COST Action FP1004

Training School - Modelling

28-30 April 2015 – Edinburgh (UK)

Wood properties variation and their probabilistic assessment via non-destructive measurement

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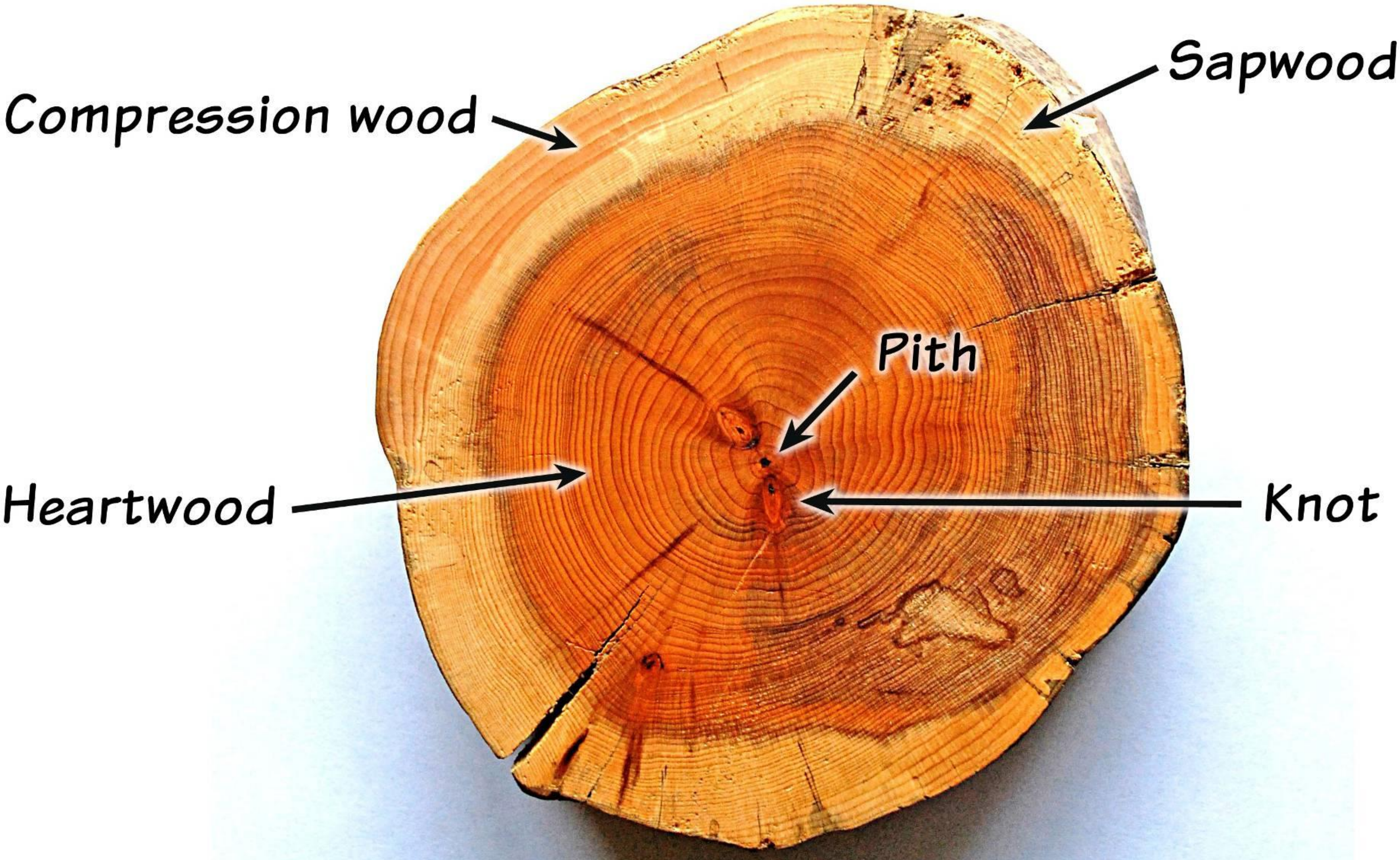
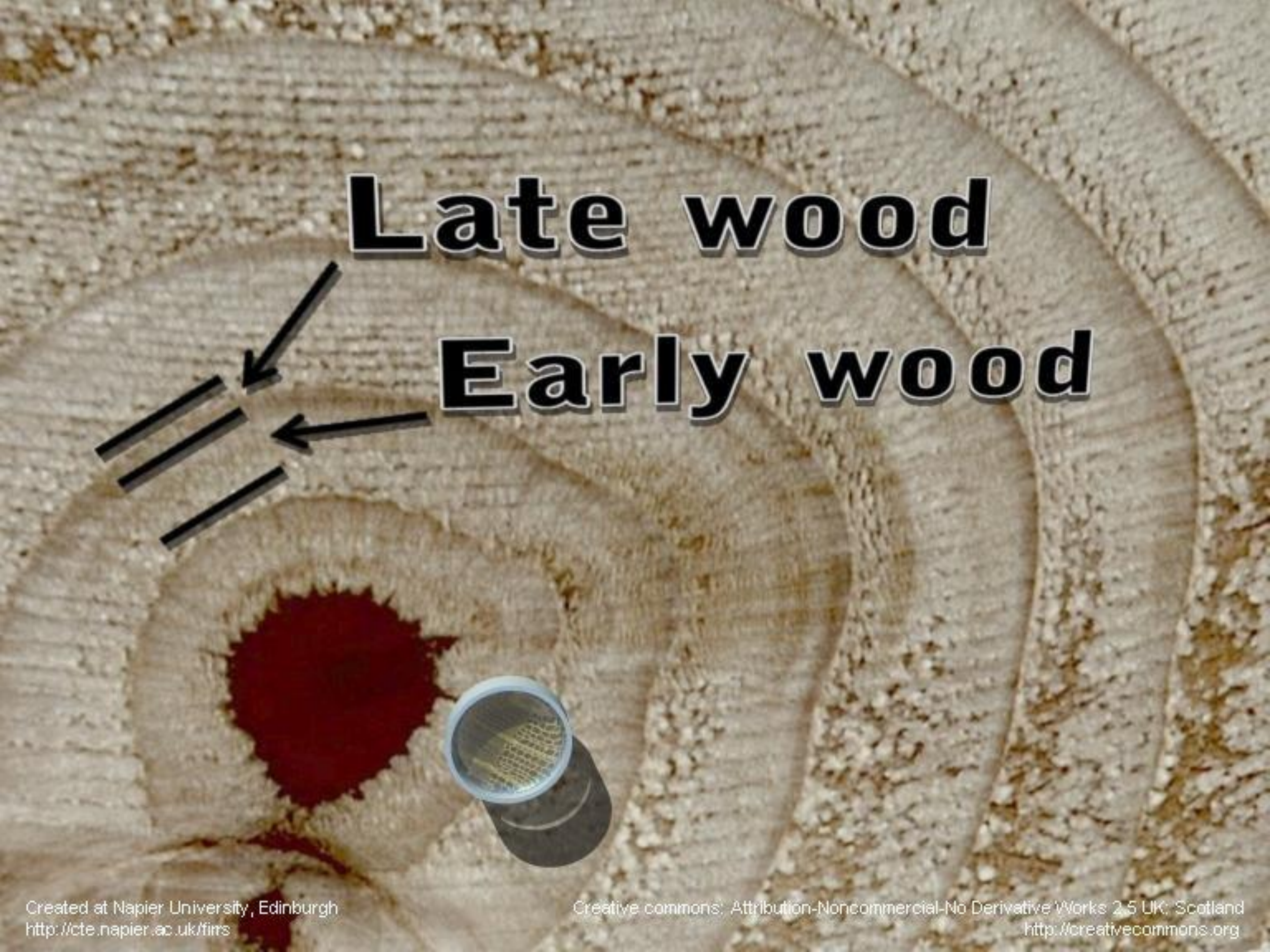
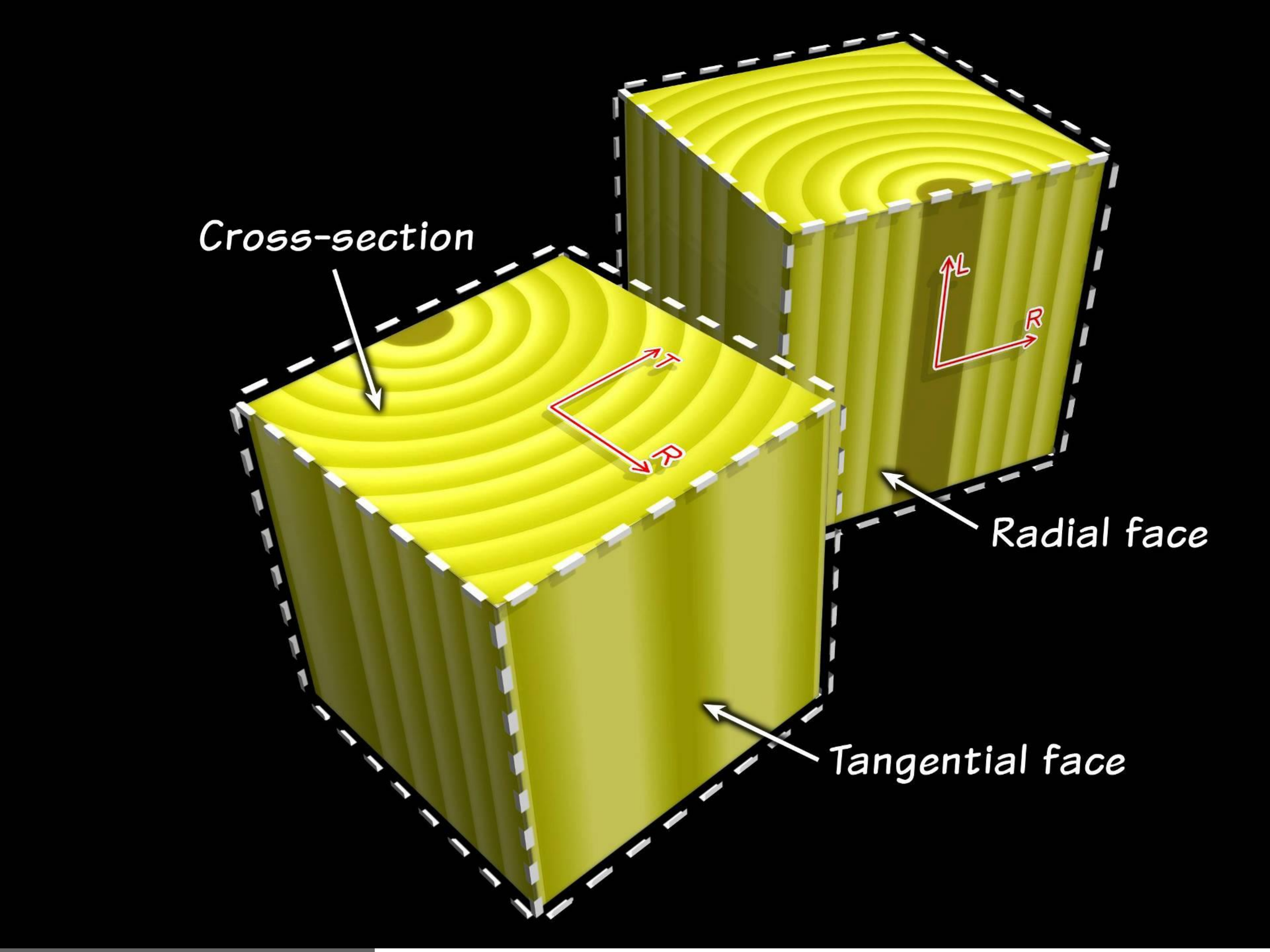
http://goo.gl/z5dHsR

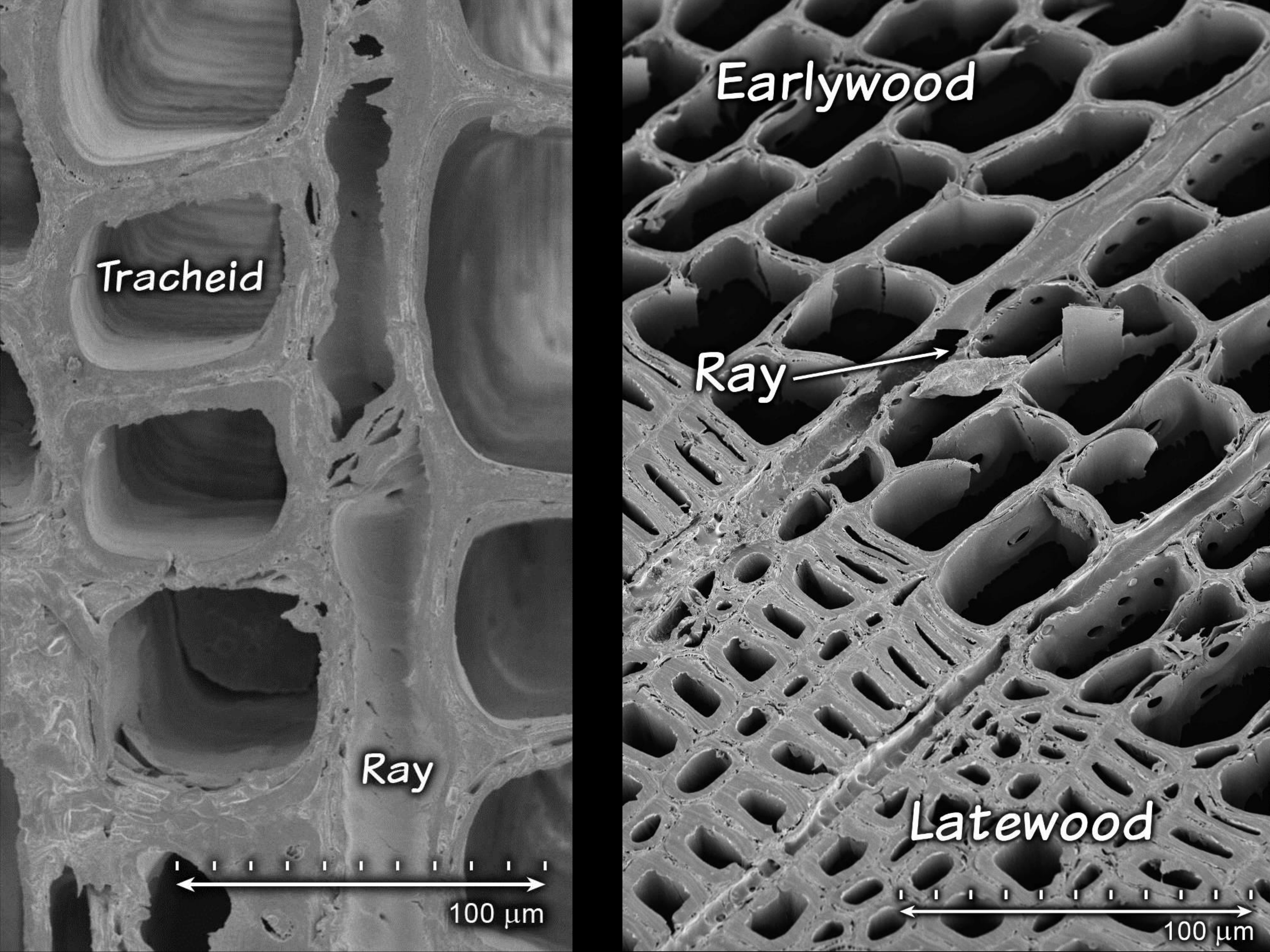
Contents

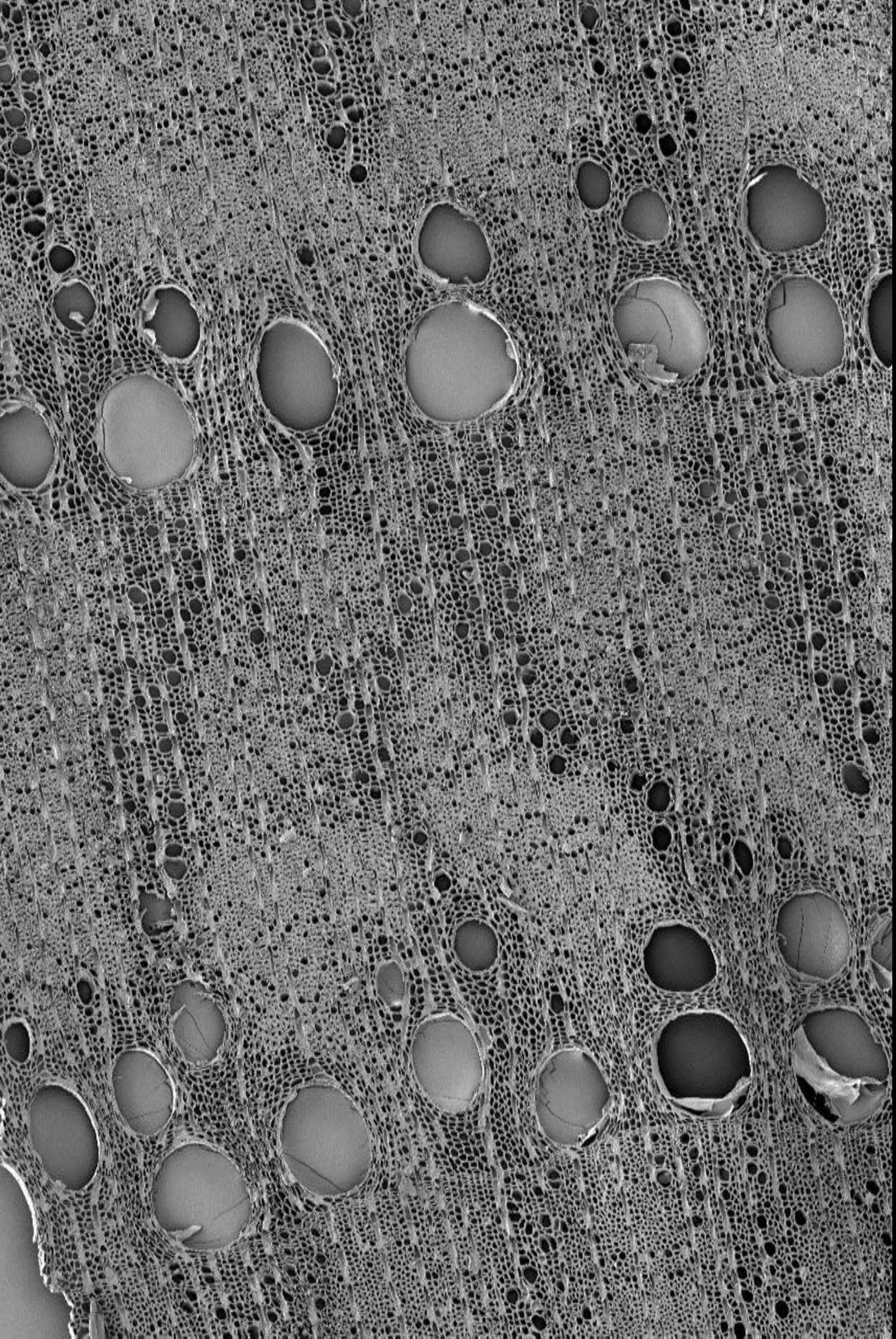

Compression wood
Sapwood
Pith
Heartwood
Knot

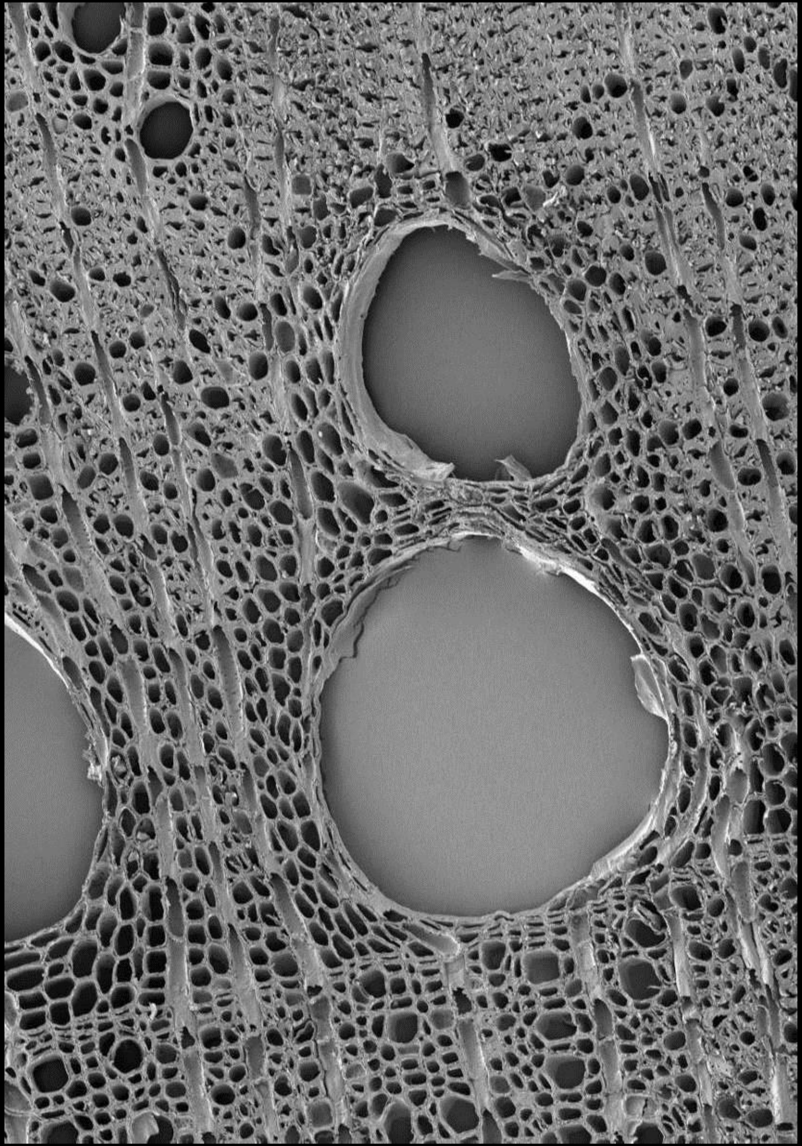


Late wood
Early wood

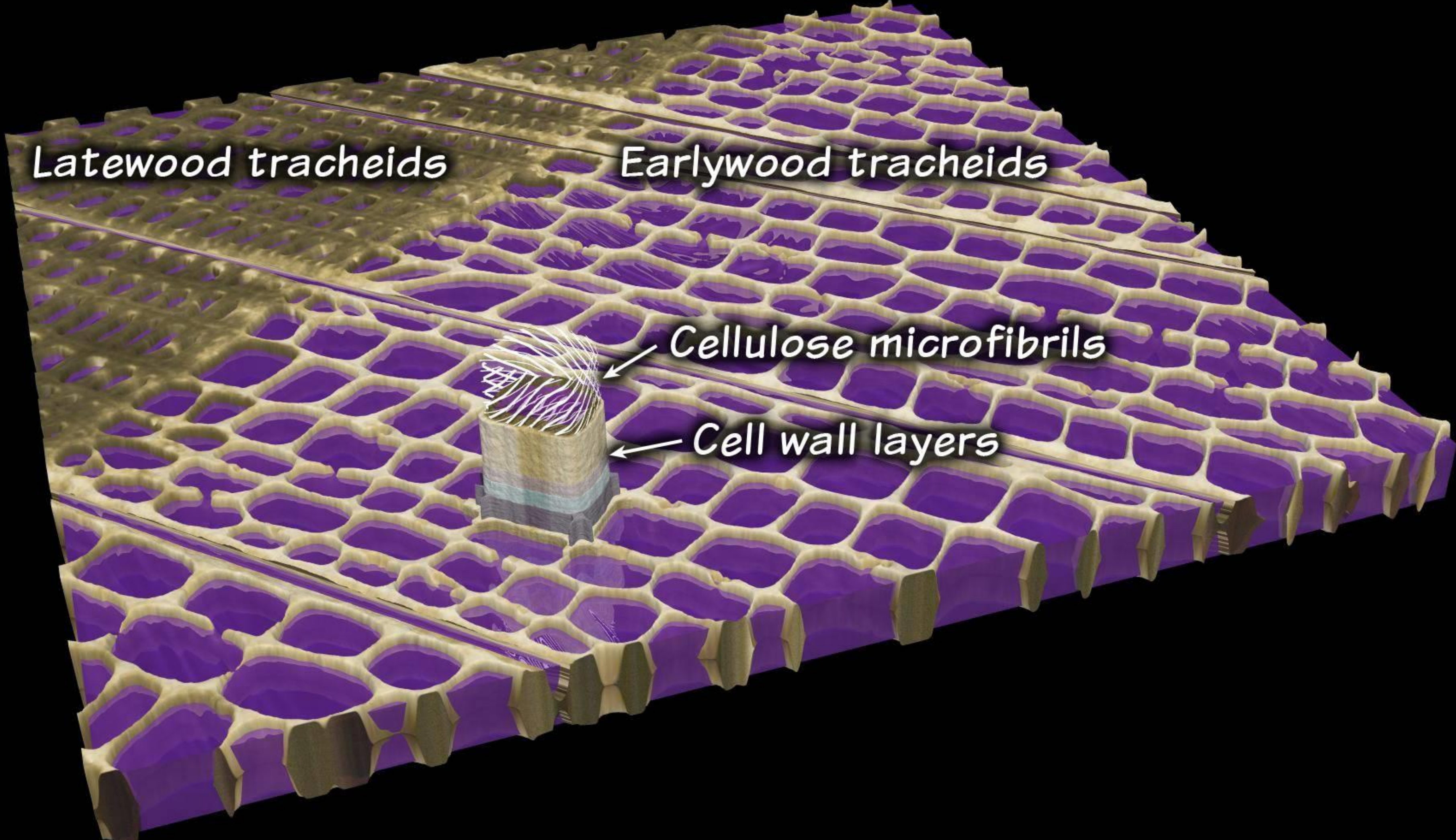

Cross-section
T
R
L
R
Radial face
Tangential face

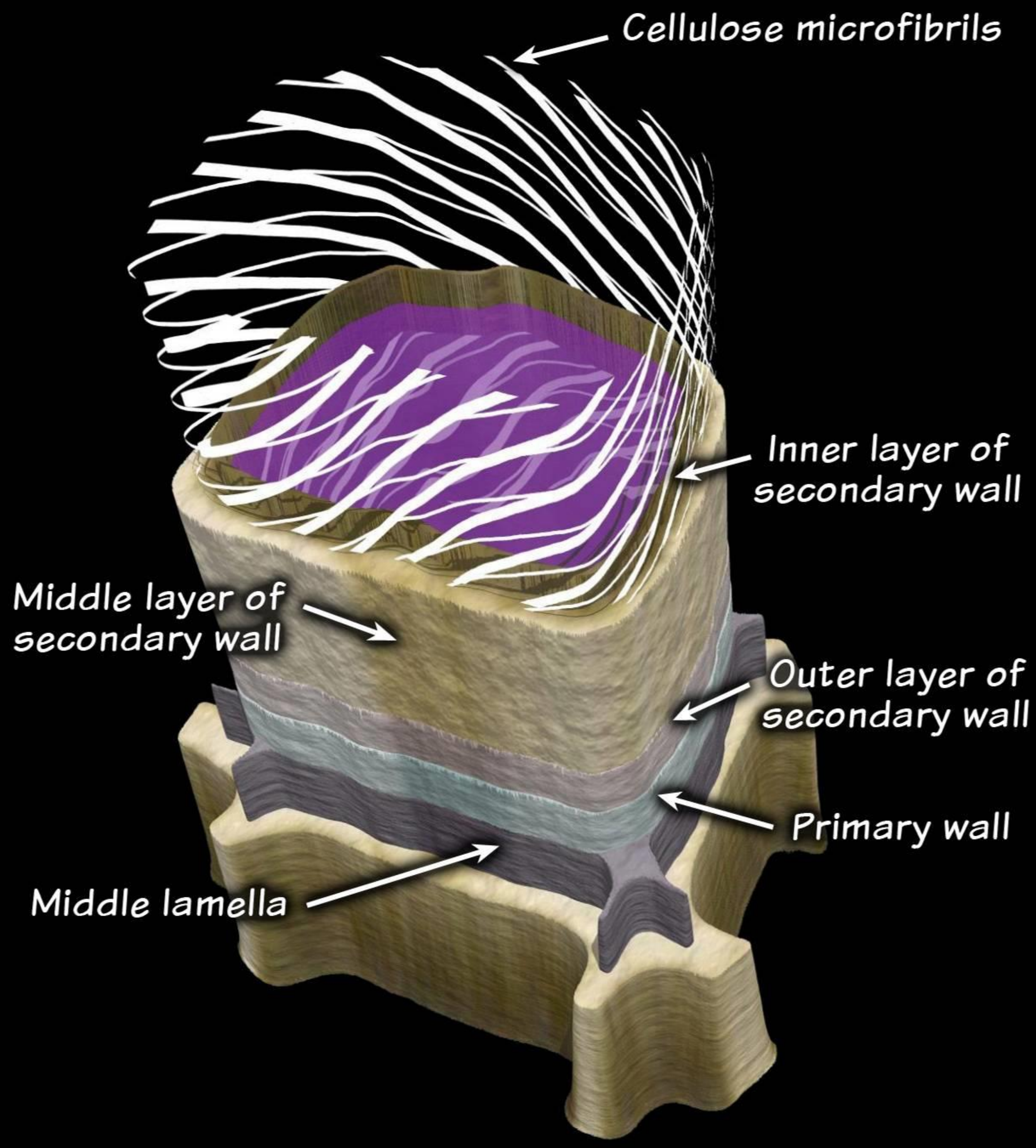

Tracheid
Ray
100 μm
Earlywood
Ray
Latewood
100 μm



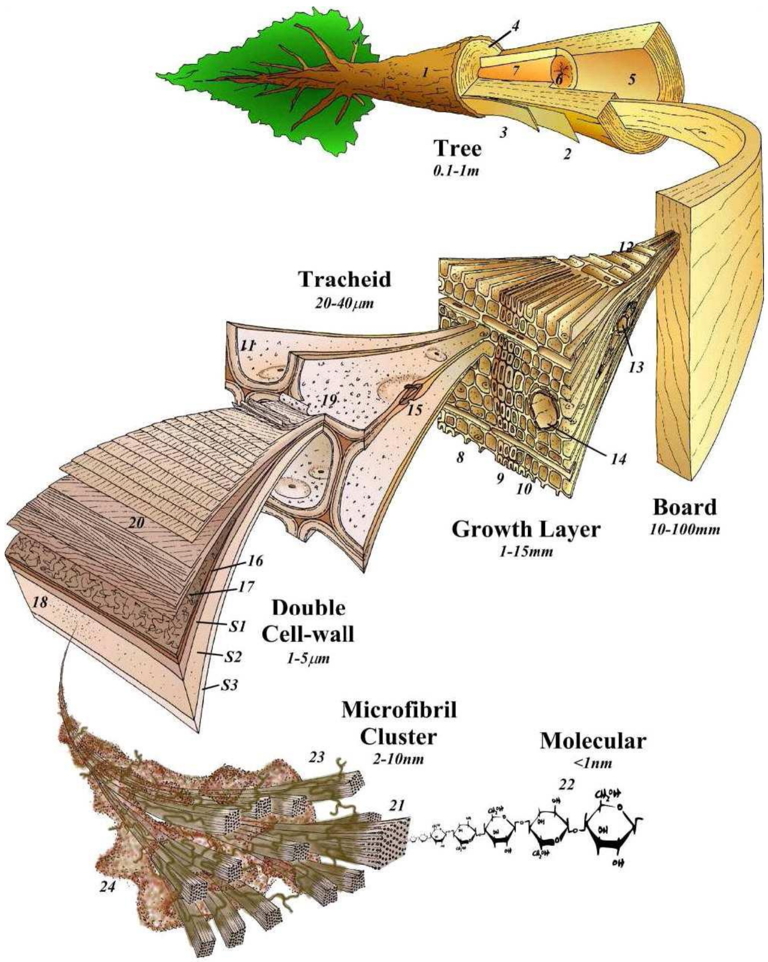


Vessels
(in hardwoods)


