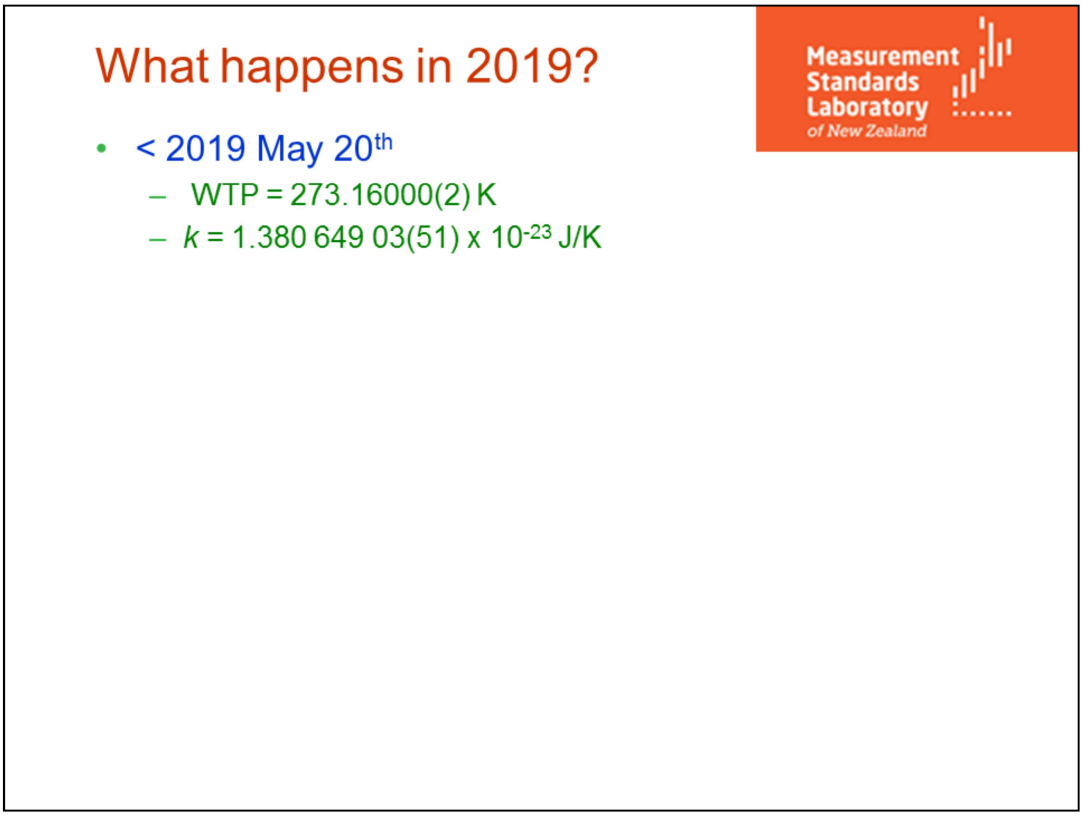
So, in anticipation of the change in definition, a lot of us have been busy, for the last decade or so, measuring Boltzmann's constant, to make sure there is no detectable glitch when we change the definition..

This one is our measurement made by noise thermometry. The bars here indicate the uncertainty in the measurements, about plus or minus 0.7 mK.

The next two points here are results from our colleagues in the UK using the nice copper acoustic gas thermometer.   You can see that their last measurement, and the one a couple above it, by a French group also using acoustic gas thermometry, are really good measurements.

There are other measurements here from the USA, Italy, Germany, and China. As you can see, despite us all using different methods, the results are quite consistent.

The CODATA committee that reviewed the results calculated a grand average of all of the measurements and decided that our best estimate of *k* is currently …….. with an uncertainty of 51 counts in the last two digits.



What happens in 2019?

- < 2019 May 20th
  - WTP = 273.16000(2) K
  - k = 1.380 649 03(51) x 10^{-23} J/K

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OK, so what happens next year when the kelvin definition changes.