Latewood tracheids
Earlywood tracheids
Cellulose microfibrils
Cell wall layers


Cellulose microfibrils
Inner layer of secondary wall
Middle layer of secondary wall
Outer layer of secondary wall
Primary wall
Middle lamella

The famous Harrington diagram

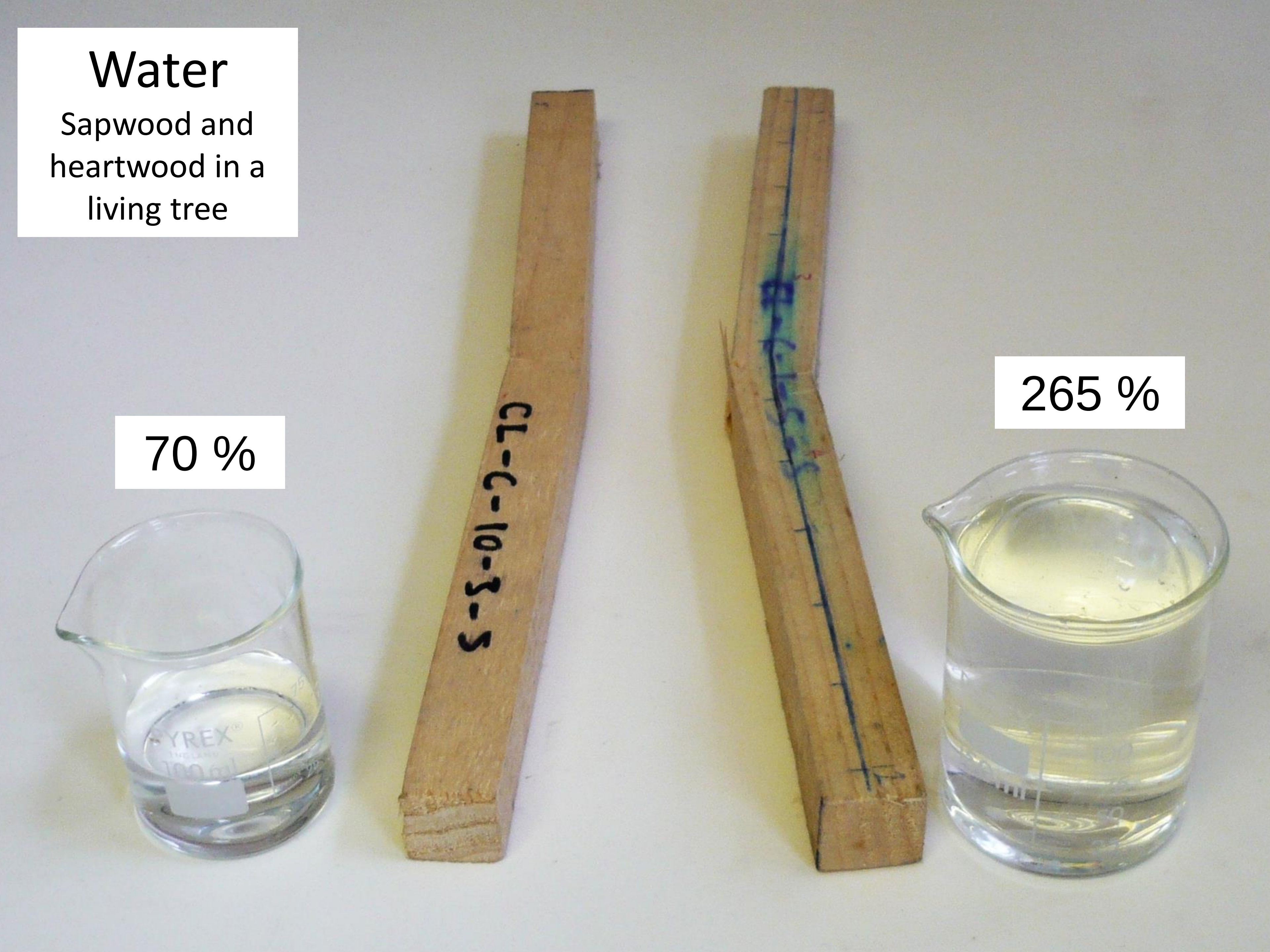


Harrington, J. J. (2002). Hierarchical Modelling of Softwood Hygro-Elastic Properties. PhD thesis, University of Canterbury.

	Tree		Building
m	Log		Assembly
		Sawn timber	
cm		Clear wood	
mm		Growth layer	
		Wood anatomy	
		Cell	
μm		Cell wall	
		Cell wall layers	
		Microfibril clusters	
nm		Molecular	

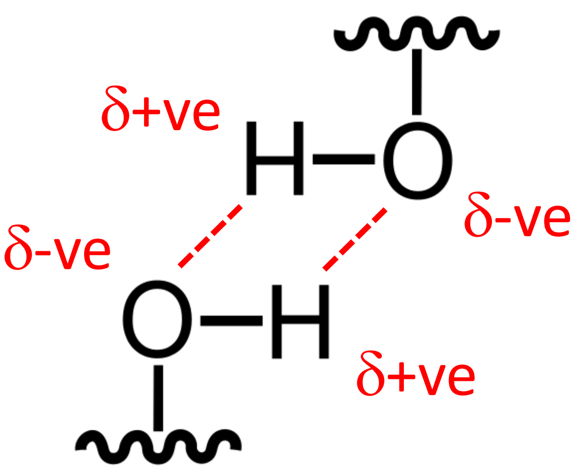
Constituents of wood

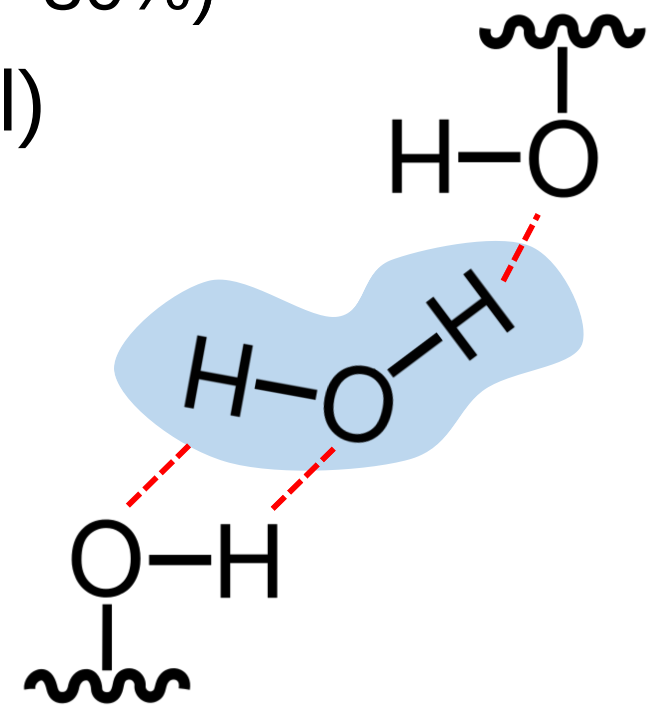
- **Cellulose**
  - A long polysaccharide molecule $(C_6H_{10}O_5)_n$
  - Crystalline and amorphous regions
  - Crystalline regions form microfibrils - analogous to reinforcing strand (main role tension)
- **Lignin**
  - A number of complex 3D biopolymers
  - Analogous to cement (main role compression)
- **Hemicelluloses**
  - Mixture of different sugar monomers
  - Links the cellulose and the lignin (giving flexibility)
- **Extractives and water**


Water
Sapwood and heartwood in a living tree
70 %
265 %
CL-C-10-3-5

Water

- Free water (in the lumen)
  - Above fibre saturation point (~30%)
- Bound water (in the cell wall)





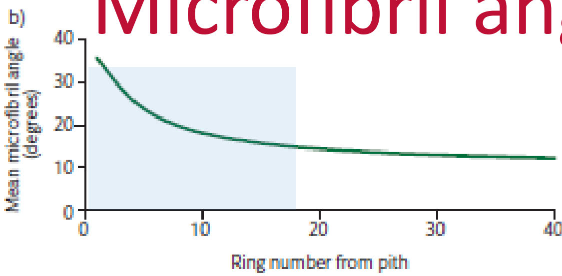
Mechanical properties depend on:

- Amount of cell wall material
  - Wood density
- How that cell wall material is arranged
  - Grain, earlywood, latewood
- How that cell wall material is made up
  - Cellulose : lignin : hemicellulose
  - Microfibril angle (orientation of crystalline cellulose)

http://goo.gl/z5dHsR

Juvenile core (softwoods) e.g. Sitka spruce

Microfibril angle



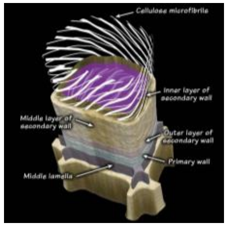


Figure 2.15 Radial profile of Sitka spruce wood density. The green lines show profiles for five individual trees sampled at Baronscourt in Northern Ireland, while the black line represents a model fitted to these data.

Density

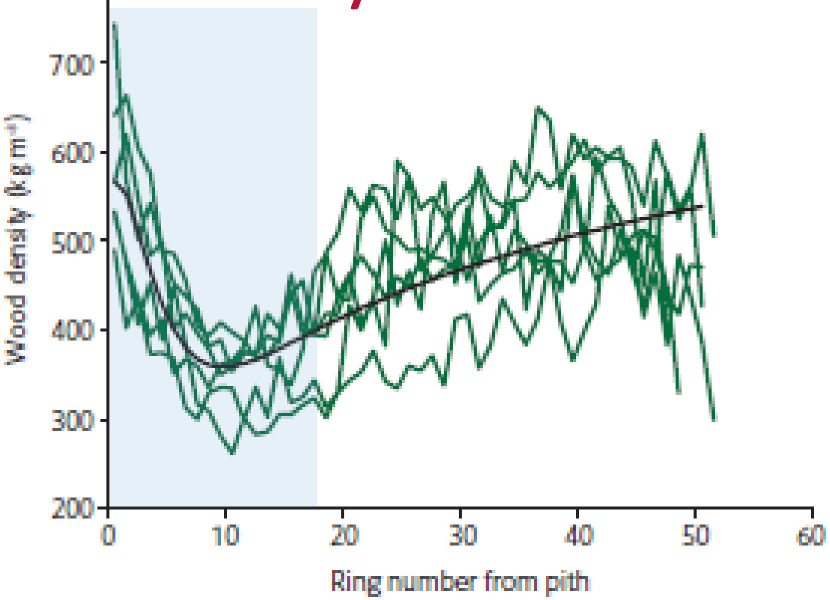
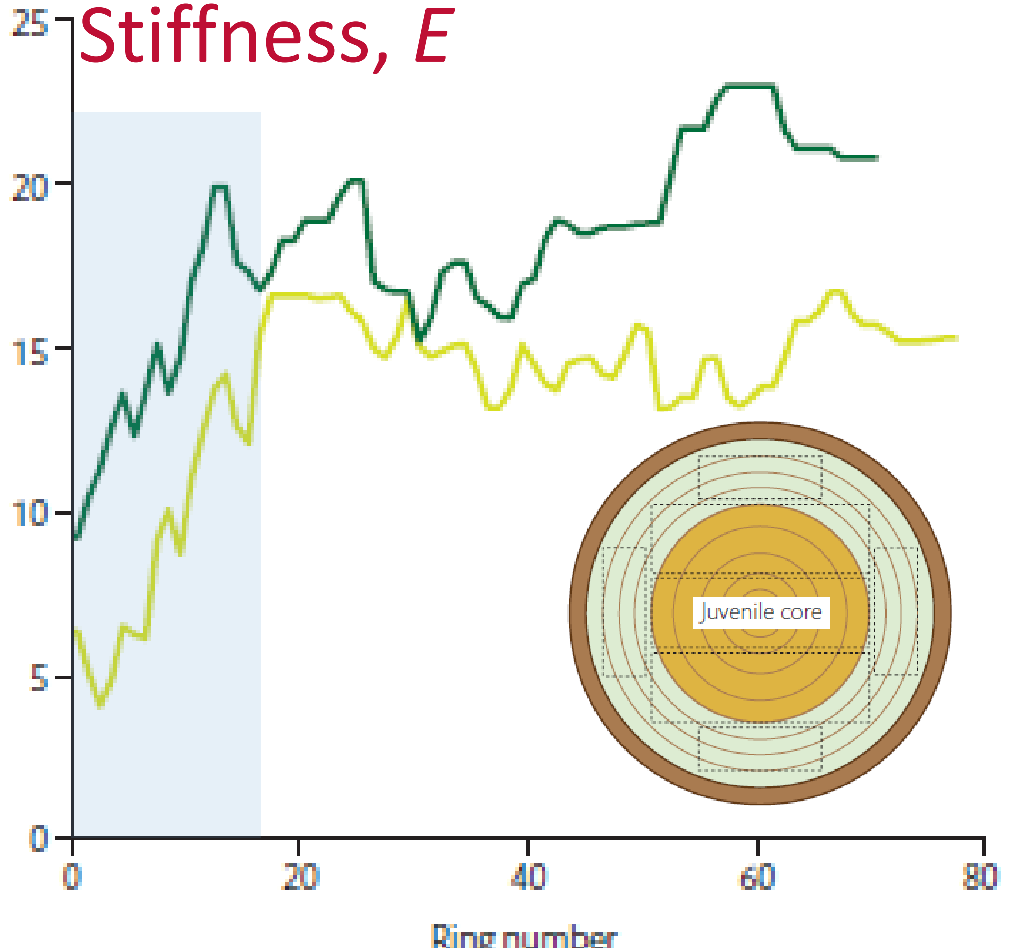
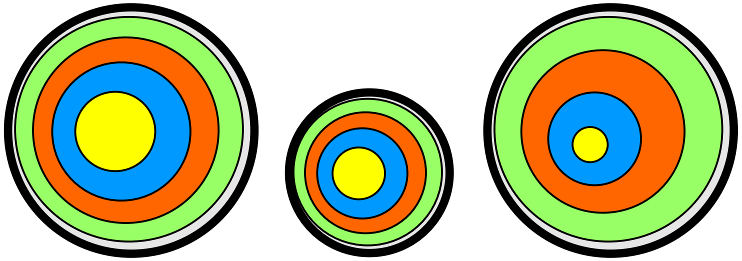


Figure 2.20 Example of the radial variation in modulus of elasticity for two specimens of Sitka spruce wood. Modulus of elasticity was estimated from data on density and microfibril angle obtained from SilviScan-3.

Stiffness, *E*



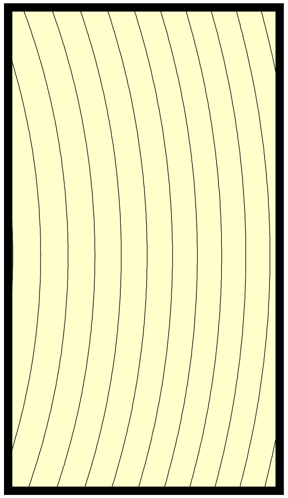
Factors affecting softwood quality



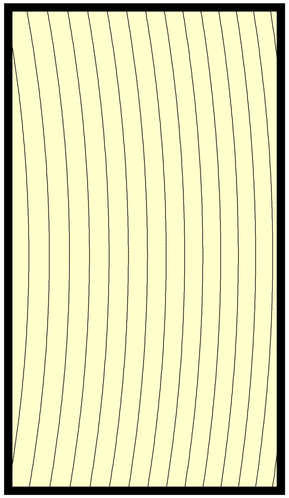
- Position within the tree
  - Radially & vertically
- Silviculture
  - Spacing, thinning, rotation length etc
- Site
  - Exposure, temperature, rainfall, soil type etc
- Genetics
  - Species, variety and individual

"Rate of growth"

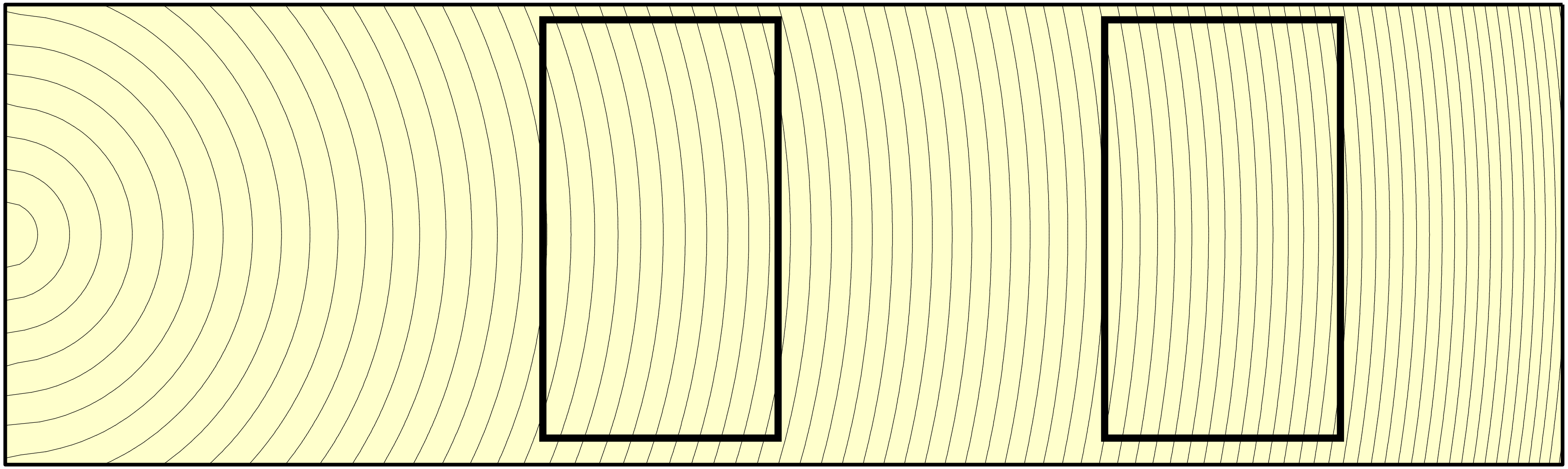
Grew in ~11 years



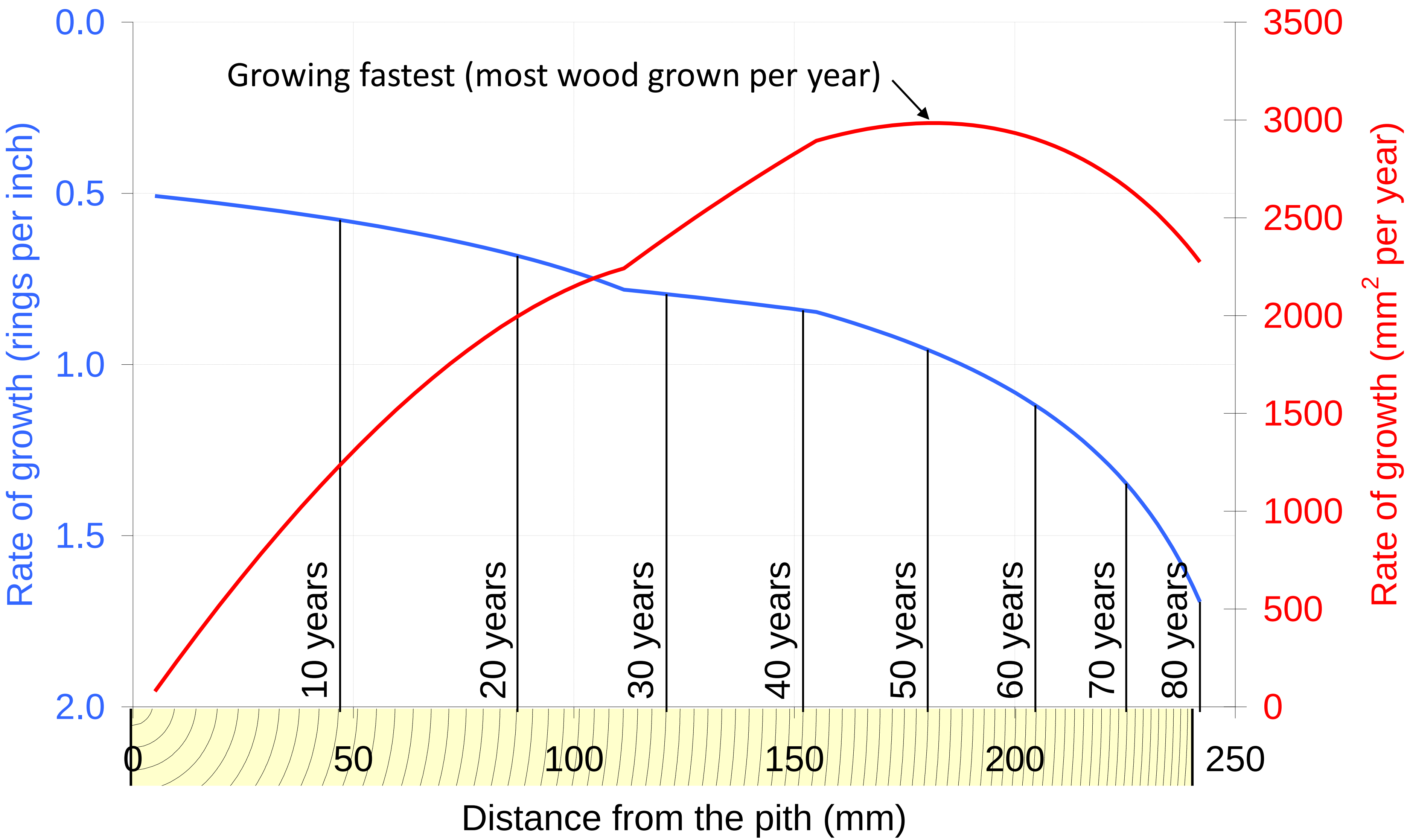
Grew in ~15 years



“Rate of growth”



“Rate of growth”



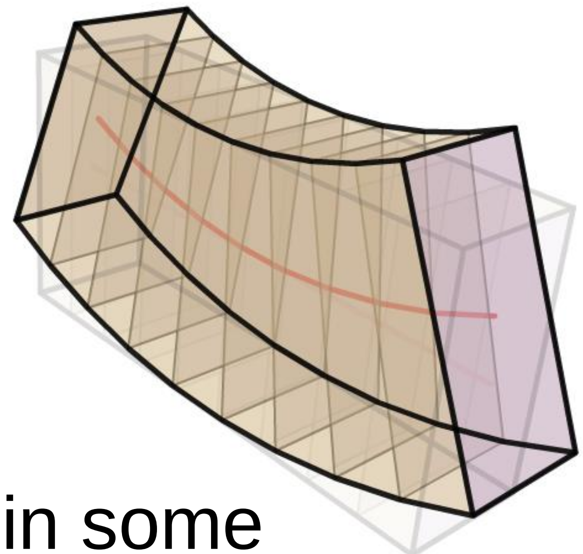
Three key properties

Strength at 12% MC

- Major axis bending strength

Stiffness at 12% MC

- Major axis bending stiffness



Density at 12% MC

- An indirect measure of strength in some elements of timber design

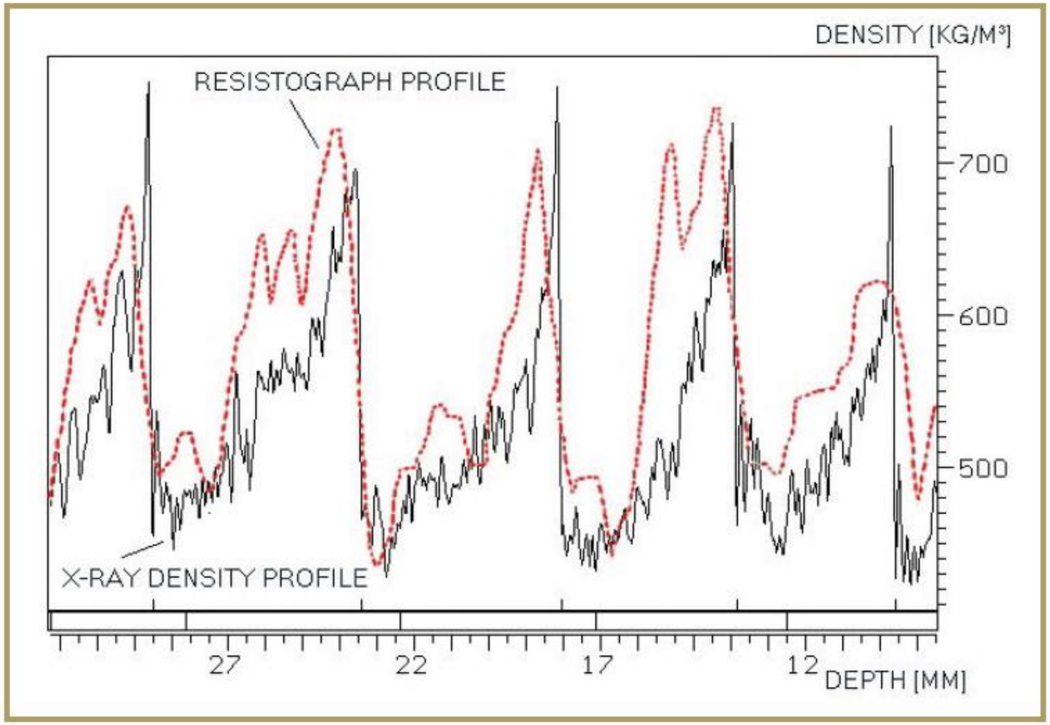
Sources of variation (e.g. UK grown Sitka spruce)

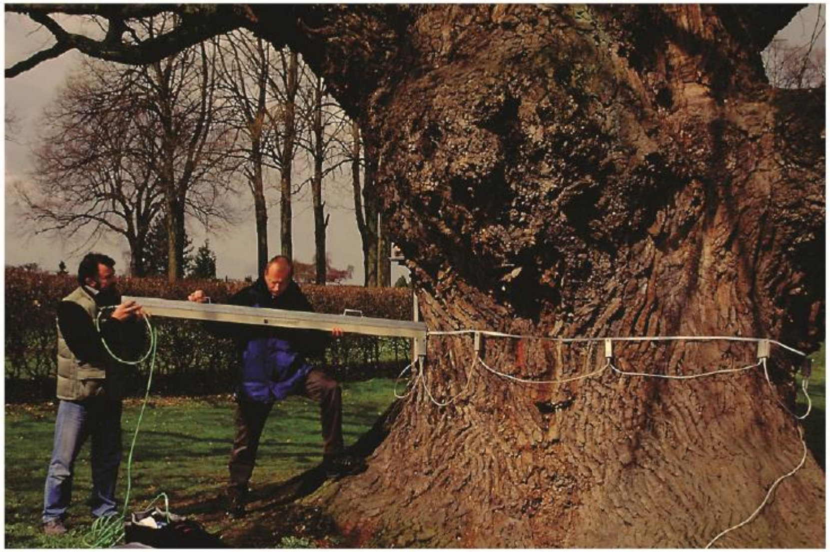
Source	Density	Strength	Stiffness
Between sites	23%	18%	26%
Between trees on a site	51%	25%	36%
Between logs in a tree	2%	5%	2%
Within log	25%	52%	35%

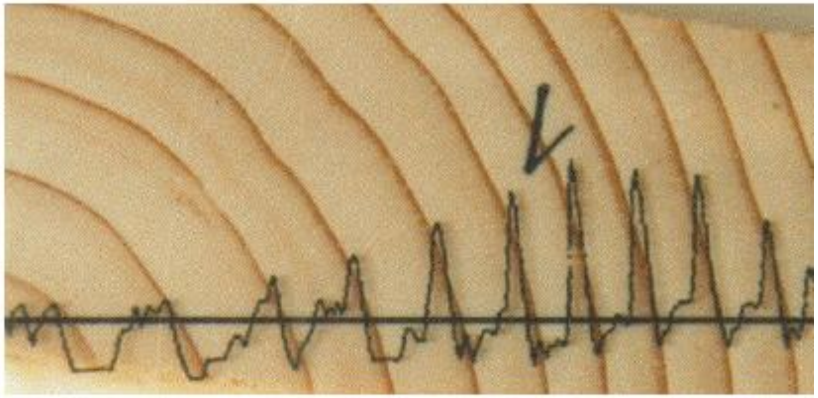
Two pieces of wood from the same tree can be very different!

Moore, J. R., Lyon, A. J., Searles, G. J., Lehneke, S. A., Ridley-Ellis, D. J. Within- and between-stand variation in selected properties of Sitka spruce sawn timber in the United Kingdom: implications for segregation and grade recovery. Annals of Forest Science (February 2013)

Earlywood – latewood variation

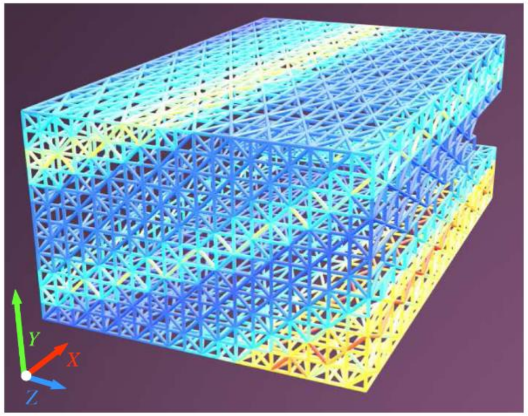


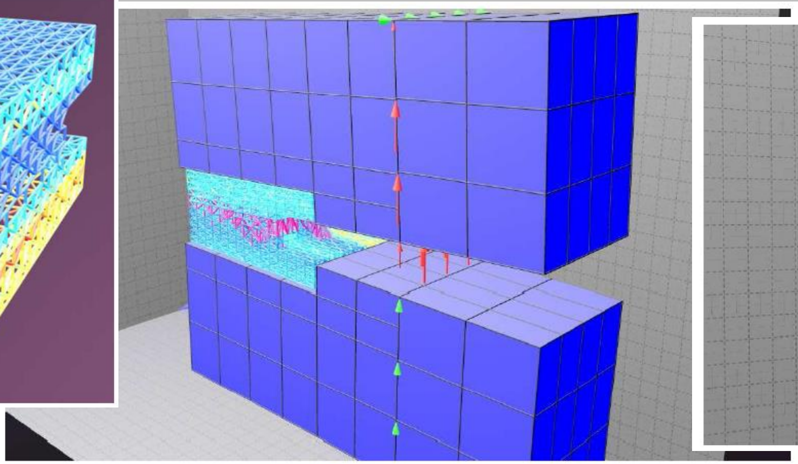


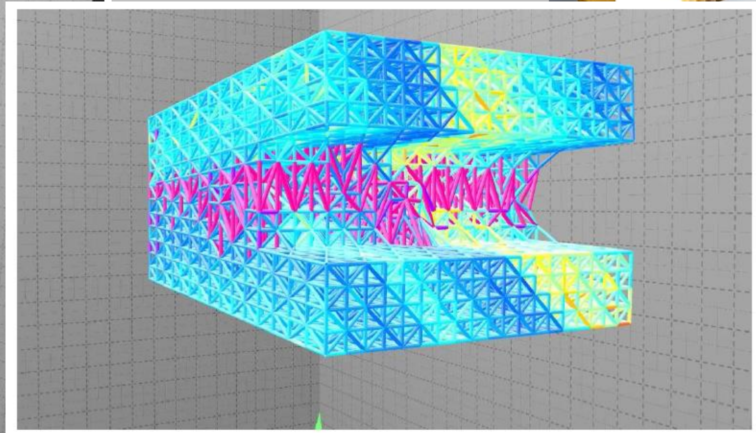


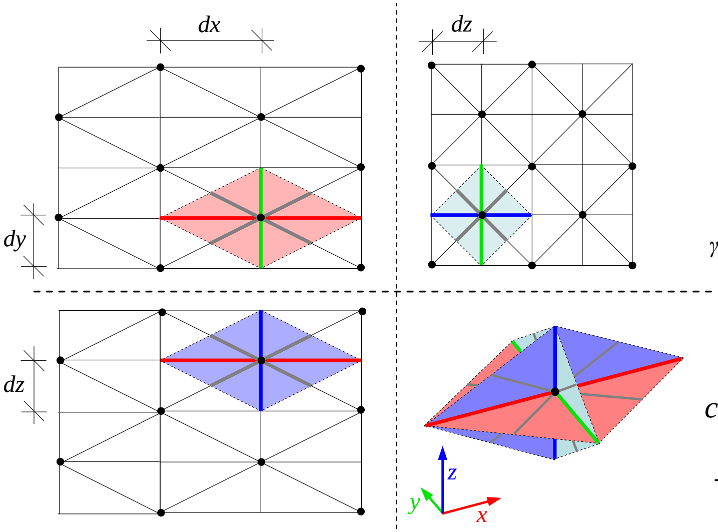
Frank Rinn “Basics of micro-resistance drilling for timber inspection” Holztechnologie March 2012

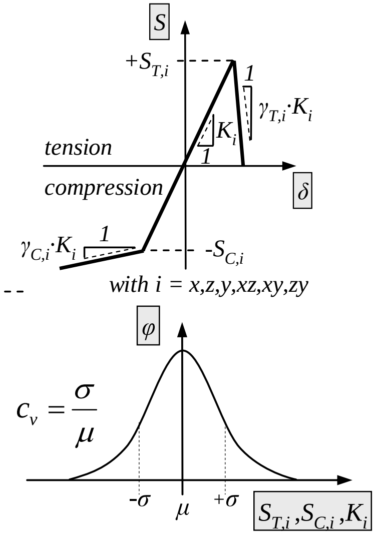
Earlywood – latewood variation - example

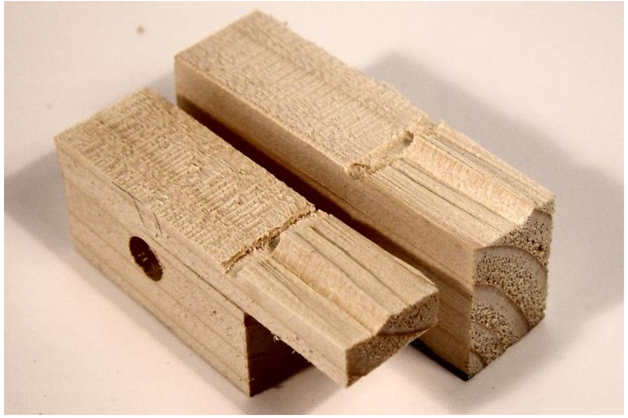






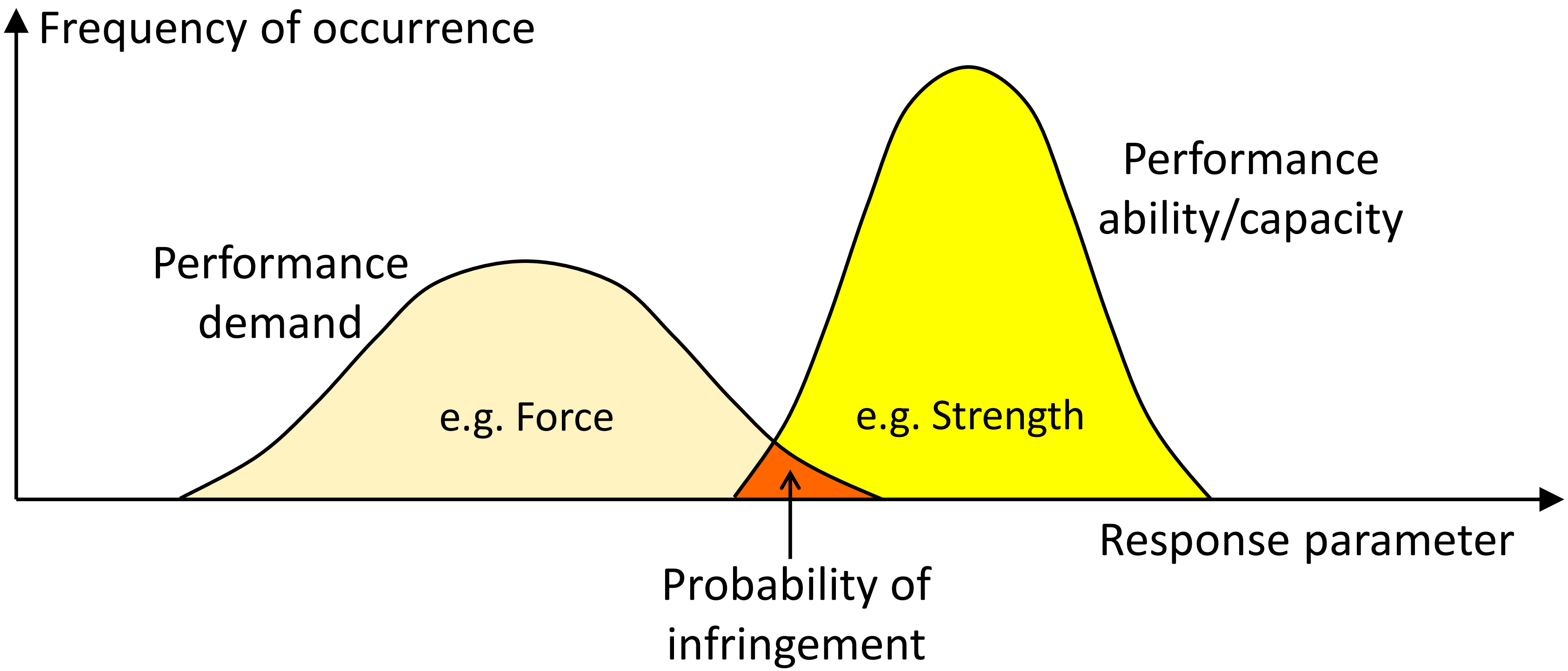






Reichert, T. (2009) “Development of 3D lattice models for predicting non-linear timber joint behaviour. PhD thesis, Edinburgh Napier University.

Dealing with uncertainty of properties



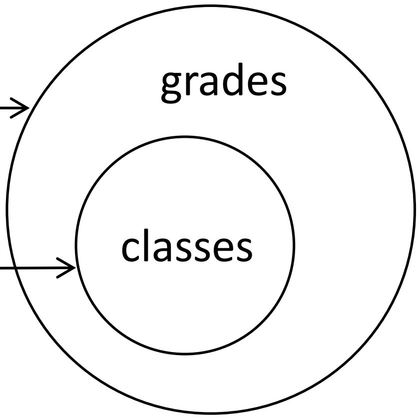
Some terms
Grades and classes

Strength grade

- Sets (e.g. “looks good” and “looks bad”

Strength class

- Has numerical properties (for design calcs)



Strength grading

1. Timber is sorted to grades
2. Grades are assigned to a class

A strength class is special kind of strength grade (one that has numerical properties)

Grade-determining properties (of a class)

Strength

- Usually major axis bending strength

Stiffness

- Usually major axis bending stiffness

Density

- An indirect measure of strength in some elements of timber design

All other properties are estimated from those 3 properties

e.g. shear strength and stiffness

tension and compression strength perpendicular to grain

What grades cannot do

Grading does not operate on individual pieces

(any individual piece could, in principle, correctly belong to several different strength classes)

(grading is concerned with collective properties of timber in a grade)

Having the same strength class does not make pieces equal

(strength classes are broad statistical distributions that overlap)

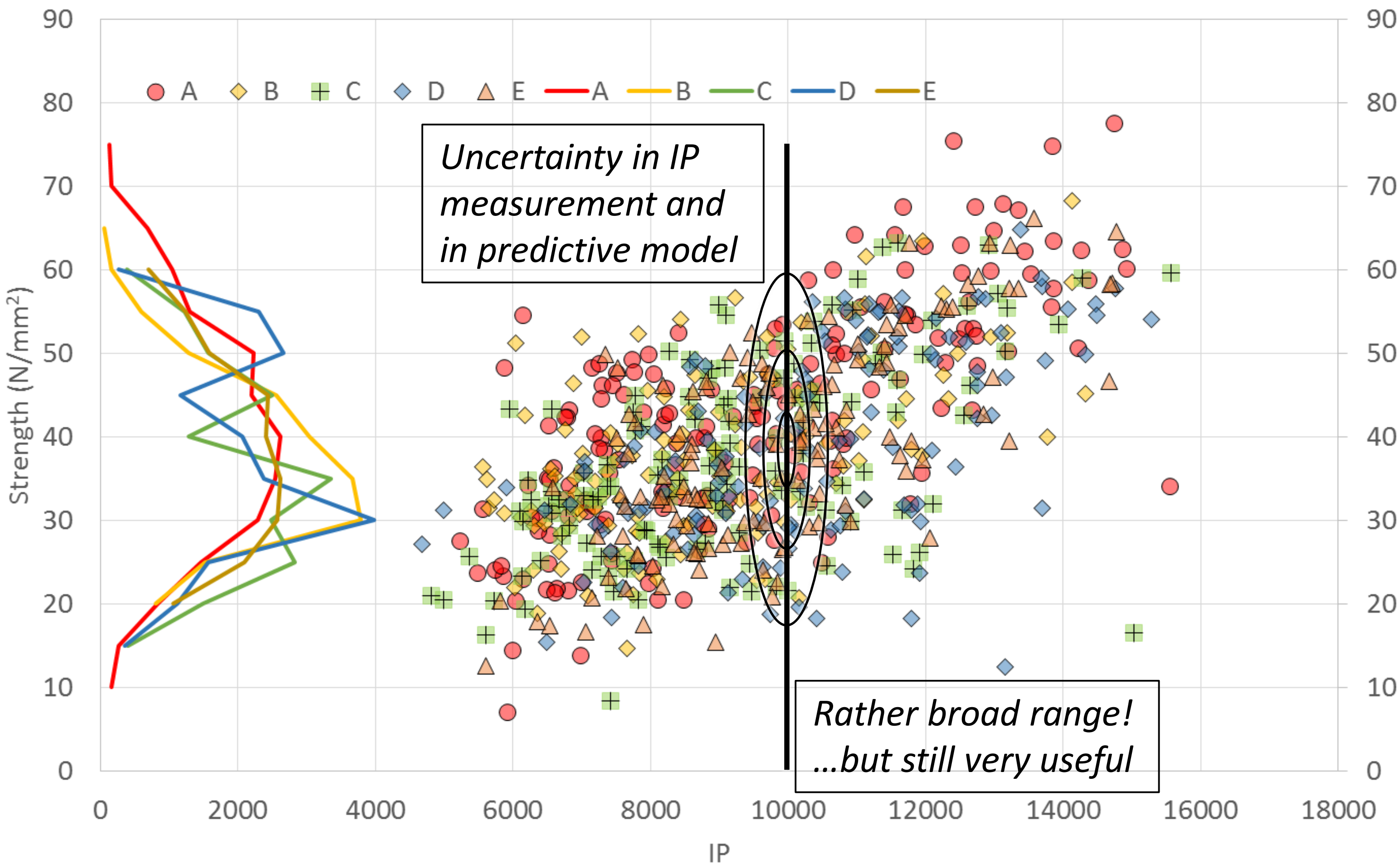
The strength class does not tell you what the properties are

(not of individual pieces)

What you need for design

(and only specifies a lower limit for timber, collectively, in the grade)

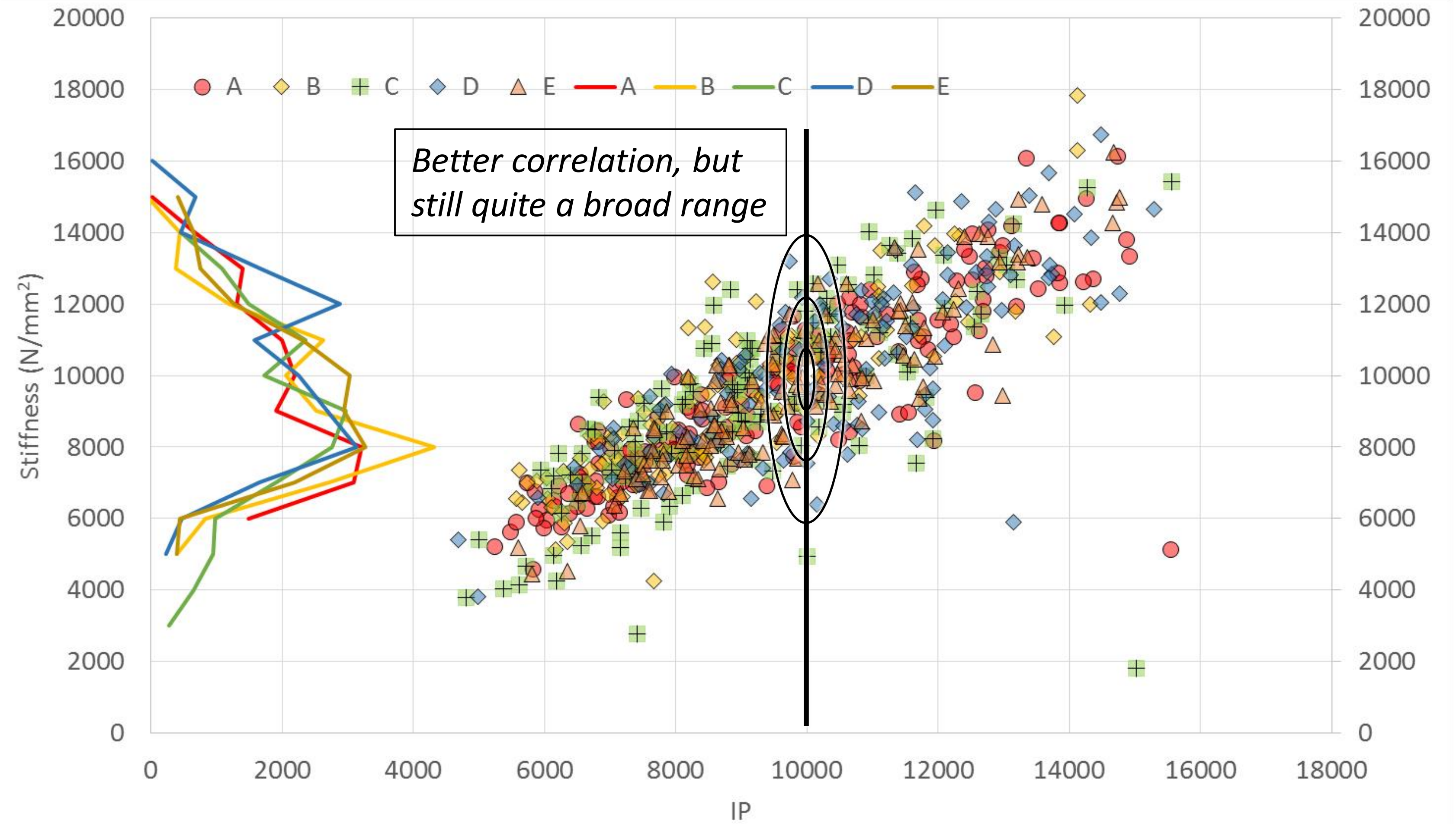
An indicating property (IP)
e.g. predicting bending strength from E_{dyn}



(Dynamic modulus of elasticity from longitudinal resonance)

http://goo.gl/z5dHsR

An indicating property (IP)
e.g. predicting bending stiffness from E_{dyn}



(Dynamic modulus of elasticity from longitudinal resonance)

The indicating property can…

Tell you something about the properties

- Although there is uncertainty in the values
- And you need to know the relationship between IP and the property

Importantly - this relationship between IP and the property varies

- By species
- By growth area

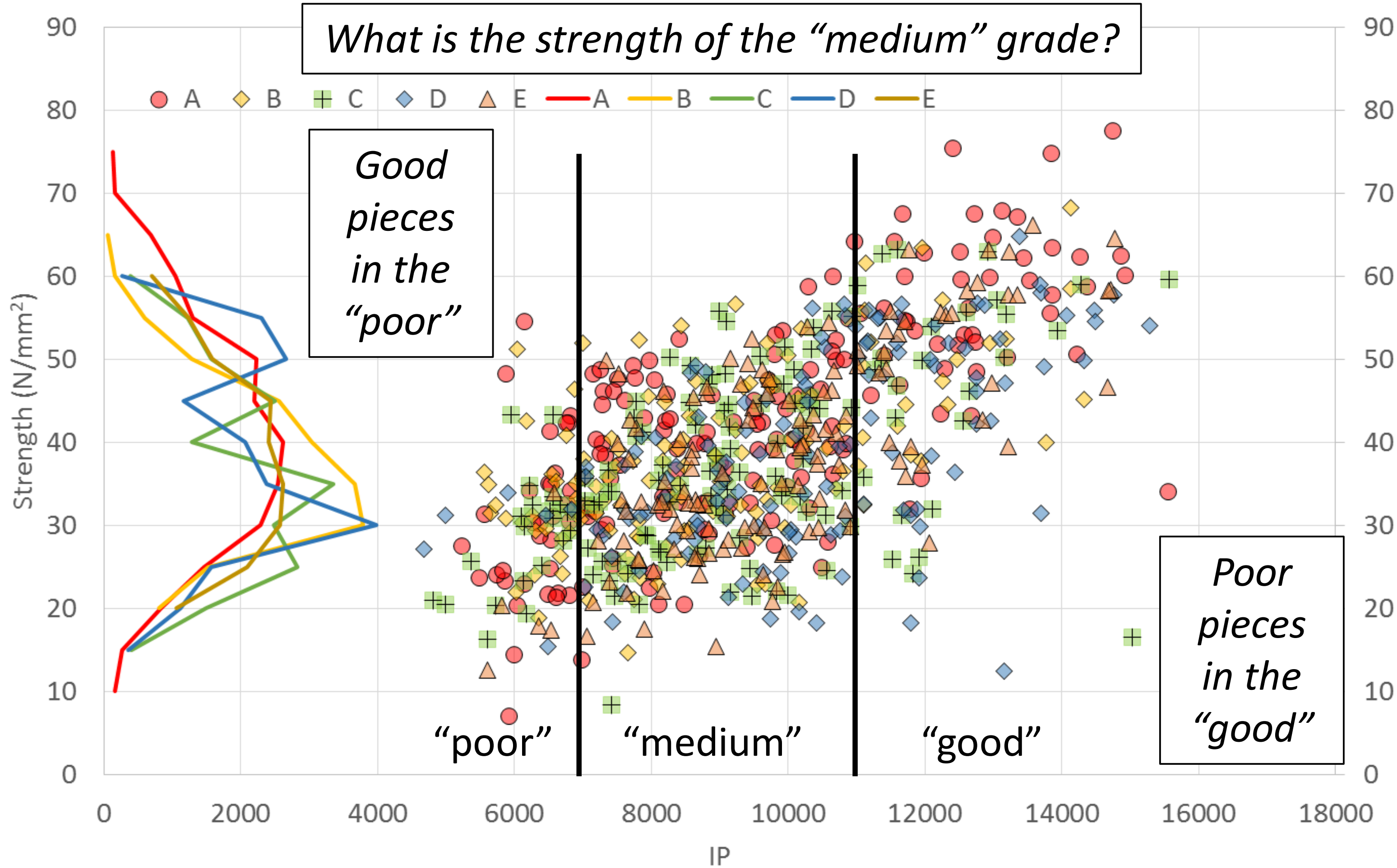
Grading is limited by growth area.
You cannot use relationships established for one growth area on timber from another (matching species is not enough!)