Until the 20th May, things will stay as they are now. The TPW will continue to be defined to be 273.16 K, nominally with zero uncertainty, but in practice limited to 20 uK or so by the water and glass technology. The uncertainty in *k* is as in the last slide…51 counts in the last two digits

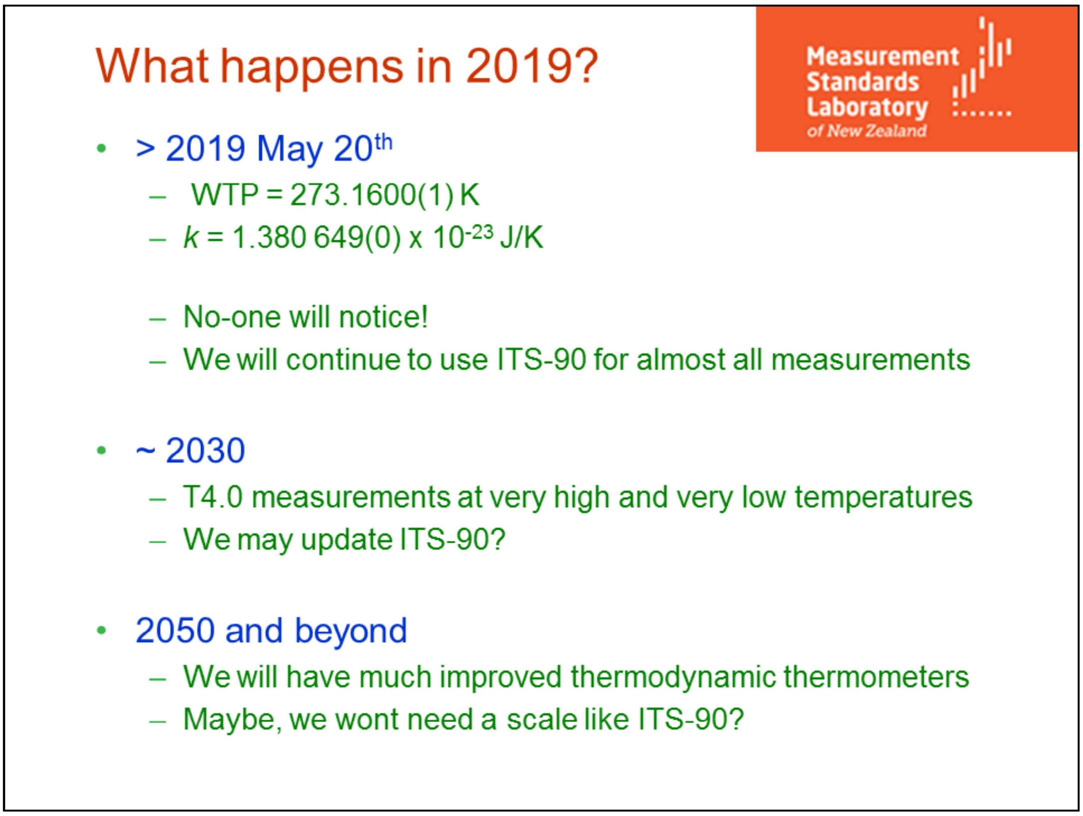
Now if you watch carefully, you see the change after 20th May. The uncertainty in *k* will collapse to zero, so it will have an exactly defined value. At the same time the uncertainty in the TPW will blow out to 100 uK.

Now whenever we make a change like this, there will be a glitch.

The 100 uK uncertainty is really is our best estimate of the magnitude of the glitch.

For the last few years we have also been investigating who makes the most accurate temperature measurements, and as best we can tell, no-one makes measurements better than maybe 300 uK to 500 uK.

That means, when we make the change, … no-one will notice.



What happens in 2019?

- > 2019 May 20th
  - WTP = 273.1600(1) K
  - k = 1.380 649(0) x 10^{-23} J/K

  - No-one will notice!
  - We will continue to use ITS-90 for almost all measurements

- ~ 2030
  - T4.0 measurements at very high and very low temperatures
  - We may update ITS-90?

- 2050 and beyond
  - We will have much improved thermodynamic thermometers
  - Maybe, we wont need a scale like ITS-90?

Also, there are no practical consequences for almost all users of the temperature scale. Most people will continue to use ITS-90.

The major change is in the minds of researchers. Instead of thinking about thermodynamic thermometers that must work at the TPW, we can think about thermodynamic thermometers that work at any temperature. That means we will have much better prospects for better temperature scales in the future

In 10 or so year’s time, it is almost certain that thermodynamic measurements will be carried out at very high and very low temperatures and replace some parts of ITS-90. There are already signs of this happening. Possibly we will update ITS-90, but that is an open question. It is very unlikely that we will make major changes. Major changes will annoy too many people.

Probably the soonest we can expect major change is maybe 30 to 40 years from now. Maybe then we will have developed thermodynamic thermometers that can measure temperatures accurately, quickly, and cheaply, so we no longer need the platinum wire scales.

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DON'T PANIC

Nothing much will happen

So , don’t panic, not much will happen.