…in terms of

- Gradient and intercept of the line…but also
- Average value of the property
- Standard deviation of the property
- The "goodness of the correlation"
- Also, the relationship between the important properties

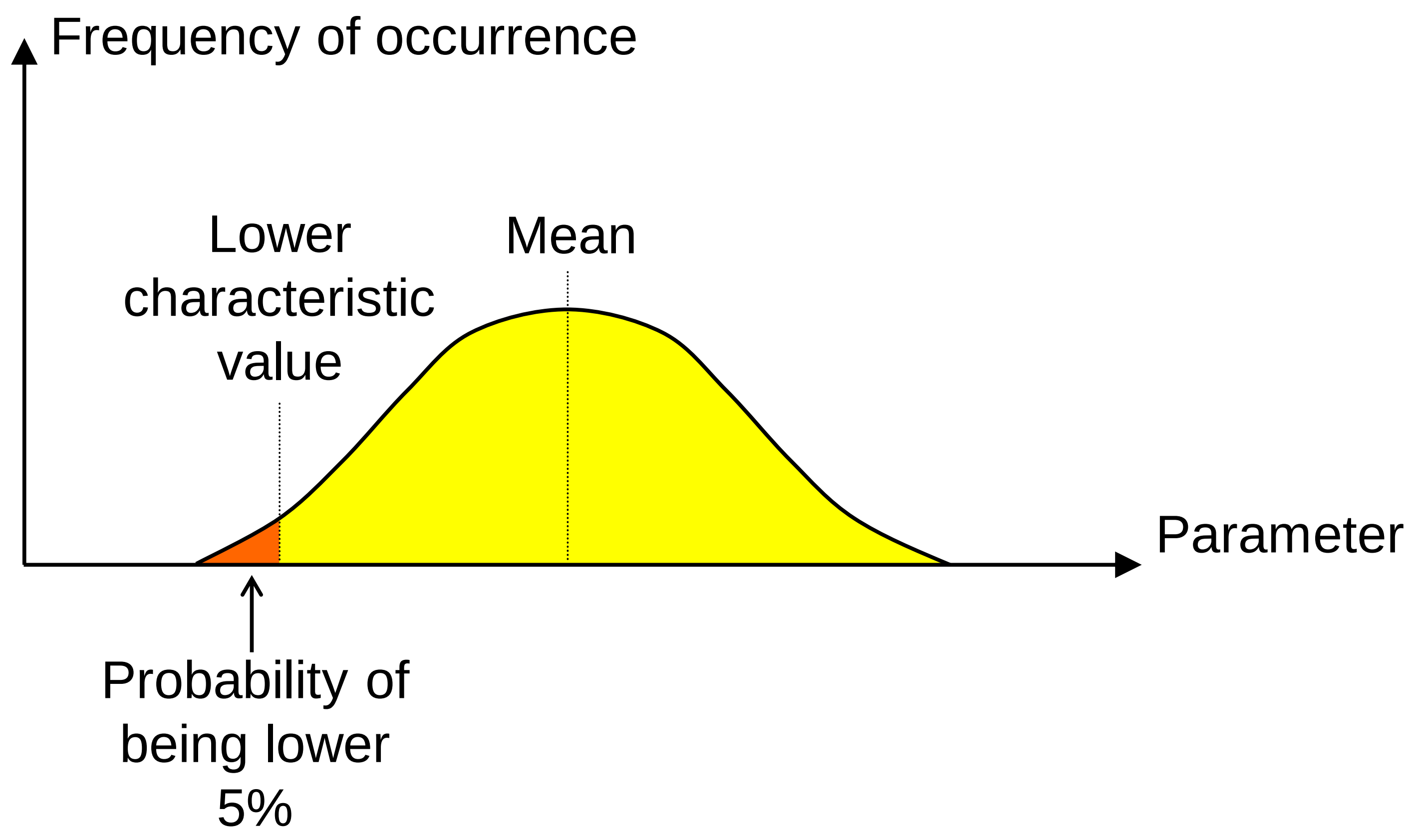
Influenced by climate and forest management

Grades are not single IP values
They are discrete sets defined by boundaries of IP



(Dynamic modulus of elasticity from longitudinal resonance)

Characteristic values



Critical property

Strength classes are defined by characteristic

- Strength (lower 5th percentile)
- Stiffness (mean)
- Density (lower 5th percentile)

For standard strength classes, the limits are general across species

- “Softwoods” (EN338 C classes...major axis bending)
- Hardwoods (EN338 D classes...major axis bending)
- Softwoods (prEN338 tension classes…tension)

Other strength class systems exist

- And you can make up your own!
- By specifying characteristic strength, stiffness and density

EN338

		Softwood species (Soon could be hardwood species too)											
		C14	C16	C18	C20	C22	C24	C27	C30	C35	C40	C45	C50
Strength properties (in N/mm^2)													
Bending	$f_{m,k}$	14	16	18	20	22	24	27	30	35	40	45	50
Tension parallel	$f_{t,0,k}$	8	10	11	12	13	14	16	18	21	24	27	30
Tension perpendicular	$f_{t,90,k}$	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4
Compression parallel	$f_{c,0,k}$	16	17	18	19	20	21	22	23	25	26	27	29
Compression perpendicular	$f_{c,90,k}$	2,0	2,2	2,2	2,3	2,4	2,5	2,6	2,7	2,8	2,9	3,1	3,2
Shear	$f_{v,k}$	3,0	3,2	3,4	3,6	3,8	4,0	4,0	4,0	4,0	4,0	4,0	4,0
Stiffness properties (in kN/mm^2)													
Mean modulus of elasticity parallel	$E_{0,mean}$	7	8	9	9,5	10	11	11,5	12	13	14	15	16
5 % modulus of elasticity parallel	$E_{0,05}$	4,7	5,4	6,0	6,4	6,7	7,4	7,7	8,0	8,7	9,4	10,0	10,7
Mean modulus of elasticity perpendicular	$E_{90,mean}$	0,23	0,27	0,30	0,32	0,33	0,37	0,38	0,40	0,43	0,47	0,50	0,53
Mean shear modulus	G_{mean}	0,44	0,5	0,56	0,59	0,63	0,69	0,72	0,75	0,81	0,88	0,94	1,00
Density (in kg/m^3)													
Density	ρ_k	290	310	320	330	340	350	370	380	400	420	440	460
Mean density	ρ_{mean}	350	370	380	390	410	420	450	460	480	500	520	550

Critical property

To comply with the grade, characteristic values must be met (at least)*

Together with some visual override requirements including

- Fissures
- Distortion

For a species and grade combination usually one property is limiting

- Strength
- Stiffness
- Density

So strength grading isn't *always* about predicting strength

*** Well, not quite…there is a bit more to it…**

The bit more…

The mean (bending or tension) stiffness only needs only to exceed 95% of the mean stiffness value of the strength class

(Because testing is currently done centred on the worst location in a specimen to get the lowest strength. In practice, the stiffness of the sample in general is more important)

For machine grading, the characteristic bending strength of strength classes up to C30 (and equivalent) only needs to exceed 89% of the characteristic bending strength of the strength class

(The k_v factor of 1.12 accounts for the reduced human involvement in machine grading and the additional confidence that this is supposed to afford)

There is a size factor (k_h) that modifies the requirement for strength to do the opposite of the (k_h) in EN1995-1

(It is not really known if there is a size factor for wood anyway)

And so…for graded timber

For the set of graded timber

It is probable that at least one of the grade determining properties exceeds the requirements of the strength class (all three might)

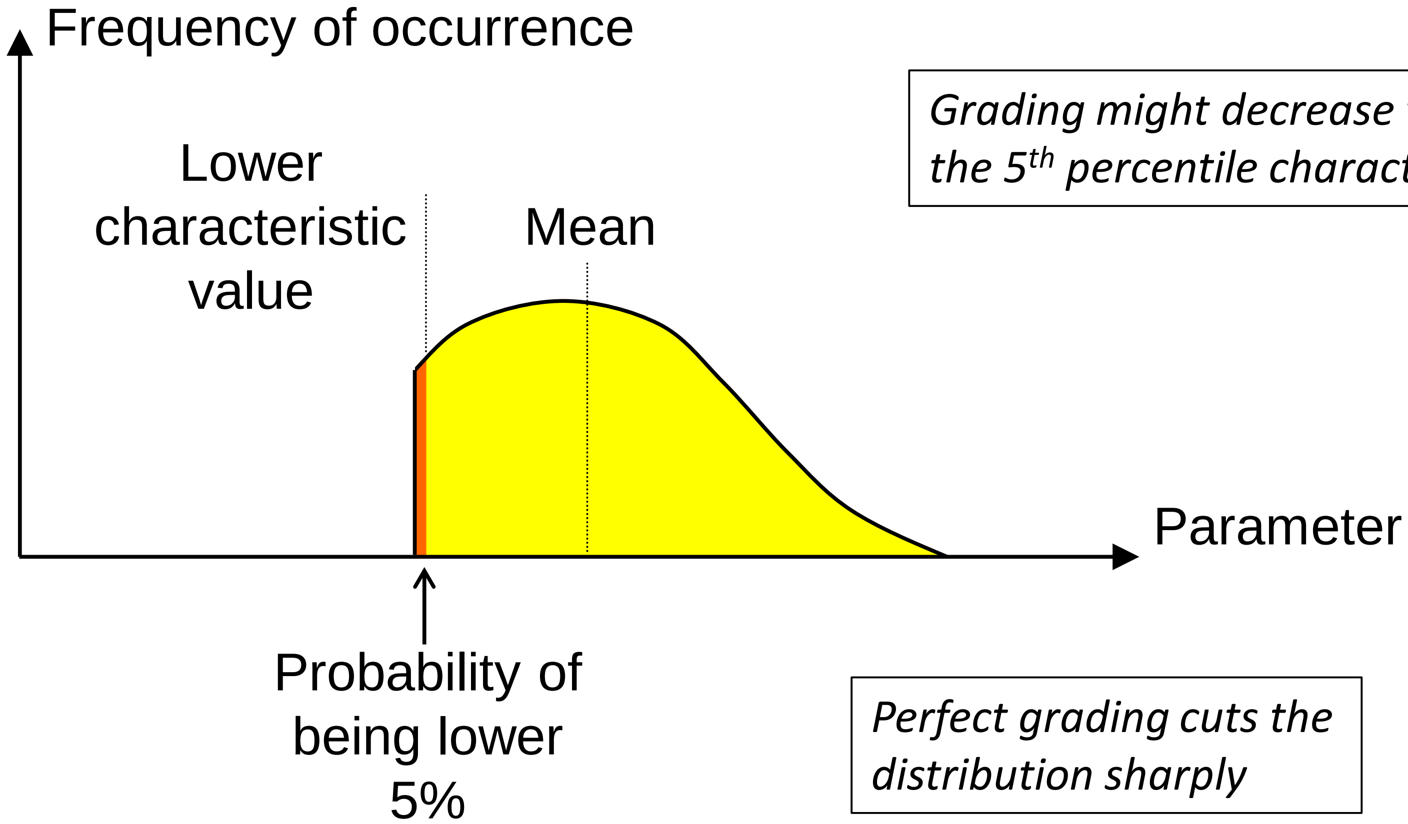
The secondary properties will exceed what is listed for that strength class – probably by quite a lot (because they are conservative estimates that have to work for all species)

For an single piece of correctly graded timber

For strength and density all you can really say is that there is at least 95% chance that the property for that piece will exceed the characteristic value of the strength class (subject to the previous slide)

For stiffness, the expected value for the piece is at least the value of the strength class (×95%), but you don't know the spread of values

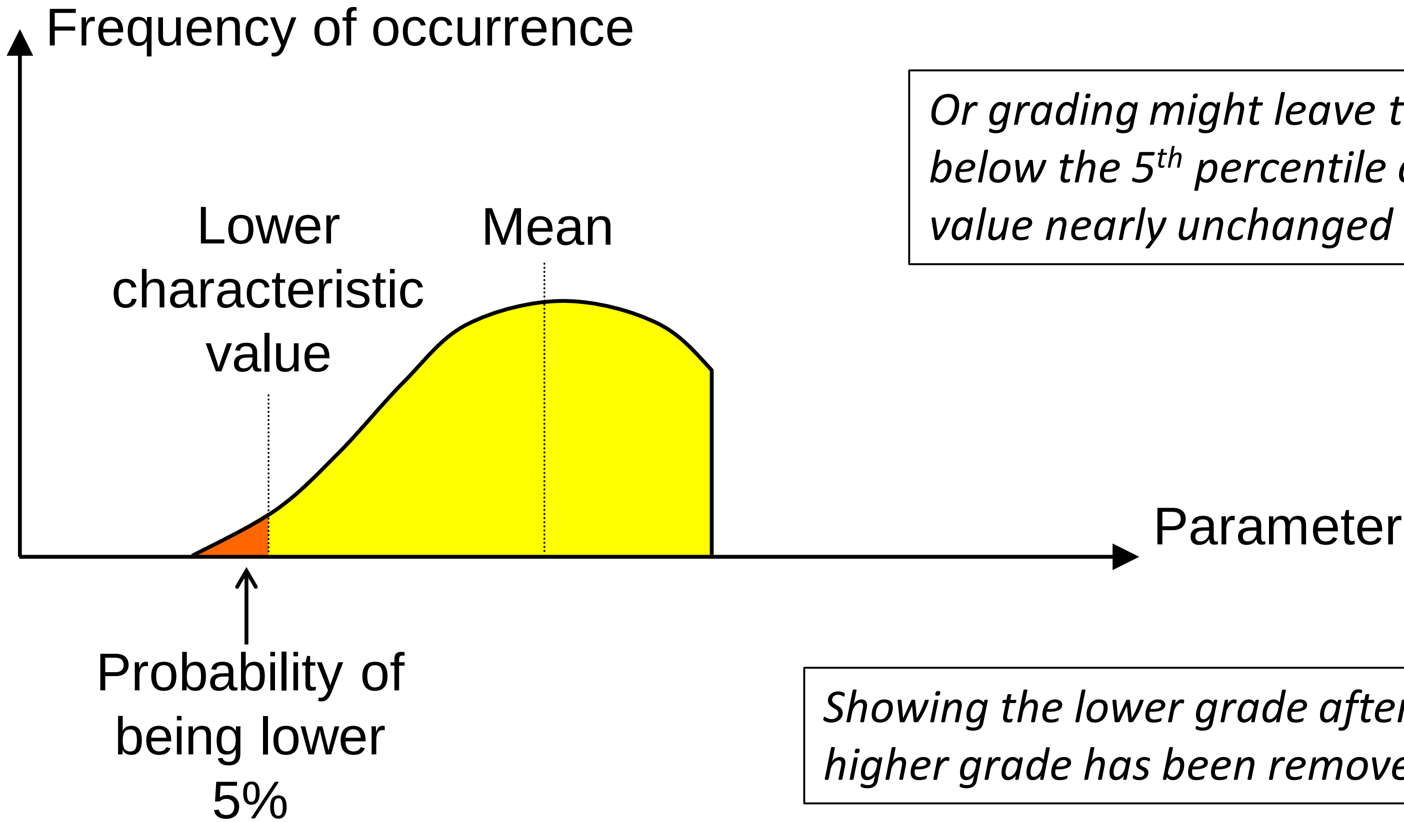
Characteristic values
Grading influences the distributions



Grading might decrease the spread below the 5th percentile characteristic value

Perfect grading cuts the distribution sharply

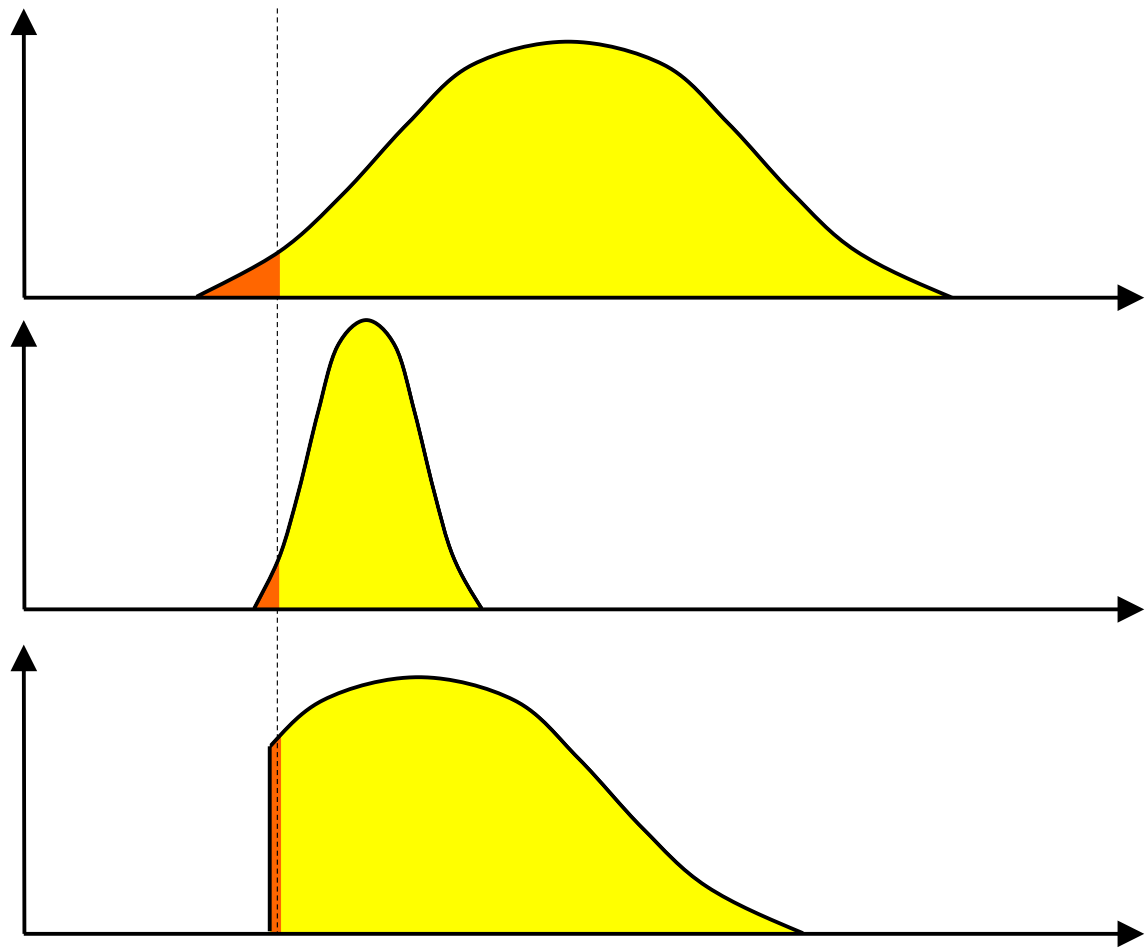
Characteristic values
Grading influences the distributions



Or grading might leave the spread below the 5th percentile characteristic value nearly unchanged

Showing the lower grade after a higher grade has been removed

Distributions with the same 5%ile

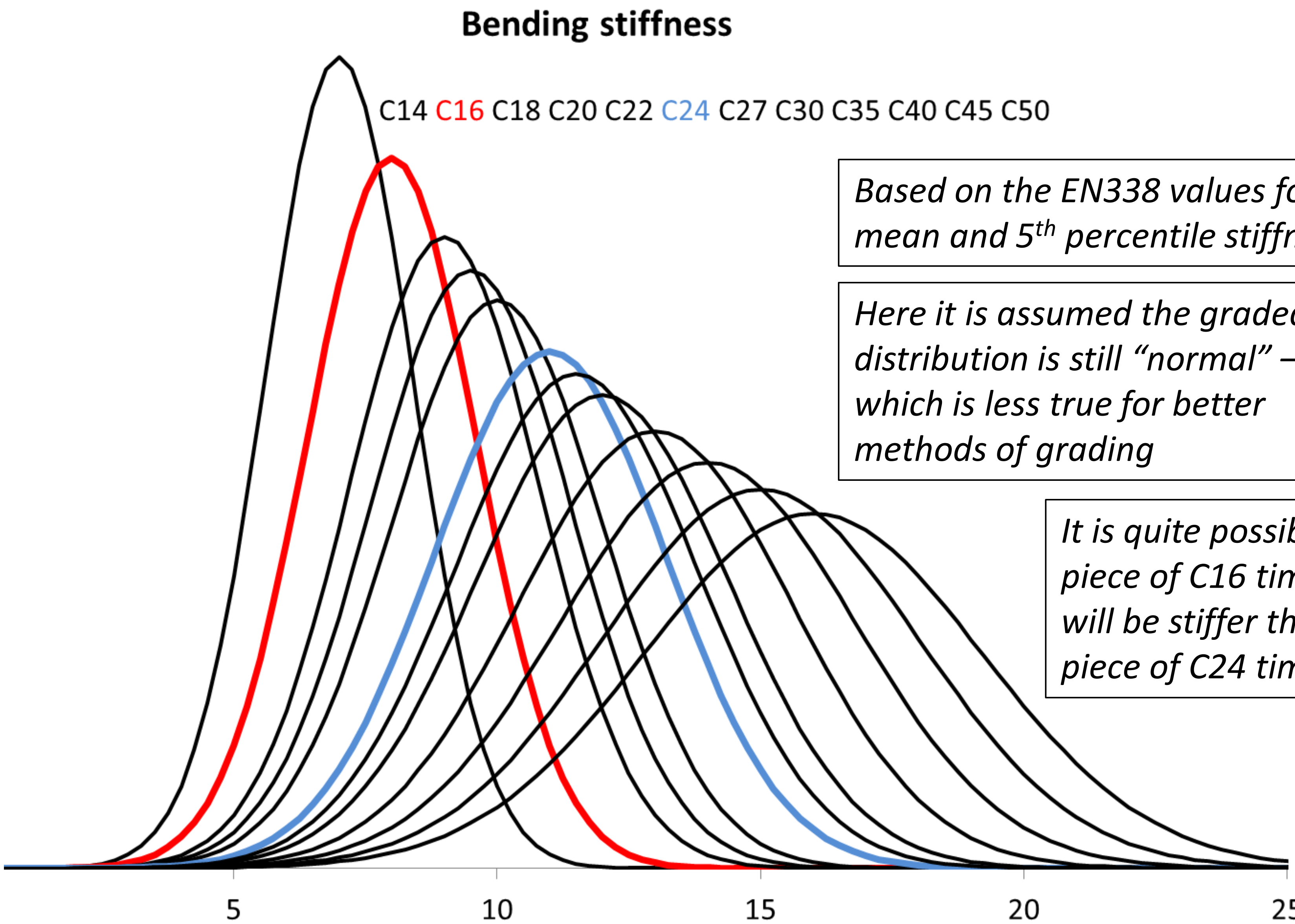


There are many ways a distribution can comply with the strength class requirements

…even before considering that any distribution with a higher 5th percentile than is required would also comply

http://goo.gl/z5dHsR

Strength classes are not distinct things
Bending stiffness distributions implied by EN338



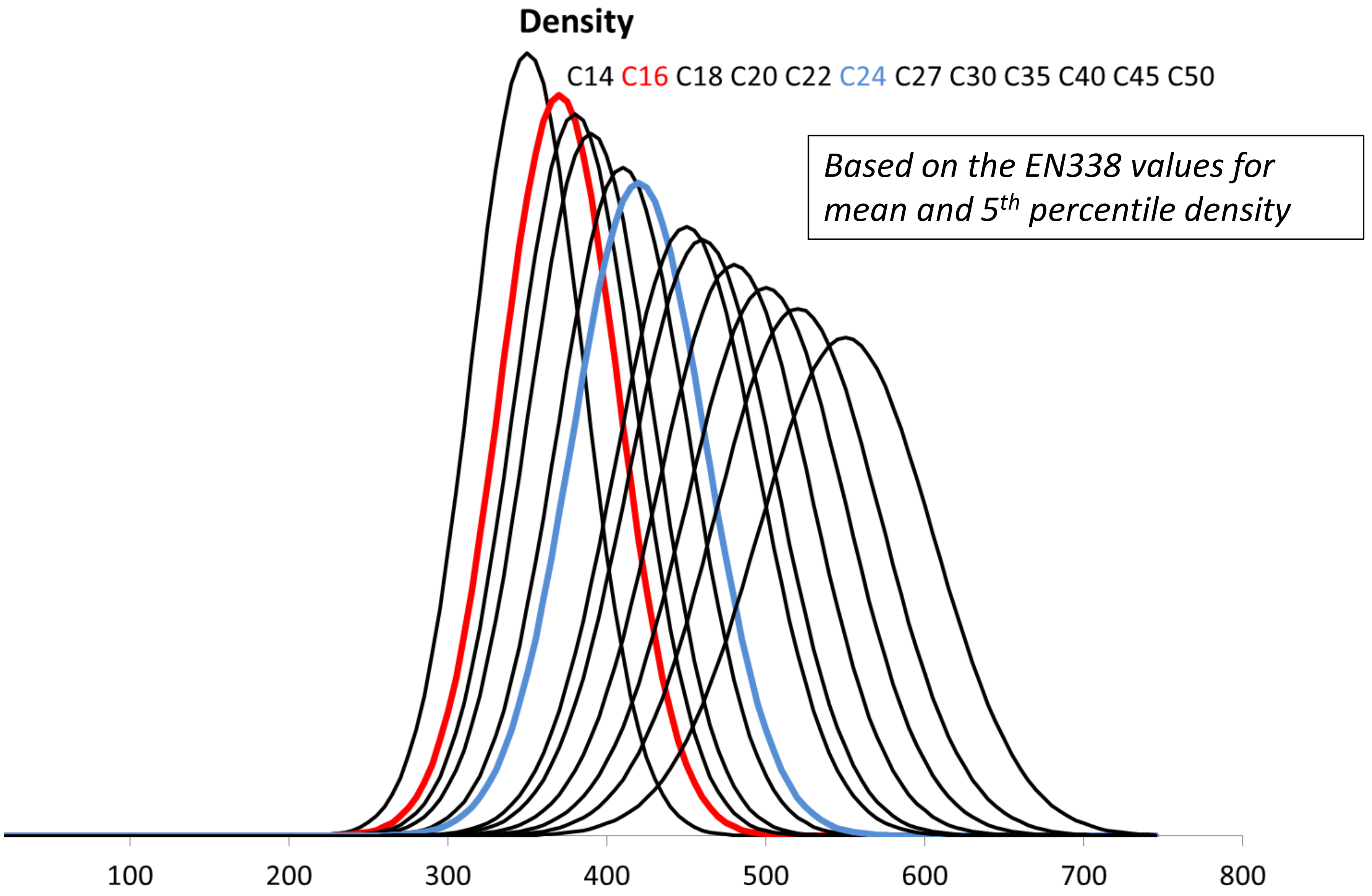
Based on the EN338 values for mean and 5th percentile stiffness

Here it is assumed the graded distribution is still "normal" – which is less true for better methods of grading

It is quite possible a piece of C16 timber will be stiffer than a piece of C24 timber

http://goo.gl/z5dHsR

Strength classes are not distinct things
Density distributions implied by EN338



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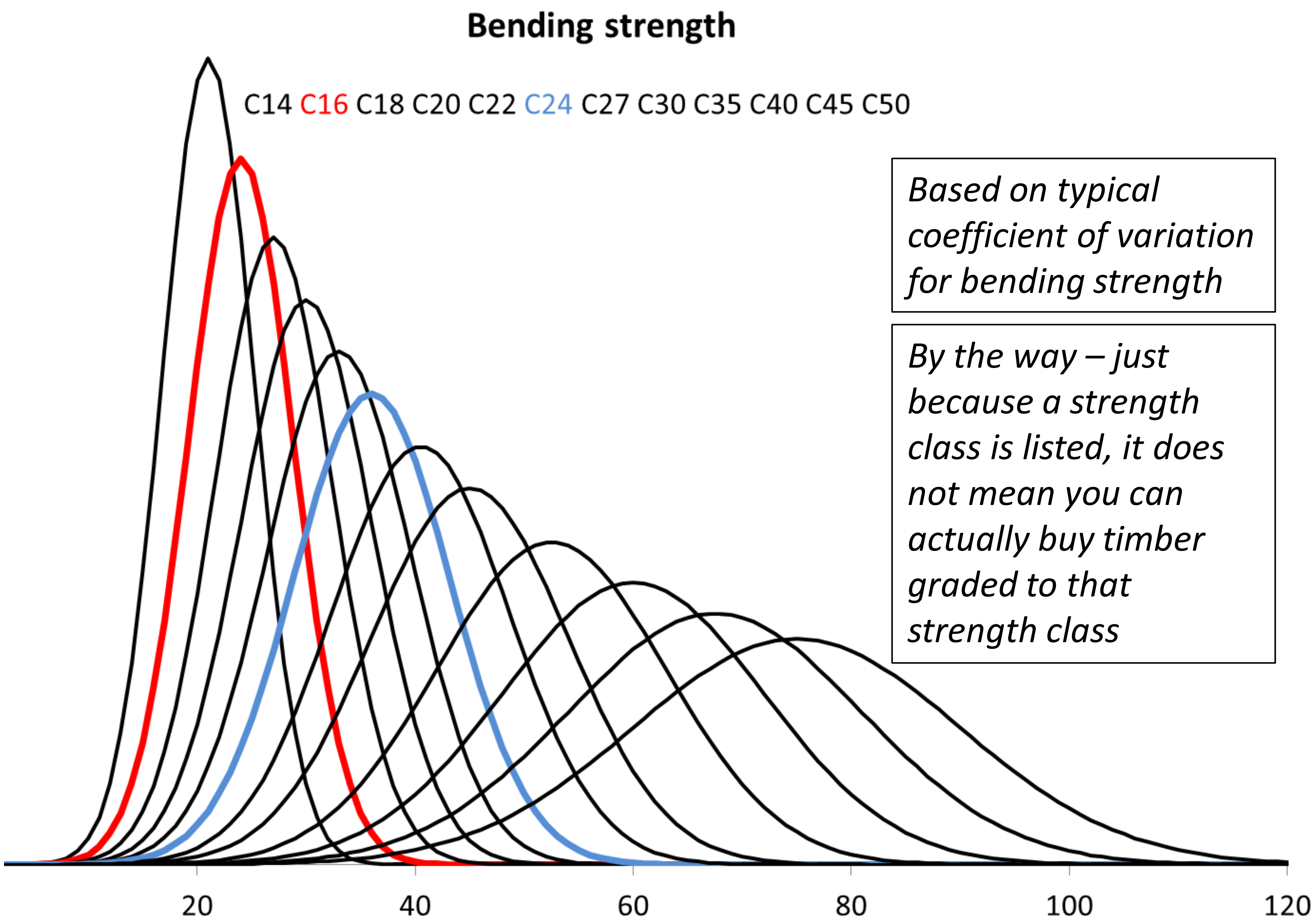
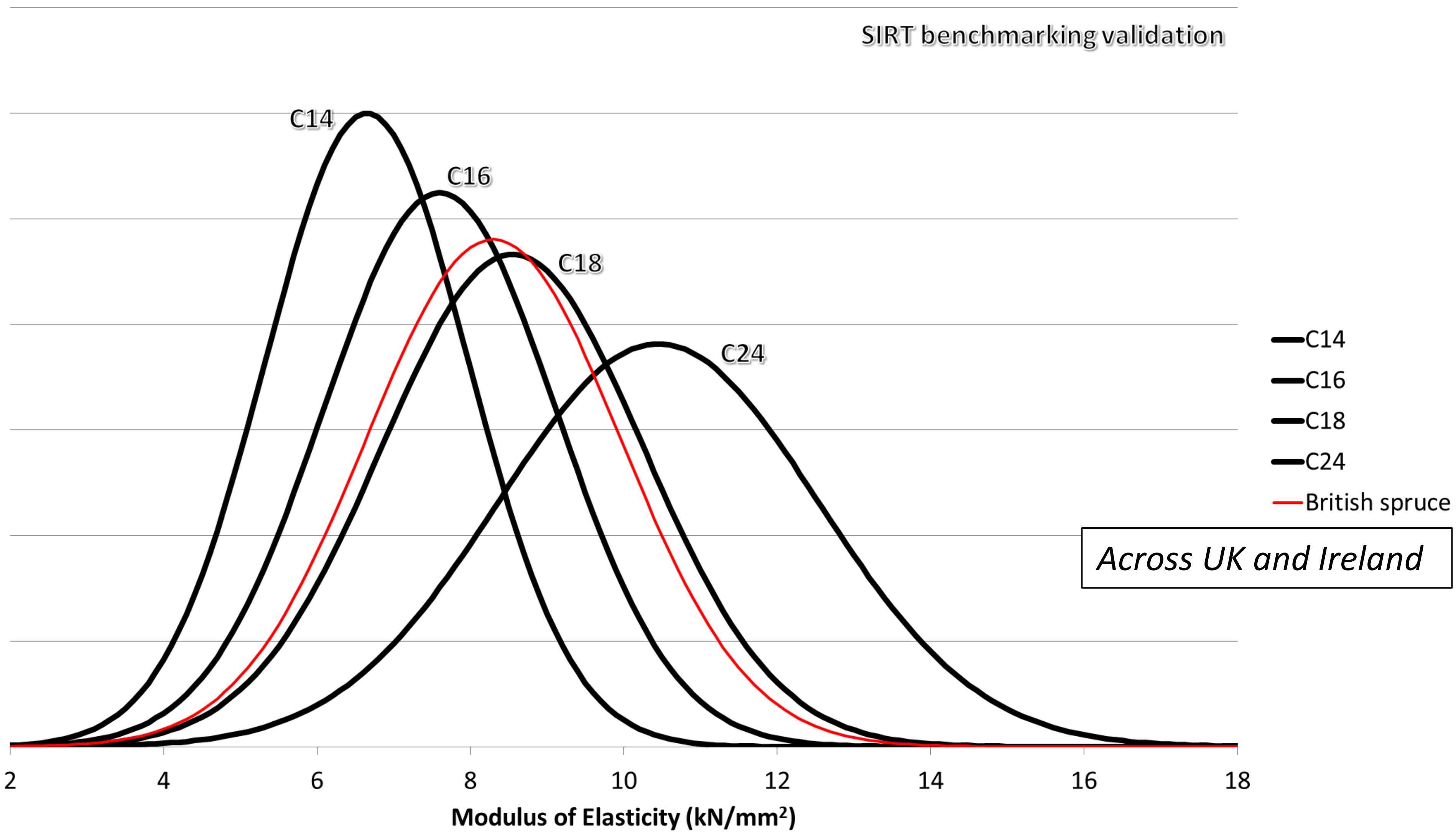
Strength classes are not distinct things
Bending strength distributions implied by EN338



Based on typical coefficient of variation for bending strength

By the way – just because a strength class is listed, it does not mean you can actually buy timber graded to that strength class

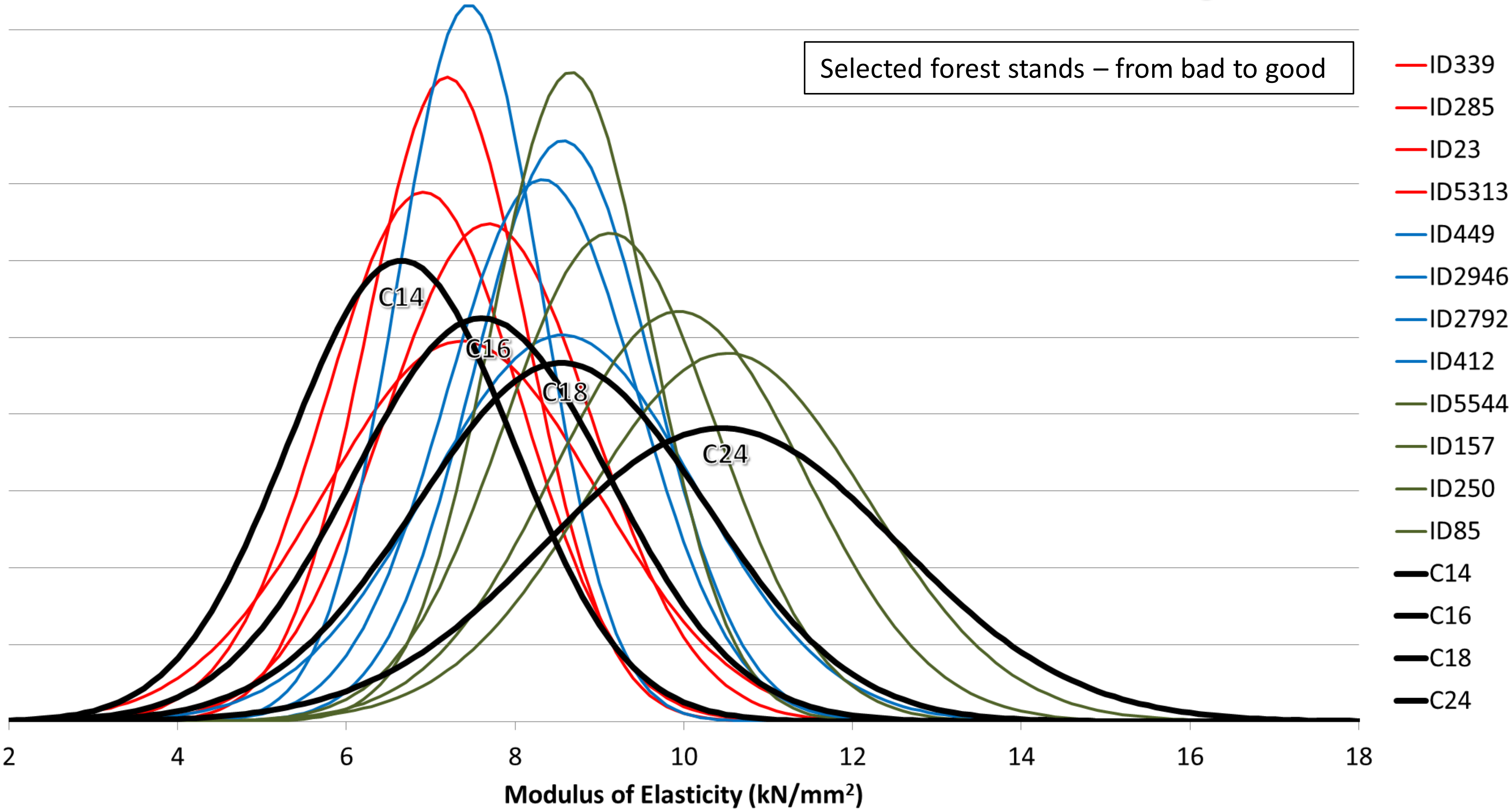
Example of variation – British spruce overall



http://goo.gl/z5dHsR

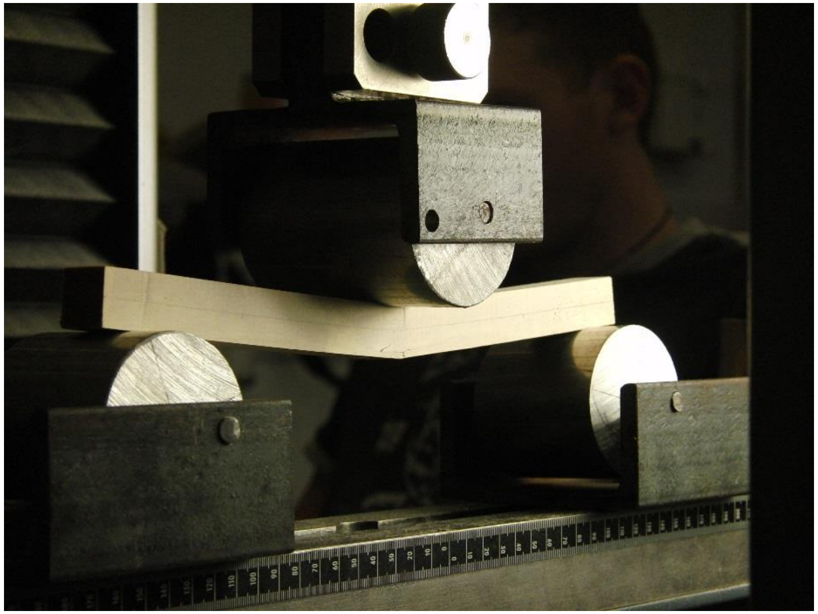
Example of variation – British spruce different sites

Moore JR, Lyon AJ, Searles GJ, Lehneke SA, Ridley-Ellis, DJ (2013) Within- and between-stand variation in selected properties of Sitka spruce sawn timber in the UK: implications for segregation and grade recovery. Annals of Forest Science 70(4):403-415. doi: 10.1007/s13595-013-0275-y



Destructive testing

Full size to EN408

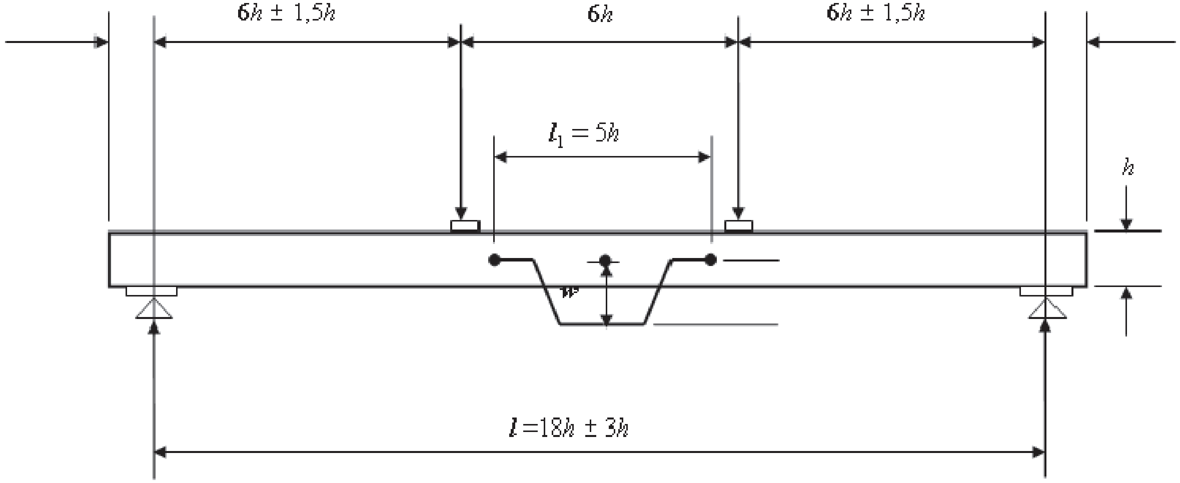


Small clears (e.g. BS373)
(no European standard)

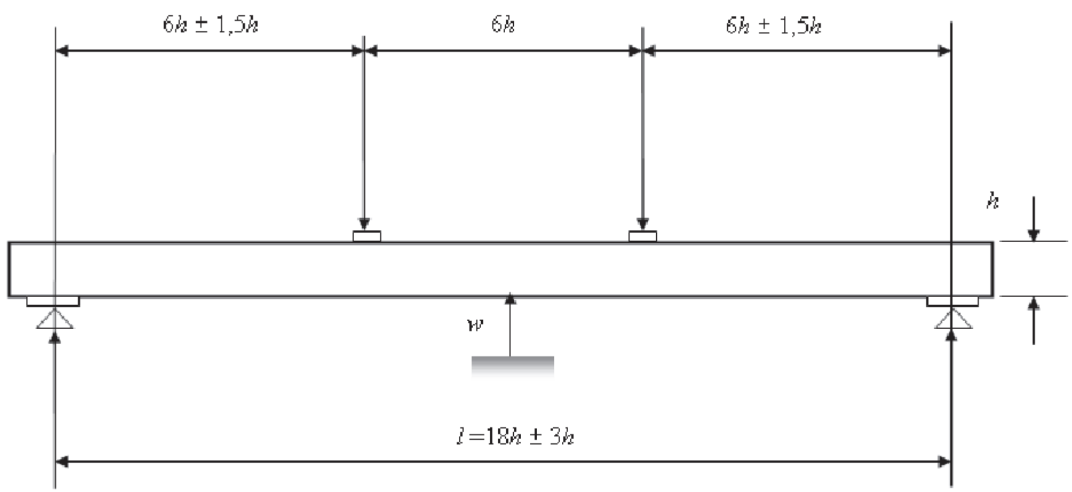
http://goo.gl/z5dHsR

Measurement of Modulus of Elasticity (EN408)

Local MoE



Global MoE



How do we predict strength?

Can only be measured destructively

But strength is correlated with:

- Stiffness
- Density
- Knots
- Grain e.g. ring width
  - Rate of tree growth & radial position
- Species
- Origin

How do we predict stiffness?

Stiffness can be measured non-destructively

- Mechanical bending (within elastic range)
- Dynamic stiffness (vibration or time of flight)

It is also correlated with

- Density
- Knots
- Grain e.g. ring width
    - Rate of tree growth & radial position
- Species
- Origin

How do we predict density?

Density can be measured non-destructively

- By weighing and measuring dimensions
- Using x-rays (and similar methods)
- Pin indent, drill resistance, screw pullout
- But is confounded by moisture content

It is also correlated with

- Stiffness
- Grain e.g. ring width
    - Rate of tree growth & radial position
- Species
- Origin

Systems of grading
All governed by EN 14081 (and EN384)

Visual grading

1. Create grading rules (usually national standards)
2. Sort timber into the grades
3. Do destructive testing to see what properties the grades have
4. Assign grades to strength classes (some listed in EN1912)

Machine control grading

1. Do destructive testing to establish relationships between IP and properties
2. Decide the strength class combination for which settings are required
3. Determine the required IP thresholds so that the grades match the required strength classes (also satisfying some other requirements)

Output control grading (also by machine)

1. Develop initial settings from destructive testing
2. Periodically proof test timber and adjust settings if required

The bodies

CEN TC124 "Timber Structures"

- WG1 "Test Methods"
- **WG2 "Solid Timber"**
  - **TG1 "Grading"**
    - For machine settings, & assignments in EN 1912

National Mirror Committees

SG18 "Sector Group 18" (Notified Bodies)

Approval of settings and assignments

Visual grading

If to be listed in EN1912 needs to be approved by CEN TC124 WG2 TG1

Otherwise examined by a Notified Body with appropriate competence

Machine control

Both machine and settings need to be approved by CEN TC124 WG2 TG1

Output control

Examined by a Notified Body with appropriate competence

Visual grading and machine control require a lot of test data – so if research is being done on wood properties it makes sense to do it in a way that allows the results to be used to for grading settings or visual assignments. This means representative sampling and passing timber through grading machines to get IP data / visually grading the timber before testing.

Representative sampling
Some rules in EN14081 & EN384 but not all

Timber is representative of what will be graded in production

Needs to be full-sized timber (not small clears*)

Ideally taken from normal sawmill production

Need to know the source – not just the country, but the geographic region within it where it grew

The specimens are long enough that they can be tested at the critical section (worst point within their length)

Nothing has been done that might bias the sampling

- **No pre-grading (other than removal of visual overrides)**
- **No selection of unusual cross-sections, lengths or trees**

*** Small clears can be used for tropical timbers under certain circumstances**

Illustration with real data (1)
Spanish sweet chestnut (visual grading)

Strength class assignments for sweet chestnut (*Castanea sativa*) grown in Spain visually graded as "MEF" (structural hardwood) to the Spanish standard UNE 56546.

Bending strength 5th %ile N/mm²	Bending stiffness mean kN/mm²	Density 5th %ile kg/m³
28.0	12.3	510

Characteristic values for timber sampled from 5 provenances in Spain (800 pieces in grade MEF)

After necessary adjustments for size, moisture, test span, sample size etc

Vega A, Arriaga F, Guaita M, Baño V (2013) Proposal for visual grading criteria of structural timber of sweet chestnut from Spain. Eur. J. Wood Prod. (2013) 71:529–532 doi 10.1007/s00107-013-0705-4

Illustration with real data (1)
Spanish sweet chestnut (visual grading)

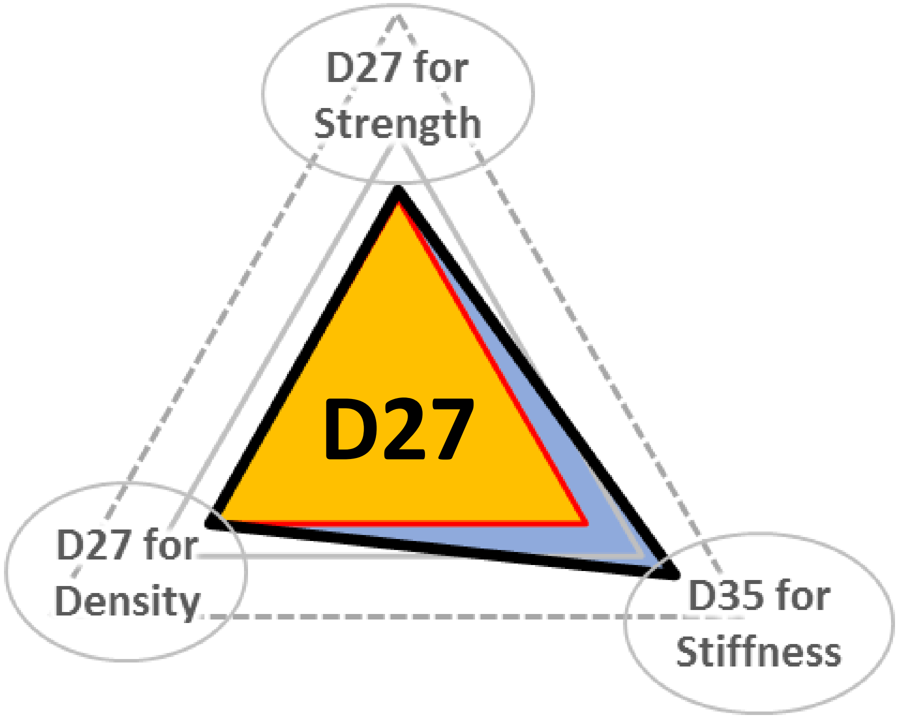
	Achieved (Vega et al. 2013)			Required			% of required		
	Bending strength	Bending stiffness	Density	Bending strength	Bending stiffness (×0.95)	Density	Bending strength	Bending stiffness	Density
EN338	N/mm²	kN/mm²	kg/m³	N/mm²	kN/mm²	kg/m³	%	%	%
MEF	28.0	12.3	510						
D24 ✓	Option for the current EN338			24.0	10.0 (9.5)	485	117% ✓	129% ✓	105% ✓
D30 ×				30.0	11.0 (10.5)	530	93% ×	118% ✓	96% ×
D27 ✓	Option for prEN338			27.0	10.5 (10.0)	510	104% ✓	123% ✓	100% ✓
Bespoke ✓				28.0	12.9 (12.3)	510	100% ✓	100% ✓	100% ✓

D27 is a new strength class being added to EN338

With the new version of EN338, C-classes are also an option

For EN338 strength classes the stiffness exceeds the requirement by some way

Illustration with real data (1)
MEF visual grade of Spanish sweet chestnut



For the generic "D" strength classes in EN338 the density is limiting…followed closely by strength. Stiffness, however, greatly exceeds what is required for the strength class. Assigning to a D class lowers performance in exchange for easy trade

Machine strength grading

Now many types of grading machines

- Bending stiffness
  - Bending about the minor axis
- Dynamic (acoustic/vibration)
  - Essentially a measure of stiffness
  - May or may not include density
- X-rays
  - A combination of knots and density
  - Perhaps with optical camera
- Surface grain angle from optical measurement
- Mixtures of the above

Bending graders

Measure mechanical stiffness

- Through application of defined load
- or defined deflection
- Minor axis
- Accounting for pre-existing bow

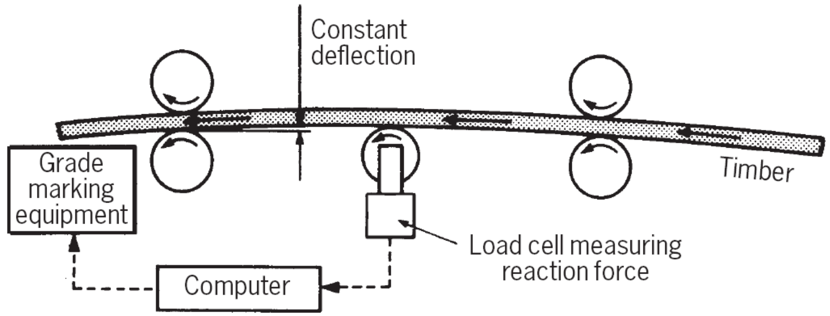
Relatively slow (with dynamic errors)

Limited by cross-section

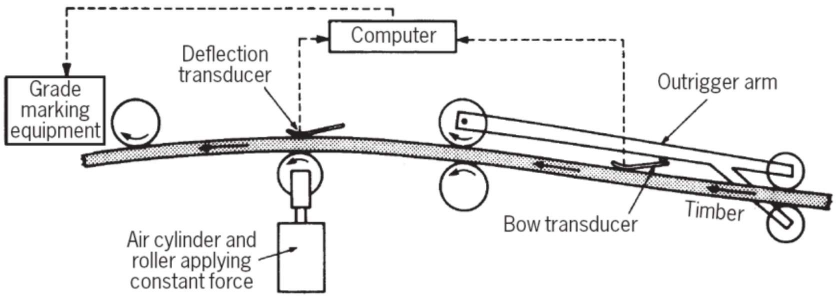
Cannot measure the whole piece

Bending graders

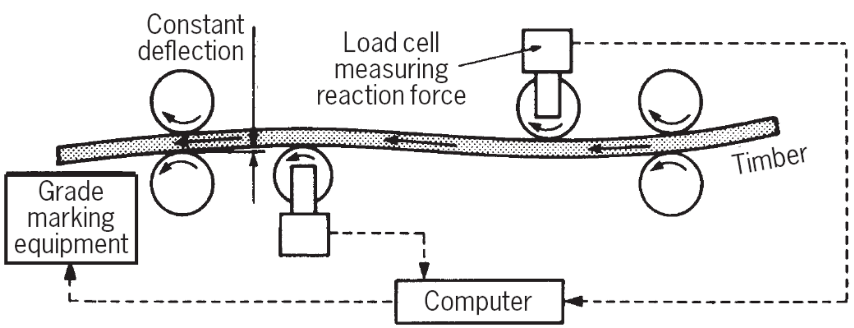
Cook-Bolinder



Computermatic



Timgrader



Figures from BRE Digest 476 “Guide to machine strength grading of timber”

Acoustic graders

Measure acoustic velocity

- Through axial or transverse vibration
- Or time of flight (including ultrasonic)
- May or may not include density ($MoE_{dyn} = \rho v^2$)

Fast

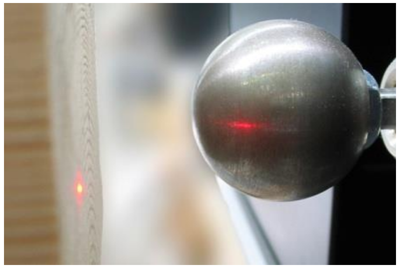
Can be hand-held

Measure the whole piece

…but all at once

Acoustic graders

ViSCAN (MiCROTEC)



MTG (Brookhuis)

Precigrader (Dynalyse AB)

Triomatic (CBS-CBT)

X-ray graders

Measure

- Clear wood and average density
- Knot size and location

Very fast (and permit board splitting)

…but big and expensive

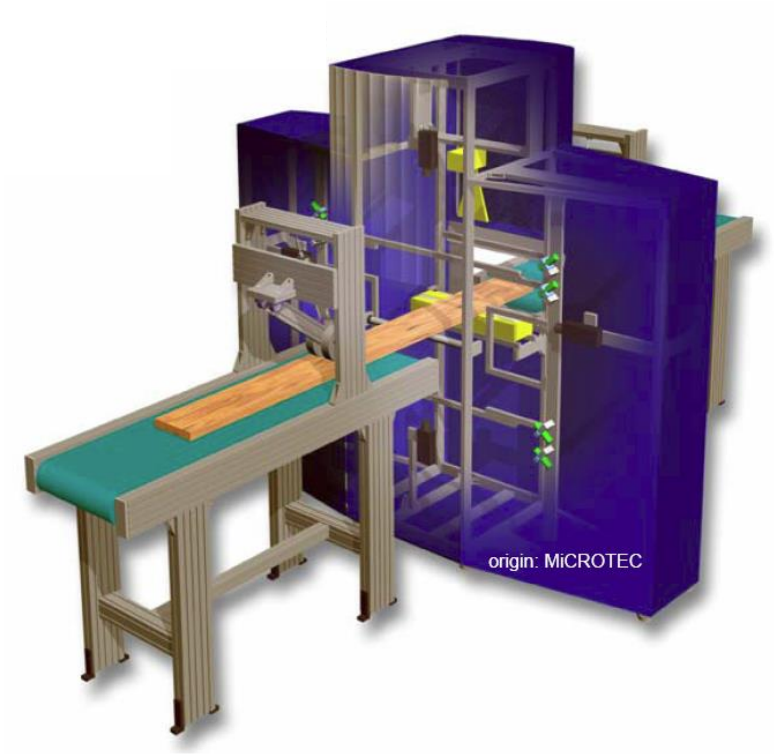
Measure the whole piece

…and all parts of it individually

But not great at predicting stiffness

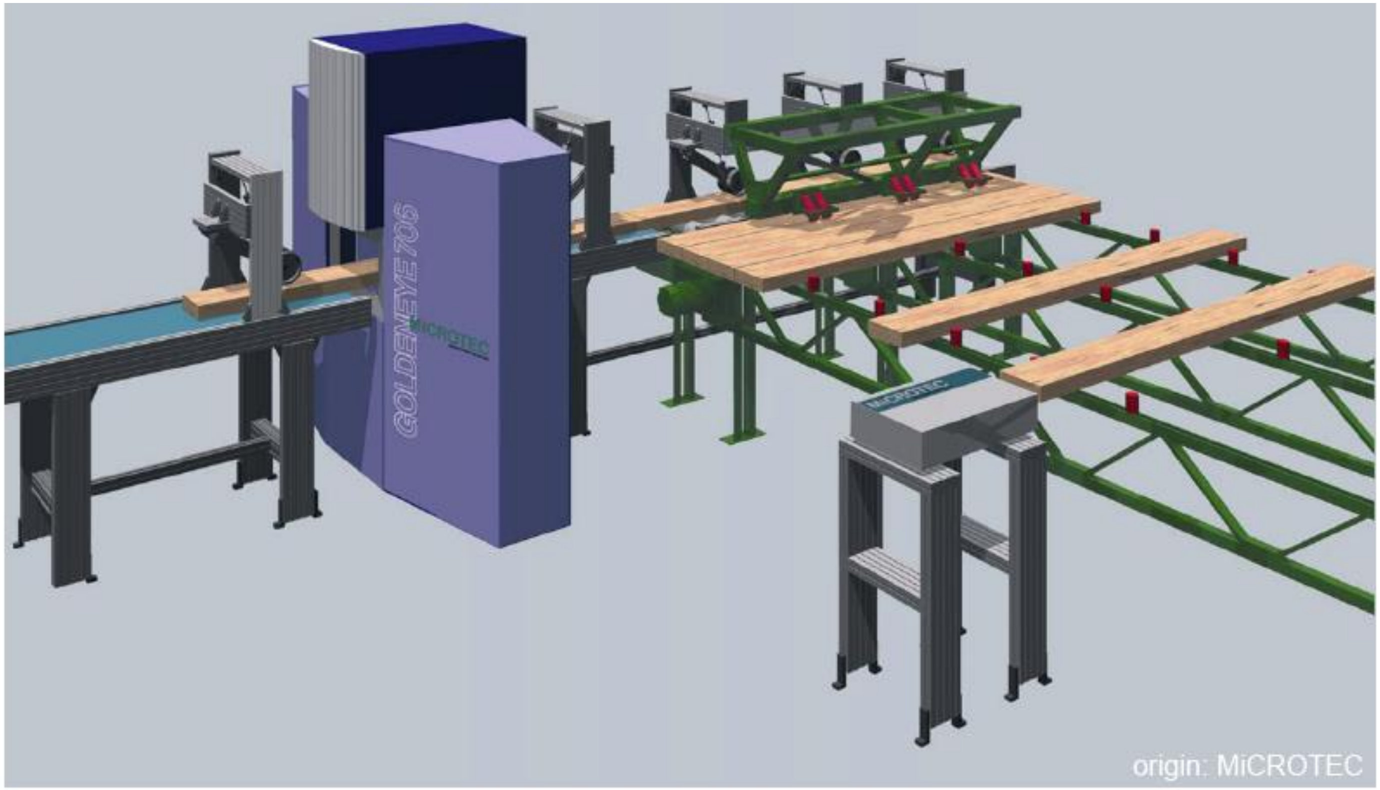
X-ray graders

GOLDENEYE 702 (MiCROTEC)



Combination graders

GOLDENEYE 706 (MiCROTEC)

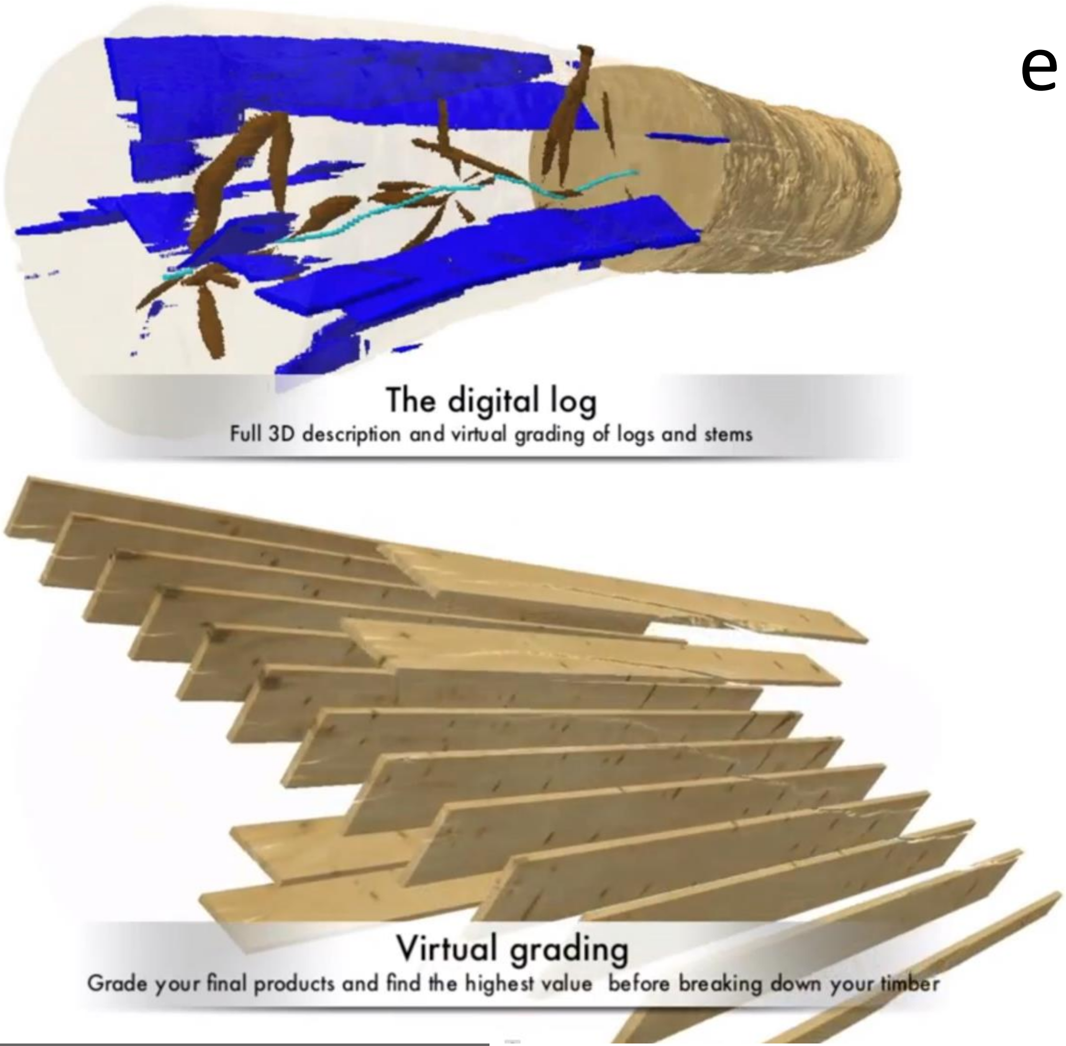


Combination graders

WoodEye 5

New technologies

e.g. MiCROTEC CT.LOG



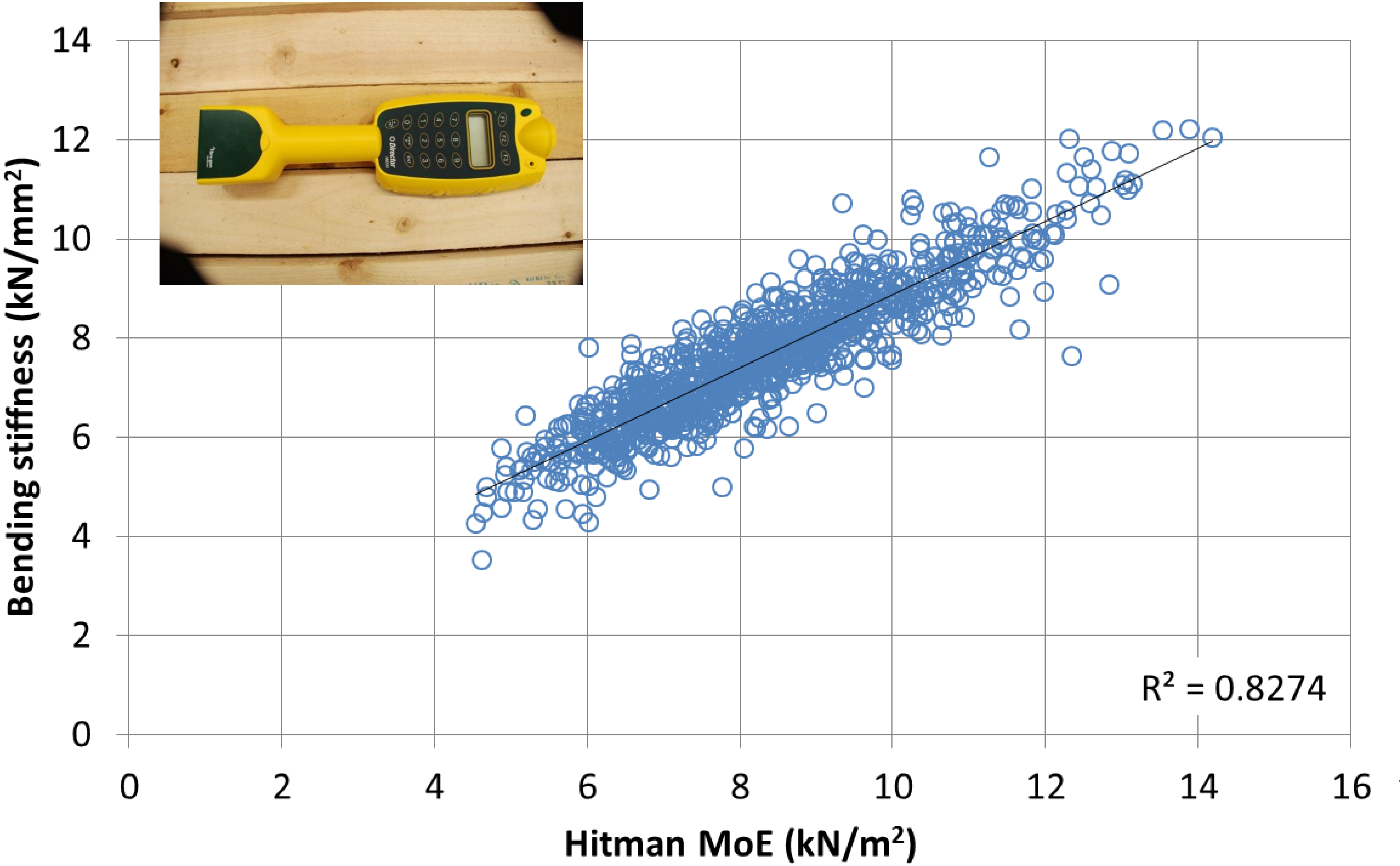
But that's not everything yet

"Visual" override

- Distortion (might be by machine)
- Fissures (cannot be detected by machine (yet))
- Wane
- Soft rot and insect damage
- Knots and slope of grain on any portion that cannot be machine graded (i.e. the ends of the timber for bending type machines)
- Anything else that causes concern

http://goo.gl/z5dHsR

Example – longitudinal resonance



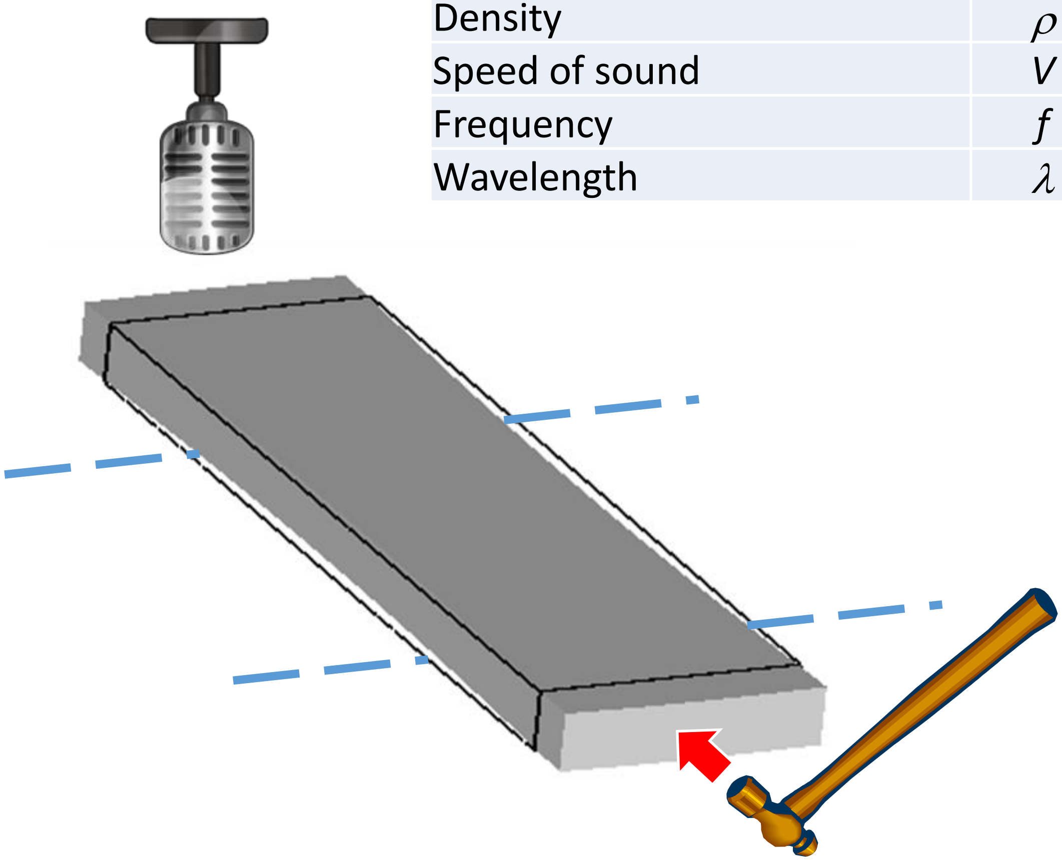
http://goo.gl/z5dHsR

Exercise one – impulse excitation

Set analysis type to linear, natural frequency modal
Set units to metric mmks
Draw construction vertices with coordinates
-1500,25,50
-1500,-25,50
-1500,-25,-50
-1500,25,-50
1500,25,50
1500,-25,50
1500,-25,-50
1500,25,-50
Mesh - 8 point 3D (make sure you go in the same order at both ends)
Set element type to brick
Set element definition to isotropic
Set material with these properties:
  Density 400 kg/m^3 (remember to convert units)
  Modulus of elasticity to 7 kN/mm^2 (remember to convert units)
  Poisson's ratio 0.3
Set analysis parameters - frequencies between 20Hz and 20kHz
Calculate 20 frequencies

Impulse excitation - longitudinal

Modulus of elasticity	E
Length	L
Density	ρ
Speed of sound	V
Frequency	f
Wavelength	λ



$$E = \rho V^2$$

$$V = f\lambda$$

For the *n*th mode

$$\lambda = 2L/n$$

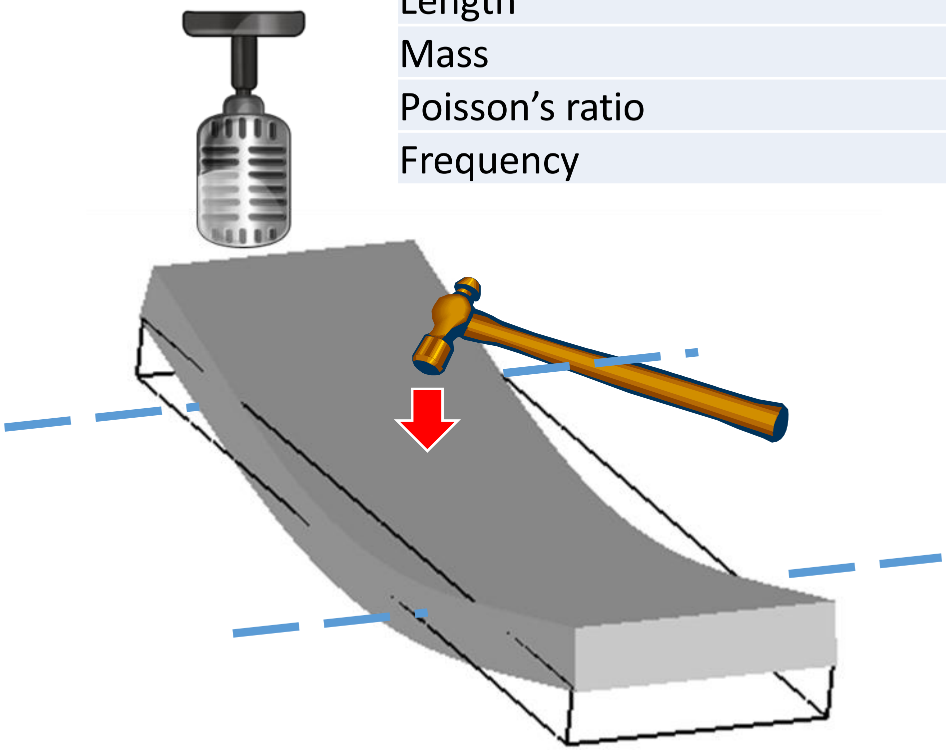
Impulse excitation - flexural

Modulus of elasticity	E
Width (larger dimension)	b
Thickness (smaller dimension)	t
Length	L
Mass	m
Poisson’s ratio	μ
Frequency	f

$$E = 0.9465\left(\frac{mf^2}{b}\right)\left(\frac{L}{t}\right)^3 T$$

When L/t ≥20

$$T = 1.000 + 6.858\left(\frac{t}{L}\right)^2$$



When L/t <20

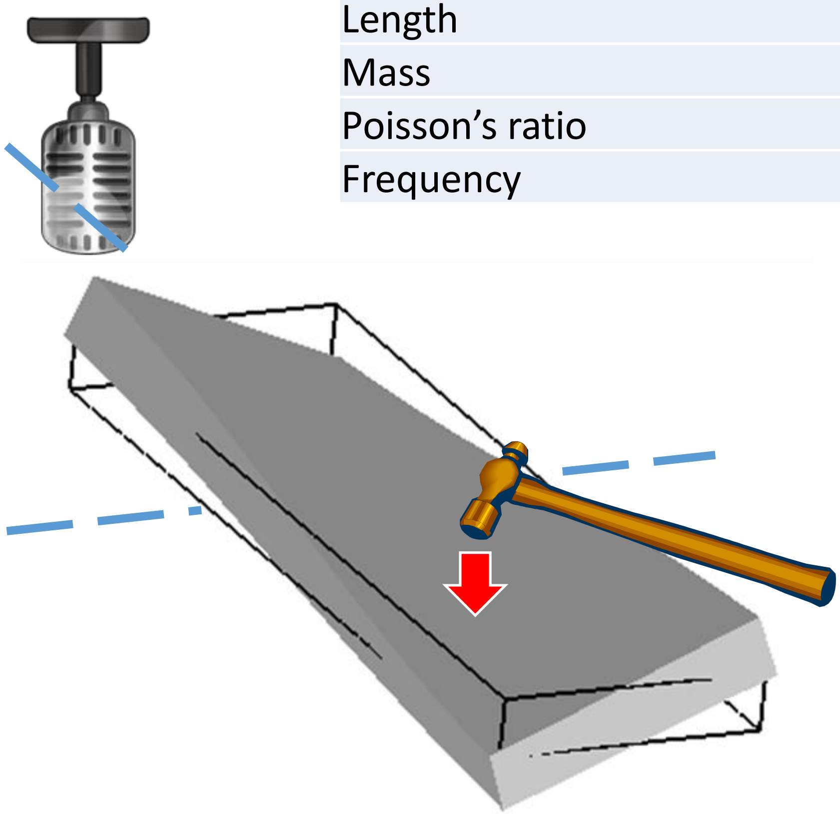
$$T = 1.000 + 6.858(1 + 0.0752\mu + 0.8109\mu^2)\left(\frac{t}{L}\right)^2 - 0.868\left(\frac{t}{L}\right)^4 - \frac{8.340(1 + 0.2023\mu + 2.173\mu^2)\left(\frac{t}{L}\right)^4}{1.000 + 6.338(1 + 0.1408\mu + 1.536\mu^2)\left(\frac{t}{L}\right)^2}$$

ASTM E1876 Standard Test Method for Dynamic Young's Modulus, Shear Modulus, and Poisson's Ratio by Impulse Excitation of Vibration, ASTM, 2009

Impulse excitation - torsional

Shear modulus	*G*
Width (larger dimension)	*b*
Thickness (smaller dimension)	*t*
Length	*L*
Mass	*m*
Poisson’s ratio	μ
Frequency	*f*

$$G = \frac{4Lmf^2}{bt}\left(\frac{B}{1+A}\right)$$

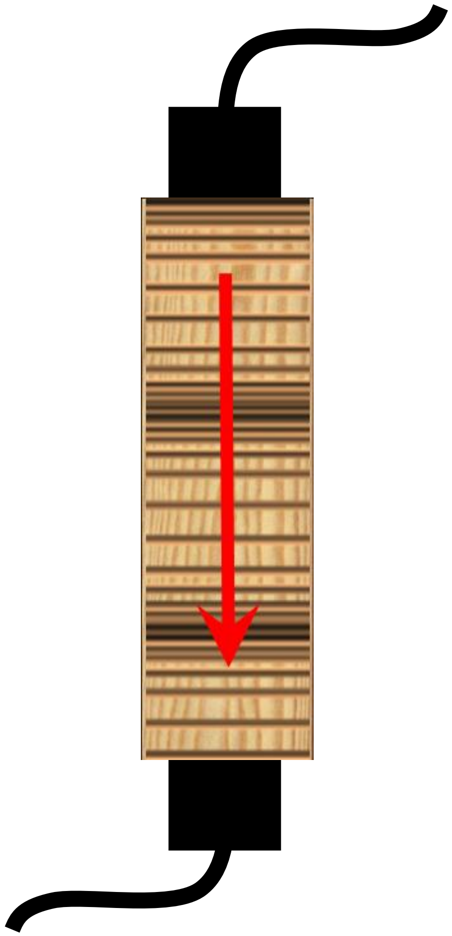


$$A = \frac{0.5062 - 0.8776\left(\frac{b}{t}\right) + 0.3504\left(\frac{b}{t}\right)^2 - 0.0078\left(\frac{b}{t}\right)^3}{12.03\left(\frac{b}{t}\right) + 9.892\left(\frac{b}{t}\right)^2}$$

$$B = \frac{\left(\frac{b}{t}\right) + \left(\frac{t}{b}\right)}{4\left(\frac{t}{b}\right) - 2.52\left(\frac{t}{b}\right)^2 + 0.21\left(\frac{t}{b}\right)^6}$$

Direct measurement of time-of-flight Ultrasonic

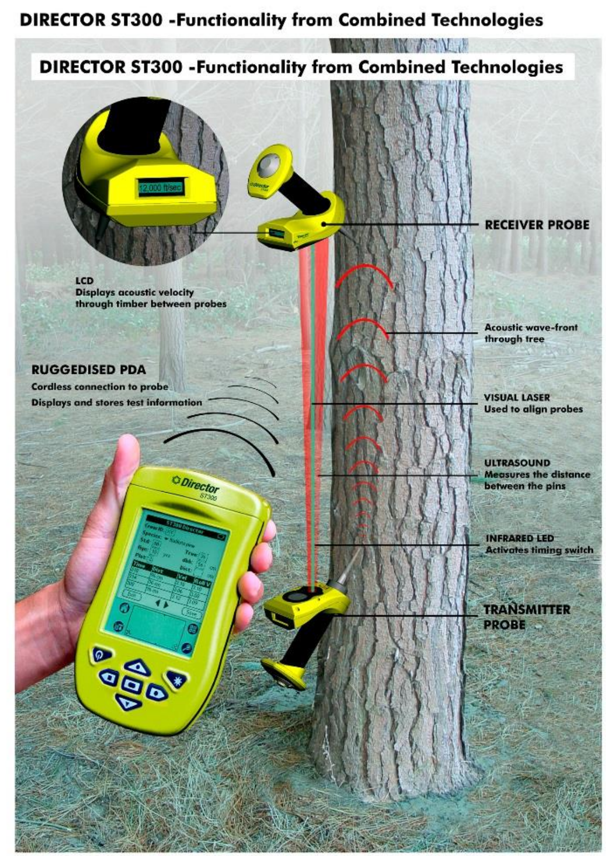
Example: the Proceq “Pundit”



Direct measurement of time-of-flight Impact

Example: the IML microhammer

Example: the Fibregen ST300



Tasks

- Create a finite element model to explore vibration modes
- Measure frequencies of vibration for a beam in the lab
  - Record the sound
  - Perform FFT analysis (Audacity or similar software)
  - Extract peak frequencies and match to modes
- Calculate properties from the measurements
  - Spreadsheet provided

Can you match the peaks to the various modes?

Is there any difference with the mesh size?

Is there any difference with orthotropic material?

What happens when the material is not isotropic?

Extra task 1
Explore time-of-flight

For the first beam model, make a new design scenario for transient stress - direct integration

Edit the design scenario so there are 20 time steps and each one is 50 microseconds in length (convert units)

Select some of the vertices that make up one end (best to take all except the ones on the outside)

Add a small nodal force along the beam that appears at time zero and remains in place (via the load curve)

Analyse

How does the result compare with the theoretical stress wave speed?

Extra task 2
Another example of vibration

Sound recordings of longitudinal, flexural and torsional impact excitations are provided. What are E and G?

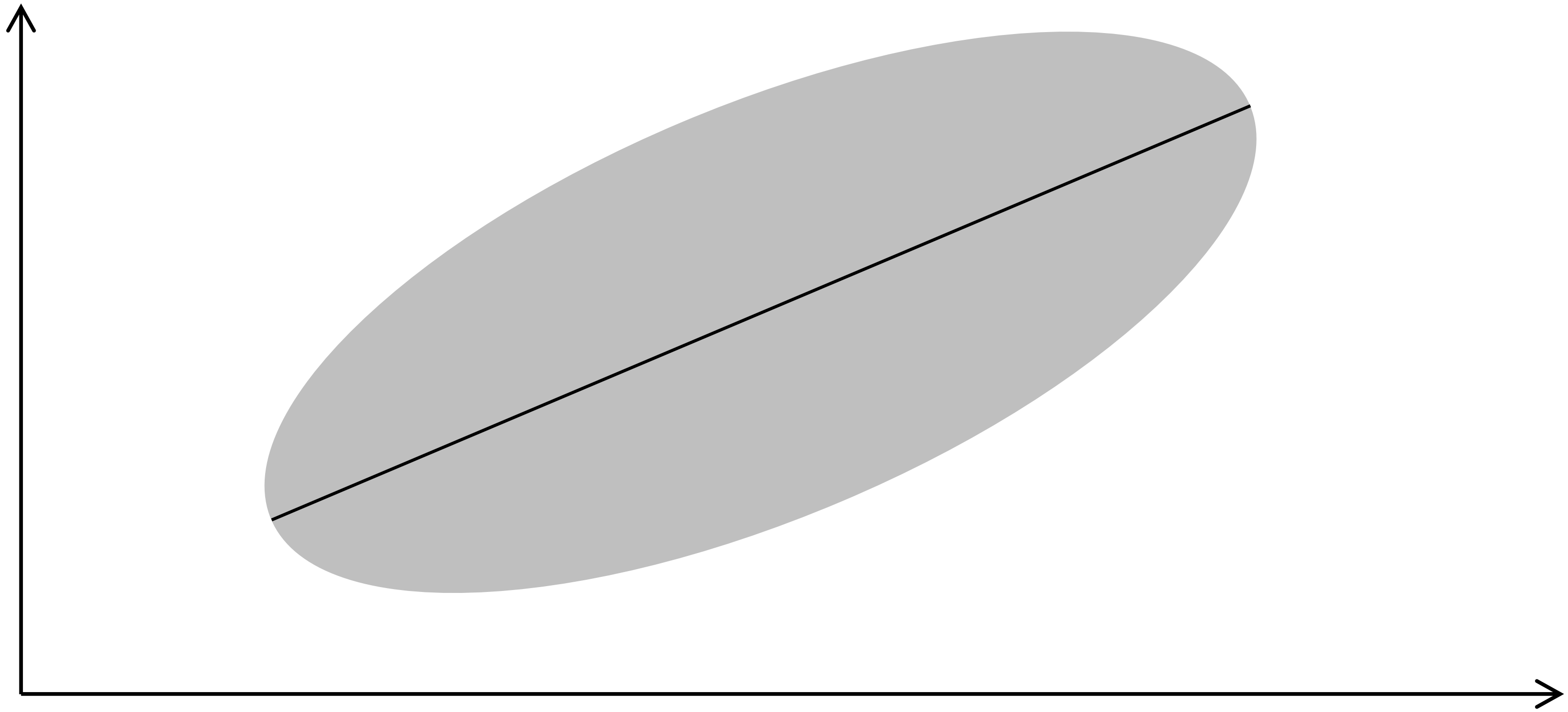
The species is Scots pine

Length	300.14 mm
Thickness	19.44 mm
Width	90.04 mm
Density	511.19 kg/m^3

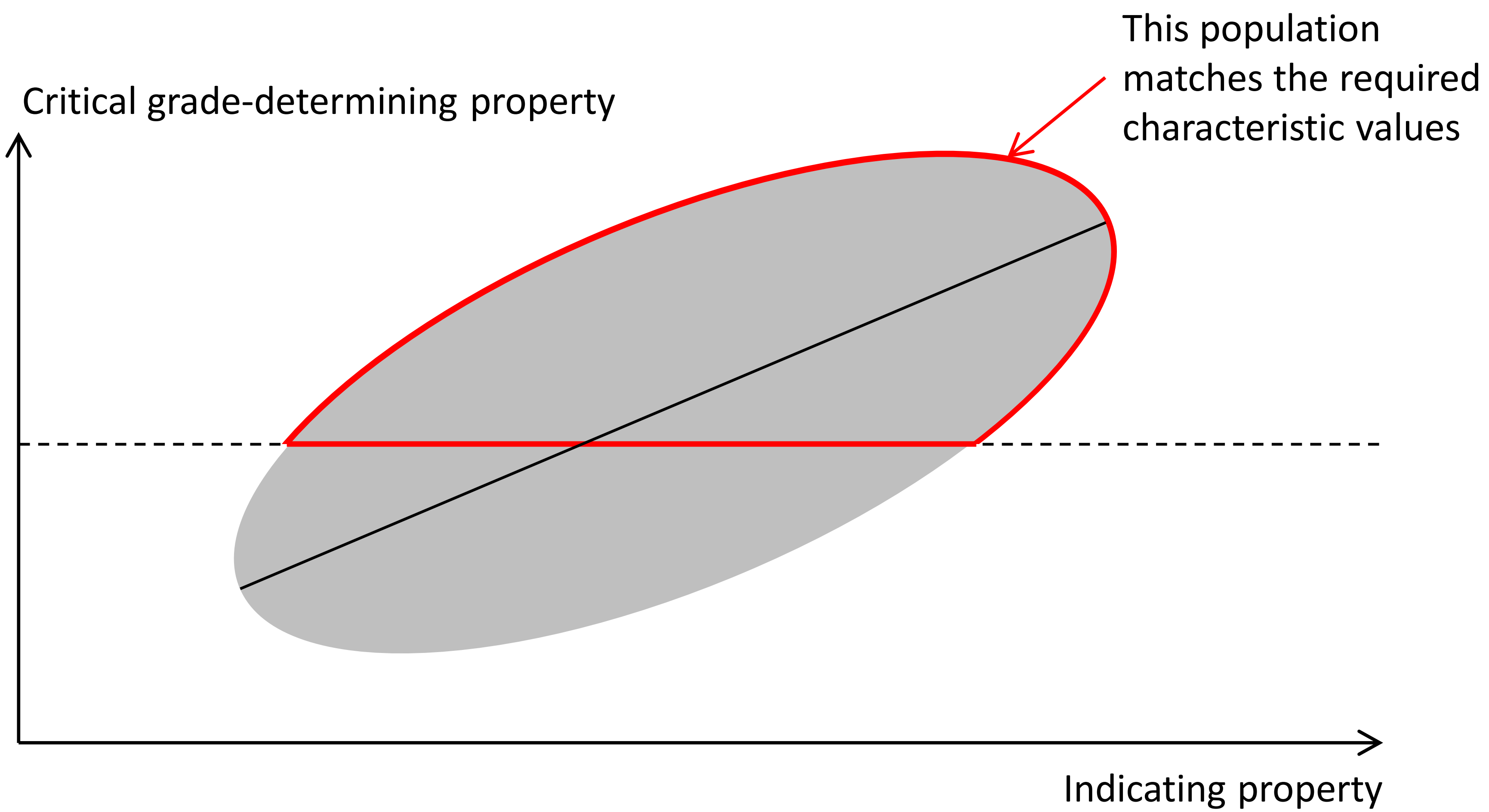
Hint 1: expect E to be about 15 kN/mm^2

Hint 2: The flexural mode is the easiest to spot in this case

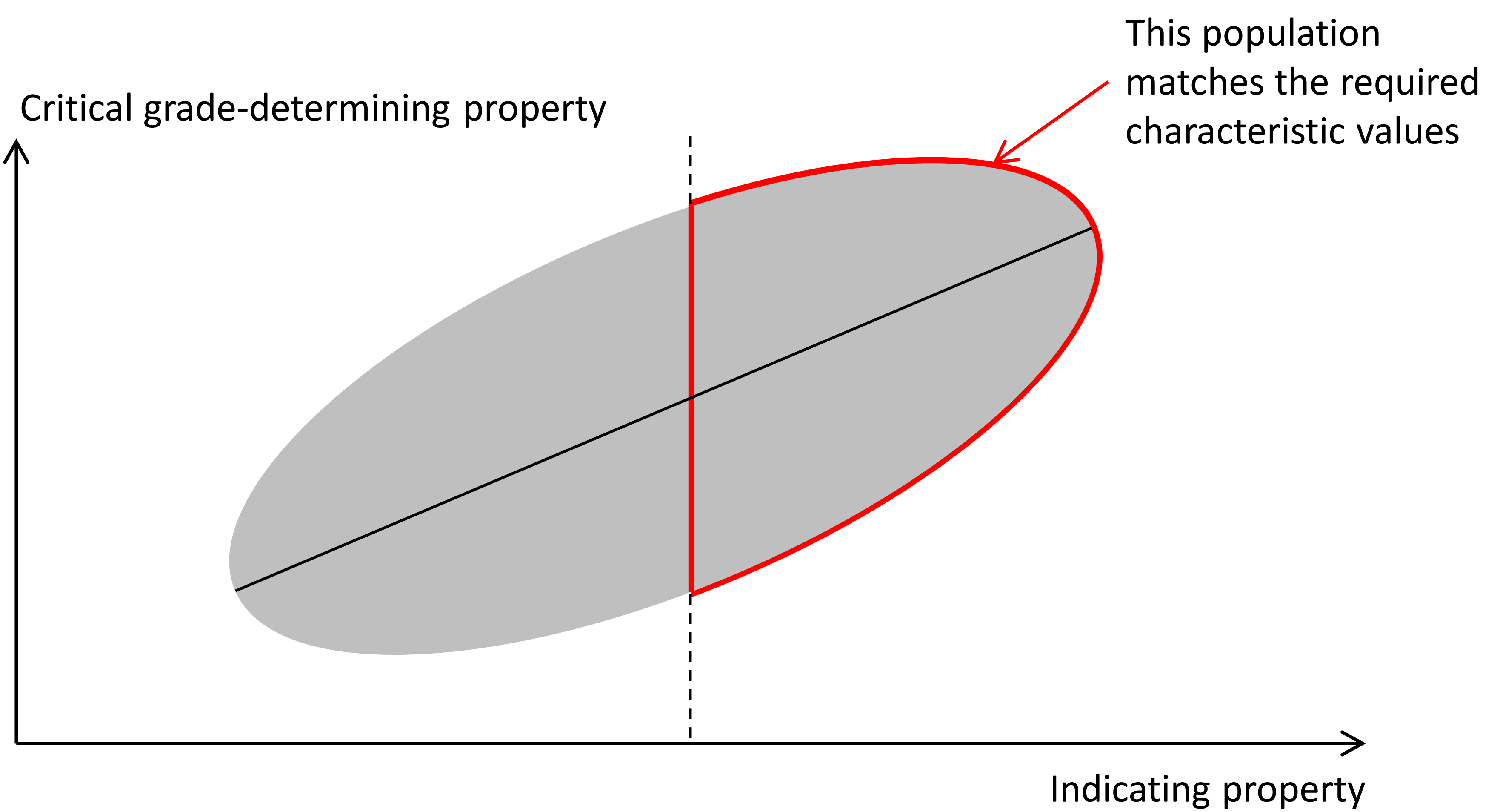
The principle of machine control (simplified)
1) Data obtained from destructive tests



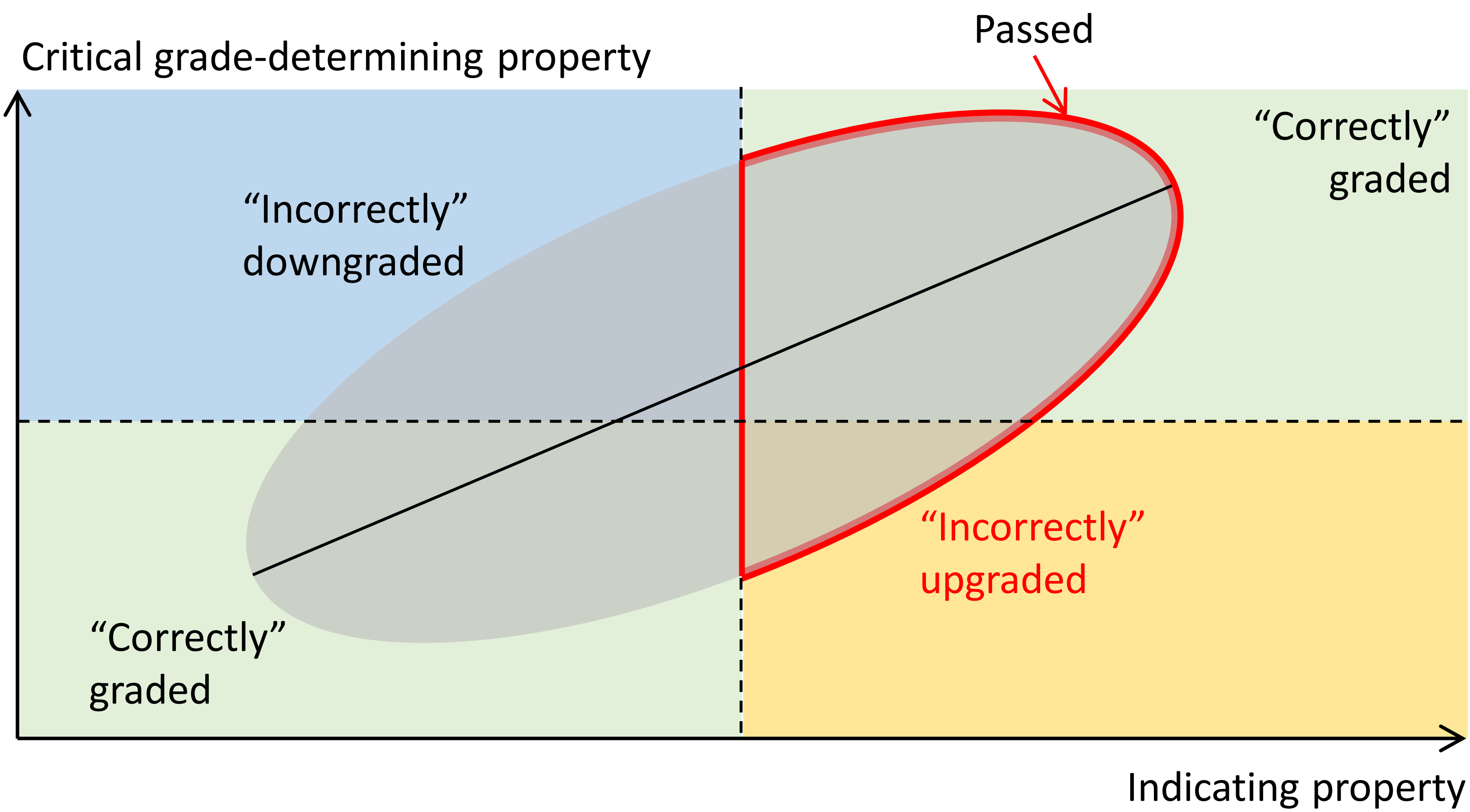
2) Optimum grade (a perfect grading machine)



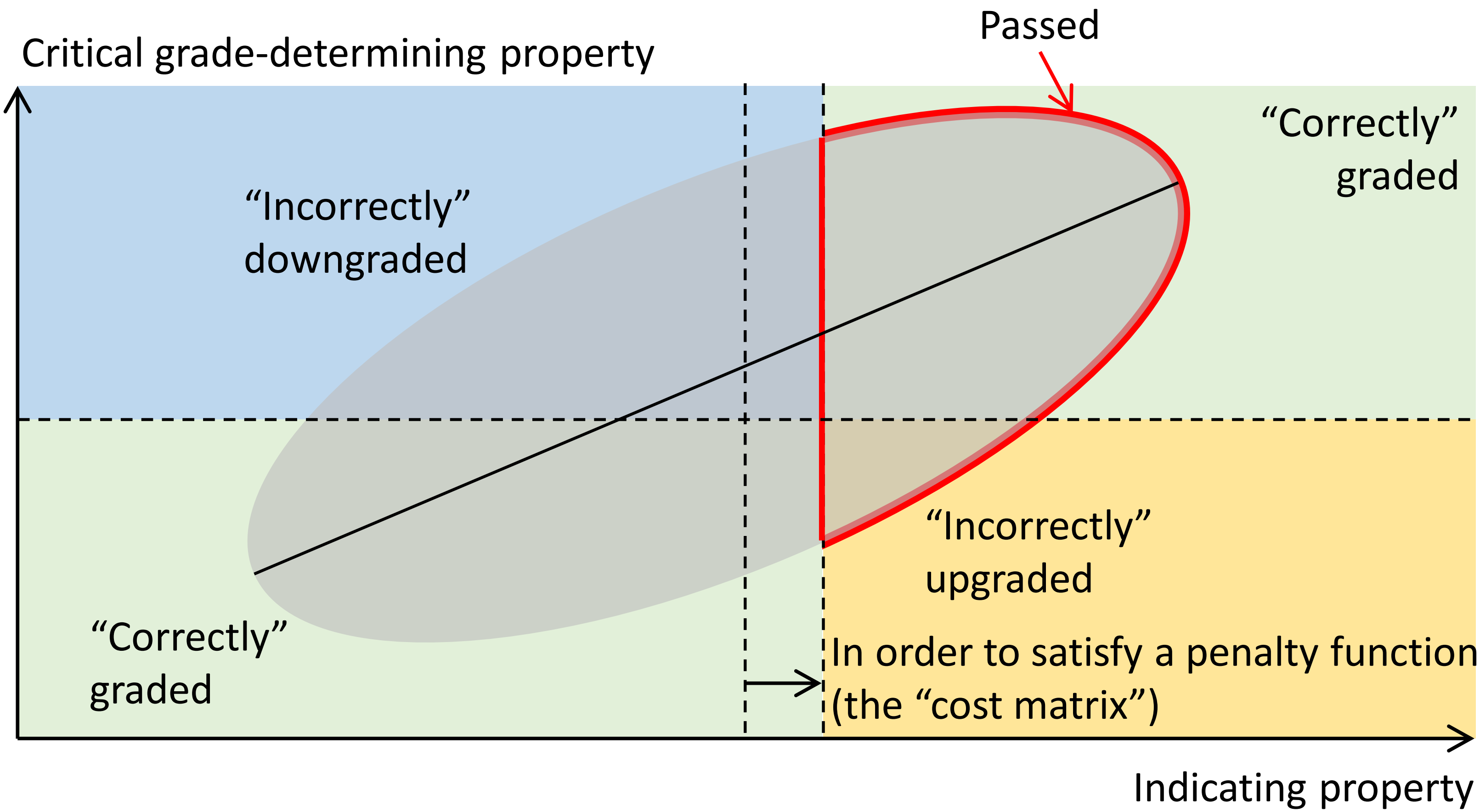
3) Using IP
The actual grading machine



4) Cost matrix



4) Cost matrix



Why a powerful IP is better
Encouraged by the cost matrix

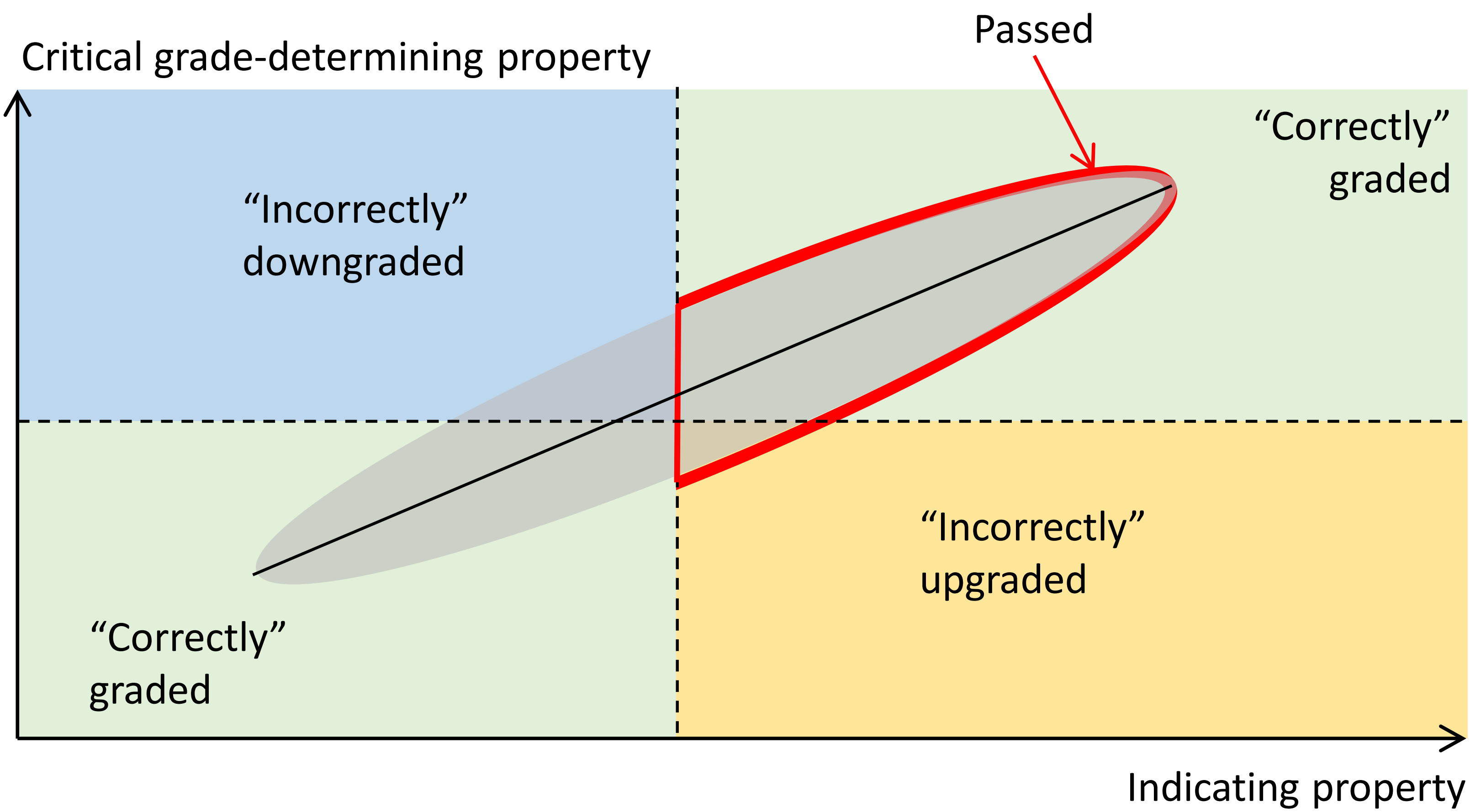
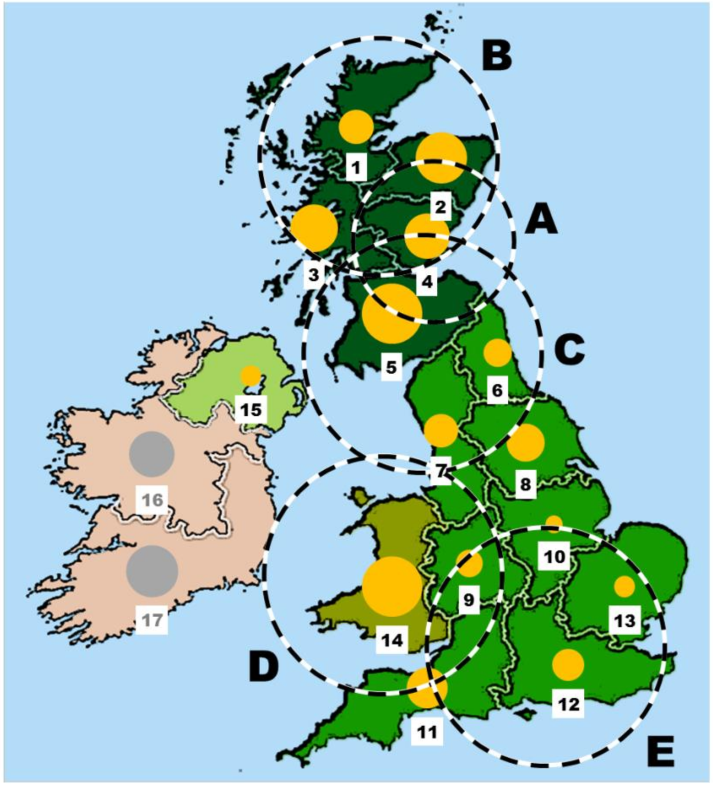


Illustration with real data (2)
UK larch (C16/C30 combination)

Property			Subsample A UK	B UK	C UK	D UK	E UK	All
Number	n		183	131	131	130	131	706
Strength	$f_{m,mean}$	N/mm^2	41.9	37.7	37.1	38.9	38.7	39.1
	$f_{m,k}$	N/mm^2	21.7	22.4	20.5	19.2	19.2	21.2
	CoV	%	31	26	32	30	31	31
Stiffness	$E_{0,12\%,mean}$	kN/mm^2	9.40	9.32	9.25	10.23	9.72	9.57
	CoV	%	26	24	29	24	24	26
Density	$\rho_{12,mean}$	kg/m^3	483	496	494	509	493	494
	$\rho_{12,k}$	kg/m^3	405	403	397	415	411	406
	CoV	%	11	11	12	13	10	12



Optimum grading for C30/C16/reject grade combination
(a perfect grading machine)

	n	Achieved $f_{m,k}$ N/mm^2	Achieved $E_{0,mean}$ kN/mm^2	Achieved ρ_k kg/m^3	Required $f_{m,k} / k_v$ N/mm^2	Required $E_{0,mean}$ x 0.95 kN/mm^2	Required ρ_k kg/m^3	n %	% of required $f_{m,k}$ %	% of required $E_{0,mean}$ %	% of required ρ_k %
C30	380	29.2	11.4	440	26.79	11.40	380	53.8%	109.0%	100.0%	115.8%
C16	309	20.0	7.61	398	14.29	7.60	310	43.8%	139.7%	100.1%	128.5%
reject	17	-	4.26	-	-	-	-	2.4%	0.0%	0.0%	0.0%
total	706										


Marshalls Transport
01259 723548

http://goo.gl/z5dHsR

Illustration with real data (2)
UK larch (C16/C30 combination)

C30	n	Achieved $f_{m,k}$ N/mm²	Achieved $E_{0,mean}$ kN/mm²	Achieved ρ_k kg/m³	Required $f_{m,k} / k_v$ N/mm²	Required $E_{0,mean}$ x 0.95 kN/mm²	Required ρ_k kg/m³	IP	% of required $f_{m,k}$ %	% of required $E_{0,mean}$ %	% of required ρ_k %
- A	68	29.3	13.0	493	26.79	11.40	380	12000	109.5%	114.4%	129.8%
- B	194	27.4	11.9	476	26.79	11.40	380	10500	102.1%	104.0%	125.3%
- C	187	29.9	12.0	476	26.79	11.40	380	10500	111.6%	105.1%	125.3%
- D	222	26.9	11.5	452	26.79	11.40	380	9840	100.5%	100.9%	118.8%
- E	171	27.6	12.0	476	26.79	11.40	380	10600	103.2%	105.0%	125.3%
							Mean	10700			
							0.85*max	10200			
All	200	29.4	12.1	479	26.79	11.40	380	10700	109.8%	105.8%	126.1%

No comments

C16	n	Achieved $f_{m,k}$ N/mm²	Achieved $E_{0,mean}$ kN/mm²	Achieved ρ_k kg/m³	Required $f_{m,k} / k_v$ N/mm²	Required $E_{0,mean}$ x 0.95 kN/mm²	Required ρ_k kg/m³	IP	% of required $f_{m,k}$ %	% of required $E_{0,mean}$ %	% of required ρ_k %
- A	375	20.5	8.68	402	14.29	7.60	310	4680	143.2%	114.2%	129.7%
- B	400	20.4	8.58	402	14.29	7.60	310	4680	142.8%	112.9%	129.7%
- C	405	20.6	8.59	402	14.29	7.60	310	4680	143.9%	113.1%	129.8%
- D	432	20.6	8.53	402	14.29	7.60	310	4800	144.3%	112.2%	129.7%
- E	412	20.9	8.55	400	14.29	7.60	310	4680	146.2%	112.4%	128.9%
							Mean	4700			
							0.85*max	4080			
All	501	20.5	8.62	402	14.29	7.60	310	5240	143.6%	113.4%	129.7%

Increased setting to fulfil the requirement for minimum number of rejects

IP Grading for C30/C16/reject grade combination — **C30 10700** — **C16 5240**

A process in which IP thresholds are calculated on the whole sample less one geographic subsample

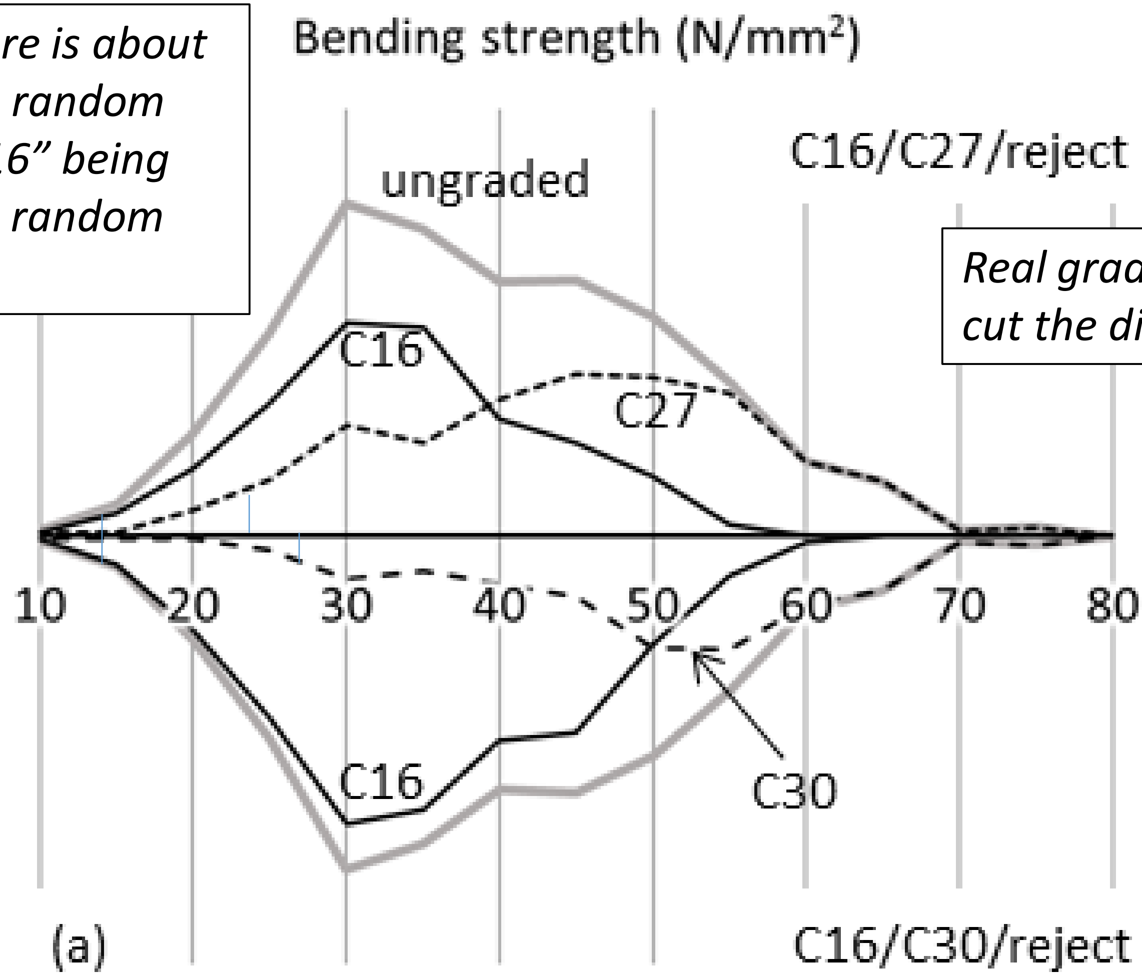
First the upper grade, and then the lower grade

Illustration with real data (2)
UK larch (C16/C30 combination)

	n	Achieved			Required			n	% of required		
		$f_{m,k}$	$E_{0,mean}$	ρ_k	$f_{m,k}$ / k_v	$E_{0,mean}$ x 0.95	ρ_k		$f_{m,k}$	$E_{0,mean}$	ρ_k
		N/mm²	kN/mm²	kg/m³	N/mm²	kN/mm²	kg/m³	%	%	%	%
C30	200	29.4	12.1	479	26.79	11.40	380	28.3%	109.8%	105.8%	126.1%
C16	501	20.5	8.62	402	14.29	7.60	310	71.0%	143.6%	113.4%	129.7%
reject	5	-	4.72	-	-	-	-	0.7%	0.0%	0.0%	0.0%
total	706										

Real world illustration (2)
UK larch (strength)

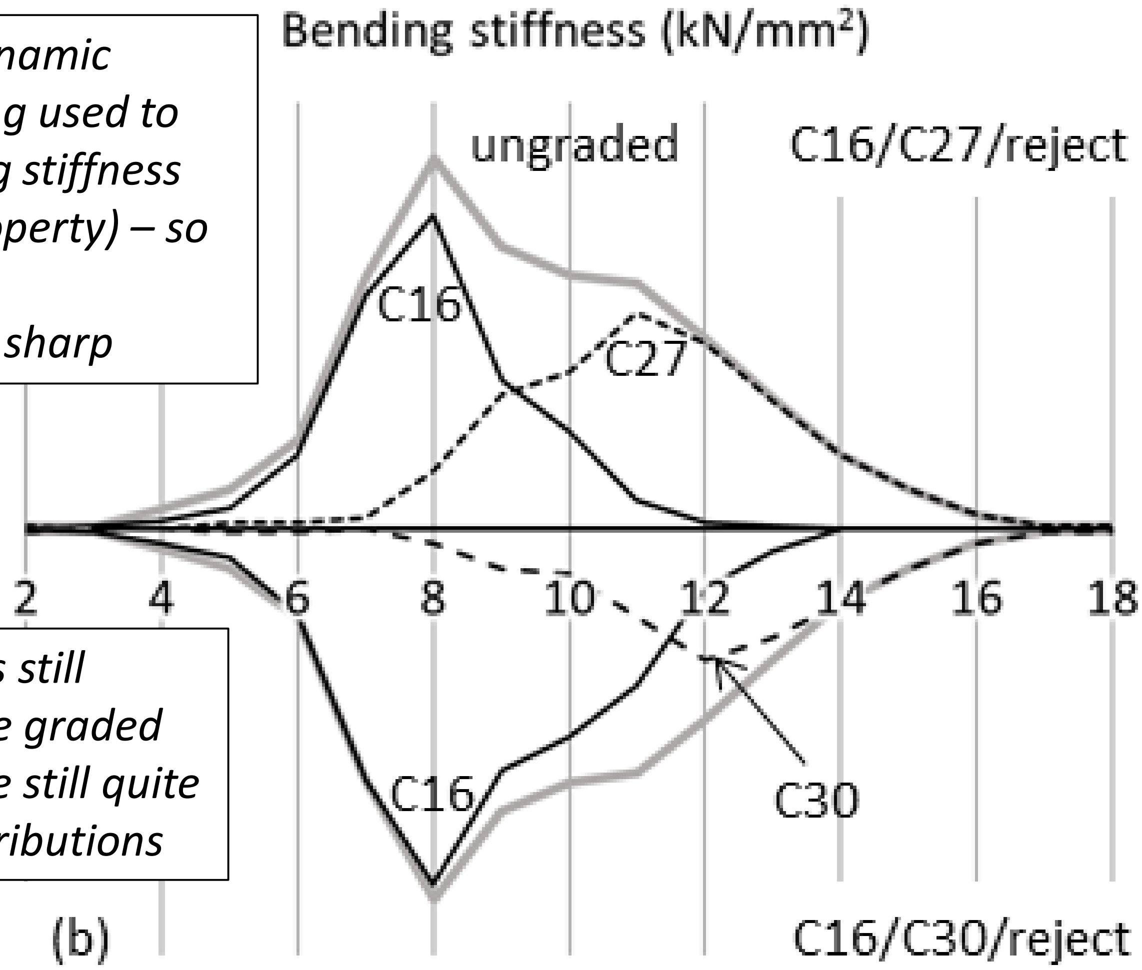
In this case, there is about 1/3 chance of a random piece of the "C16" being stronger than a random piece of "C27"



Real grading is not able to cut the distribution sharply

Real world illustration (2)
UK larch (stiffness)

In this case, dynamic stiffness is being used to predict bending stiffness (the critical property) – so the grading is, comparatively, sharp



Even so, there is still overlap, and the graded distributions are still quite like normal distributions

Real world illustration (2)
UK larch (density)

Density could be graded more accurately, as, in this case, mass is actually measured, but in this case density is not critical and so only dynamic stiffness is used as the IP

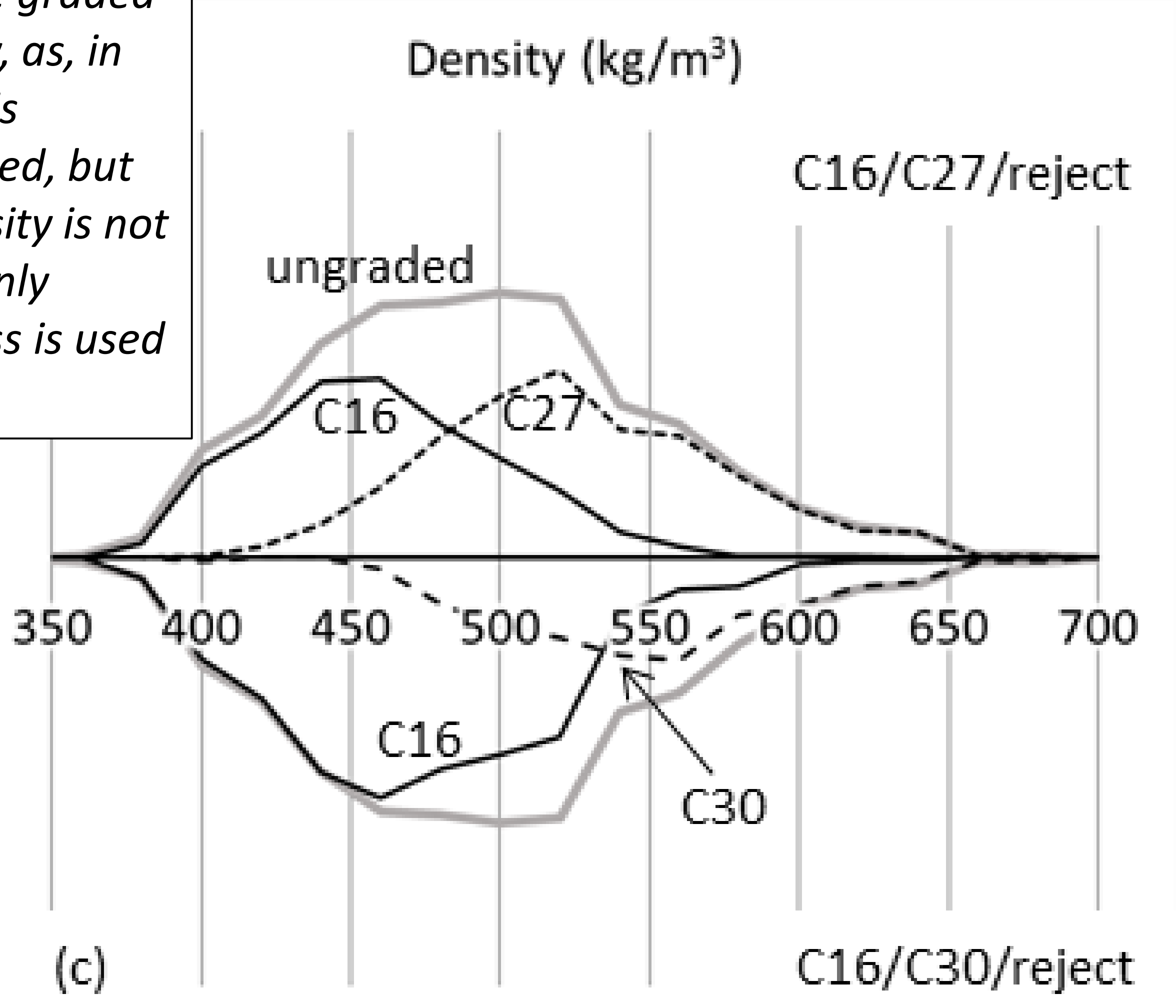


Illustration with real data (2)
UK larch

EN338	Achieved (Ridley-Ellis 2014) Bending strength N/mm²	Bending stiffness kN/mm²	Density kg/m³	Required Bending strength (/1.12) N/mm²	Bending stiffness (×0.95) kN/mm²	Density kg/m³	% of required Bending strength %	Bending stiffness %	Density %
C16 ✓	20.4	8.0	399	16.0 (14.3)	8.0 (7.6)	310	143% ✓	105% ✓	129% ✓
C27 ✓	24.1	11.2	451	27.0 (24.1)	11.5 (10.9)	360	100% ✓	103% ✓	125% ✓
C16 ✓	20.5	8.6	402	16.0 (14.3)	8.0 (7.6)	310	144% ✓	113% ✓	130% ✓
C30 ✓	29.4	12.1	479	30.0 (26.8)	12.0 (11.4)	380	110% ✓	101% ✓	126% ✓

In all cases, the density greatly exceeds the value for the strength class. For C16 the strength greatly exceeds the strength class value.

Illustration with real data (2)
UK larch (C16/C27 combination)

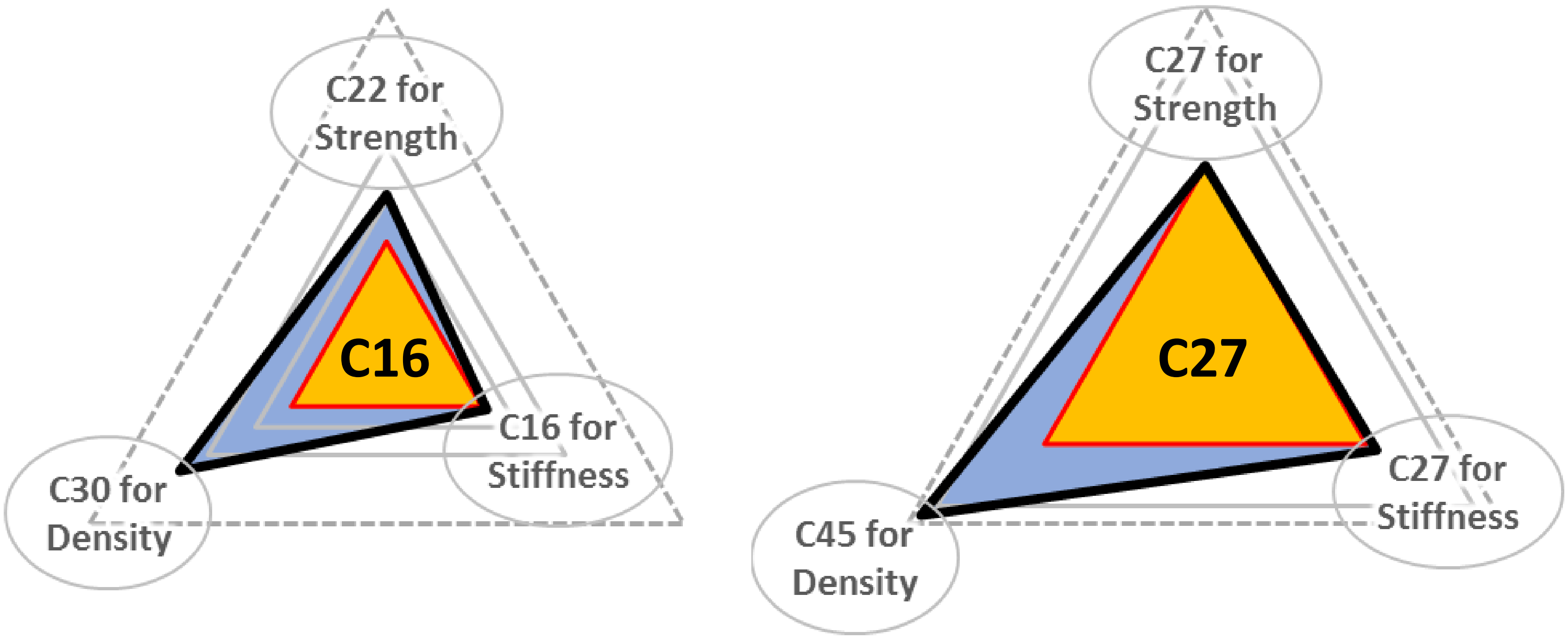
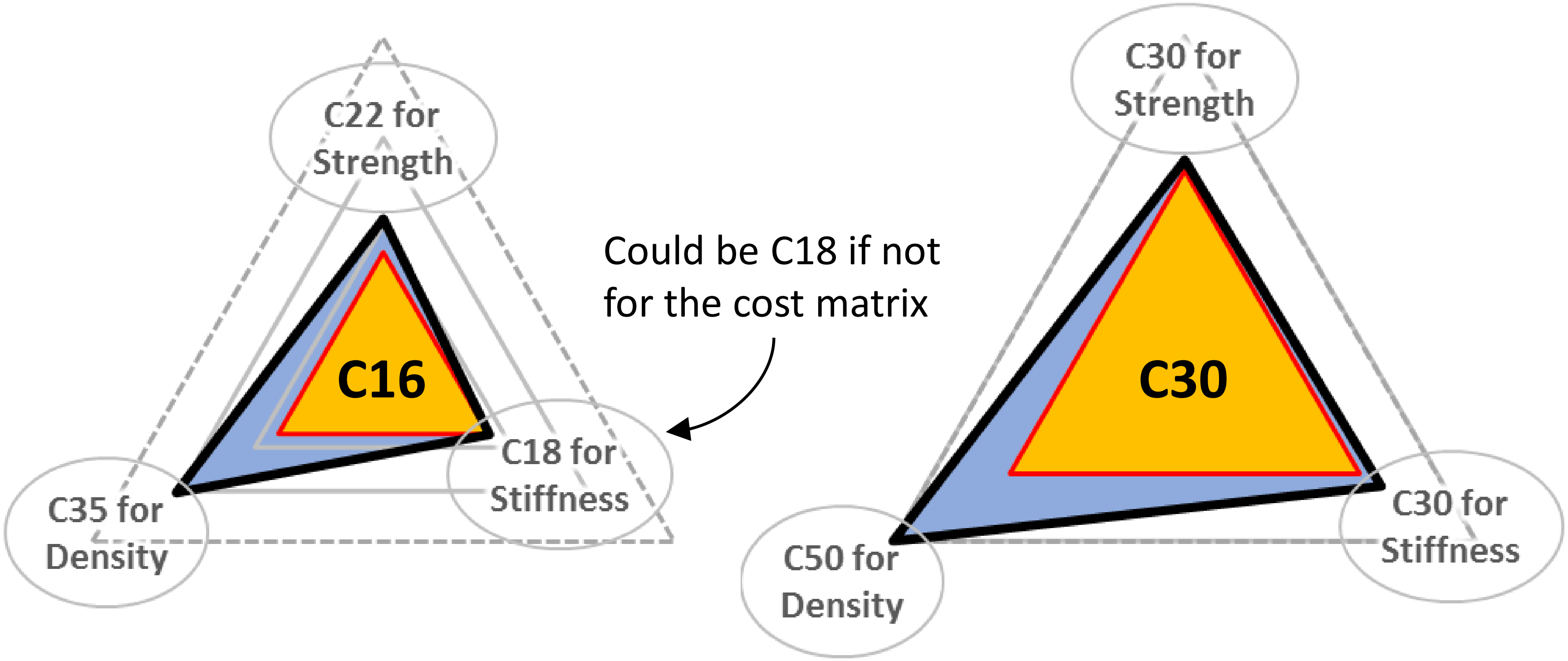


Illustration with real data (2)
UK larch (C16/C30 combination)



Summary
Things you cannot do include

Use the values of the strength class in models for lab testing

(although you can use grading methods to estimate properties if you have the background data for the species and growth area. See also EN14358)

Assume test specimens are equivalent because the strength class is the same

(although you can use grading methods to make sets of timber specimens with similar properties)

For example you cannot necessarily conclude that one method of reinforcement is better than another if they were tested on C24…and it was not checked that the C24 for the first set of tests really was similar to the C24 used for the other.

Use grading settings or assignments from other growth areas and expect them to work

What can you do?

Use non-destructive techniques to:

Estimate properties (with some background knowledge)

Make sets of timber specimens that are similar by matching density, dynamic modulus of elasticity and grain/knots

Make a subset of specimens with a similar range of properties as a larger set (e.g. by ranking by dynamic modulus of elasticity and picking every *n*th specimen).

Calculate estimates of means and standard deviations for the parent population, accounting for statistical uncertainty (exercise following)

Use knowledge of the underlying structure of the variation of wood properties to make more realistic models

Calculation of 5th%ile characteristic values

There is more than one way to calculate to (100*_k_)th percentile of _n_ results

e.g. Excel

Percentile inclusive (percentile in older versions)

- **Works for _k_ between 0 and 1**

Percentile exclusive

- **Works for k between 1/n and 1-1/n**
- **Meets a stricter statistical definition that the _k_ %ile is the (interpolated) point <u>below which</u> _k_% of the data lie**

The European Standards (EN14081 and EN384) use a different method: Ranking

Ranking to obtain 5th %ile

Sort the *n* results in order from low to high

The 5th %ile is the result that is 0.05n* in the list**

If *n* = 20, then it is the lowest value (e.g. 1, 2, 3, 4, 5, 6, 7, 8…20)

If *n* = 100, then it is the 5th lowest value (e.g. 1, 2, 3, 4, 5, 6, 7, 8…100)

If *n* = 80, then it is the 4th lowest value (e.g. 1, 2, 3, 4, 5, 6, 7, 8…80)

If *n* = 90, then it is half way between the 4th and 5th lowest values (e.g. 1, 2, 3, 4, 5, 6, 7, 8…80)

If *n* = 19, then it cannot be calculated

It can be achieved in Excel using percentile(range,(0.05n*-1)/(*n*-1))**

Exercise two - percentiles

Calculate the 5th percentile by ranking for the following density results (units are kg/m^3):

489	529	421	490	400	507	403	451	424
400	439	369	503	539	455	408	440	371
399	370	413	449	374	405	405	500	409
444	419	410						

The values are in a text file http://goo.gl/z5dHsR

Statistical uncertainty

The smaller the sample, the more uncertain the result

There are several ways to calculate confidence limits

e.g. the procedure in EN14358 (method which follows in the new version currently out for formal vote)

4.2.2 Parametric calculation

a) The parametric approach shall not be used on test data not fitting the assumed distribution. In that case non-parametric method should be used.

b) It is assumed that n test values are available and that these may be assumed to originate from a statistically homogeneous population. The test values, which are assumed to be logarithmically normally distributed or normally distributed and independent, are denoted $m_1, m_2, \ldots, m_n$. The n test values constitute the sample.

c) Strength parameters should be assumed as logarithmically normally distributed unless analysis of the data shows that a normal distribution is more appropriate. Density shall be assumed as normally distributed.

NOTE 1 Some product standards define the statistical distribution to be used.

d) The mean value $\bar{y}$ and the standard deviation s_y shall be determined as:

logarithmically normally distributed	normally distributed
$\bar{y} = \frac{1}{n}\sum_{i=1}^{n} \ln m_i$ (1)	$\bar{y} = \frac{1}{n}\sum_{i=1}^{n} m_i$ (2)
$s_y = \max\begin{cases}\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(\ln m_i - \bar{y})^2} \\ 0{,}05\end{cases}$ (3)	$s_y = \max\begin{cases}\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(m_i - \bar{y})^2} \\ 0{,}05\bar{y}\end{cases}$ (4)

The sample coefficient of variation shall not be taken as less than 0,05. For logarithmically normally distributed test values, the standard deviation s_y shall not be less than $\sqrt{\ln\left(1+0{,}05^2\right)} \approx 0{,}05$.

For normally distributed test values, the standard deviation s_y shall not be less than $0{,}05\,\overline{y}$.

e) The characteristic value of the sample shall be determined as follows:

percentile	logarithmically normally distributed	normally distributed
5-percentile	$m_k = \exp\left(\overline{y} - k_s(n)s_y\right)$ (5)	$m_k = \overline{y} - k_s(n)s_y$ (6)
95-percentile	$m_k = \exp\left(\overline{y} + k_s(n)s_y\right)$ (7)	$m_k = \overline{y} + k_s(n)s_y$ (8)

f) $k_s(n)$ shall be taken as:

$$k_s(n) = \frac{k_\alpha(n)}{\sqrt{n}} \tag{9}$$

where $k_\alpha(n)$ is the α-percentile in a non-central t-distribution with $n - 1$ degrees of freedom and the non-centrality parameter $\lambda = u_{1-p} \cdot \sqrt{n}$.

whereby -u_{1-p} is the (1 – p)-percentile of the standardised normal distribution function.

NOTE 2 The following simplified expression may be used to evaluate $k_s(n)$

$$k_s(n) = \frac{6{,}5\,n + 6}{3{,}7\,n - 3} \tag{10}$$

http://goo.gl/z5dHsR

Some values of $k_s(n)$ calculated according to equation (9) are given in Table 1.

Table 1 — $k_s(n)$ values for strength properties for p = 5 % and α = 75 %"

Number of test specimens	Factor
n	$k_s(n)$
3	3,15
5	2,46
10	2,10
15	1,99
20	1,93
30	1,87
50	1,81
100	1,76
500	1,69
∞	1,64

NOTE 3 For other numbers of test specimens, one should take the next larger value for $k_s(n)$,

4.3 Calculation of characteristic mean values

a) The characteristic value m_{mean} for a material stiffness m modelled as a stochastic variable is defined as the mean value in the distribution function for m, corresponding to an assumed infinitely large test series.

b) It is assumed that n test values are available and that these may be assumed to originate from a homogeneous population. The test values, which are assumed to be normally distributed and independent, are denoted $m_1, m_2, \ldots, m_n$. The n test values constitute the sample.

c) The sample mean value $\overline{y}$ and the sample standard deviation s_y for the stochastic variable $y = m$ shall be determined as:

$$\overline{y} = \frac{1}{n}\sum_{i=1}^{n} m_i \qquad (14)$$

$$s_y = \max\begin{cases}\sqrt{\dfrac{1}{n-1}\displaystyle\sum_{i=1}^{n}(m_i - \overline{y})^2} \\ 0{,}05\overline{y}\end{cases} \qquad (15)$$

d) For stiffness properties, the characteristic mean value shall be taken as the sample mean value $\bar{y}$ as given in equation (16)

e) When it is required to make use of confidence intervals, the characteristic mean value m_{mean} shall be determined as

$$m_{\text{mean}} = \bar{y} - k_s(n)s_y \tag{16}$$

where

$$k_s(n) = \frac{t_{\alpha,n-1}}{\sqrt{n}} \tag{17}$$

$t_{\alpha,n-1}$ is the α percentile in a central t-distribution with n-1 degrees of freedom.

Some values of $k_s(n)$ are given in Table 2. For other numbers of test specimens, one must either interpolate or take the safer value for $k_s(n)$, i.e. the one which is larger.

NOTE The following simplified equation may also be used to evaluate $k_s(n)$:

$$k_s(n) = \frac{0{,}78}{n^{0{,}53}} \tag{18}$$

Table 2 — $k_s(n)$ values for stiffness properties

Number of test specimens	**Factor**
n	$k_s(n)$
3	0,471
5	0,331
10	0,222
15	0,179
20	0,154
30	0,125
50	0,096
100	0,068
500	0,030
∞	0,000

Exercise three – some real data

Take a sheet containing the test results from 20 randomly chosen specimens from the larch study earlier in this presentation

Using these 20 samples, calculate

From the sample alone

5^{th} %ile bending strength (ranking)

Mean bending stiffness (simple mean)

5^{th} %ile density (ranking)

Using EN14358

5^{th} %ile bending strength (lognormal approach)

Mean bending stiffness

5^{th} %ile density (normal approach)

How will this compare to the statistics of the full dataset (706 specimens)?

But…a big assumption

This all assumes that the data is normally (or log-normally) distributed. This might not be the case when the sample has been graded – indeed, the better the grading works, the less we would expect this to be true.

So what else might we do?

Bootstrapping

Make many more samples that are made from drawing randomly from the samples we do have <u>with replacement</u> making sets of the <u>same number of samples</u>.

Exercise four – bootstrapping prediction

Using the 20 samples (from exercise three), calculate

From the sample alone

A prediction of bending stiffness when dynamic MoE = 13 kN/mm^2

Using bootstrapping

A prediction of bending stiffness when dynamic MoE = 13 kN/mm^2

(There is a spreadsheet called "Bootstrap1predictor.xlsx" you can use for this. I haven't checked it yet! It comes from here

http://www.sportsci.org/2012/wghboot.htm

How will this compare to the statistics of the full dataset (706 specimens)?