Unit 5 Technical and functional textiles
Lecture 5.3 Advanced and intelligent textiles

D 2.1 Training toolkit and e-book

July 2021 – H. Ventura, M. Ardanuy, D. Cayuela (UPC)

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Lecture 5.3
Advanced and intelligent textiles

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Contents

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Introduction

Advanced and intelligent textiles

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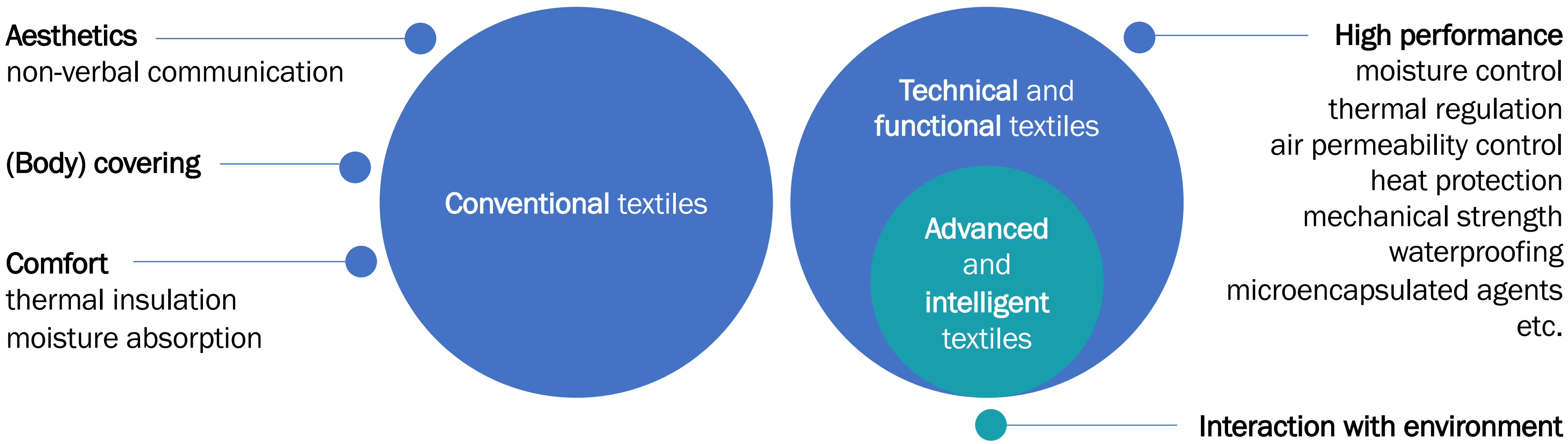
Introduction: Lesson context



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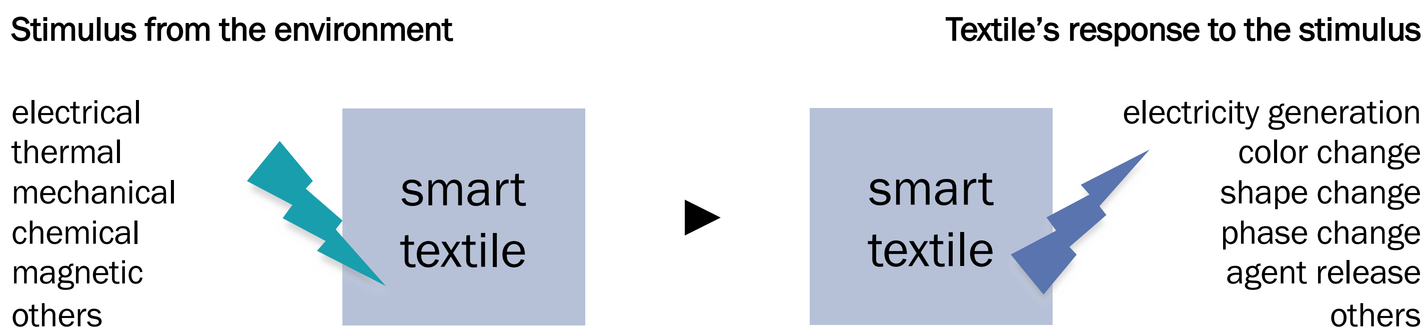
Definition

- ***Advanced and intelligent textiles*** **(or *smart textiles*) interact with their surroundings, being be able to sense and/or respond to environmental stimuli.**
- **The origin of both the stimulus and the response can be either from an electrical, thermal, mechanical, chemical or magnetic source.**



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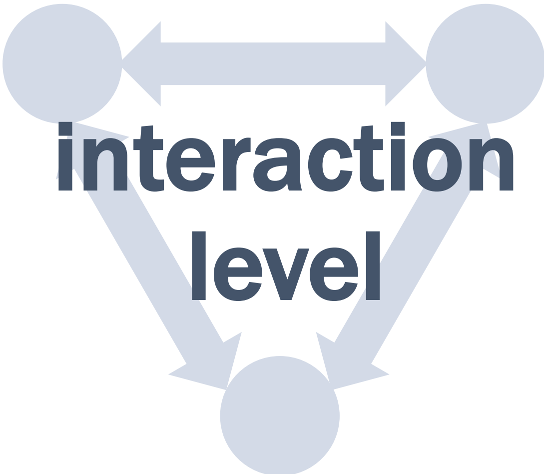
Classification



- *Passive* smart textiles
- *Active* smart textiles
- *Very smart* textiles
  or *ultra smart* textiles

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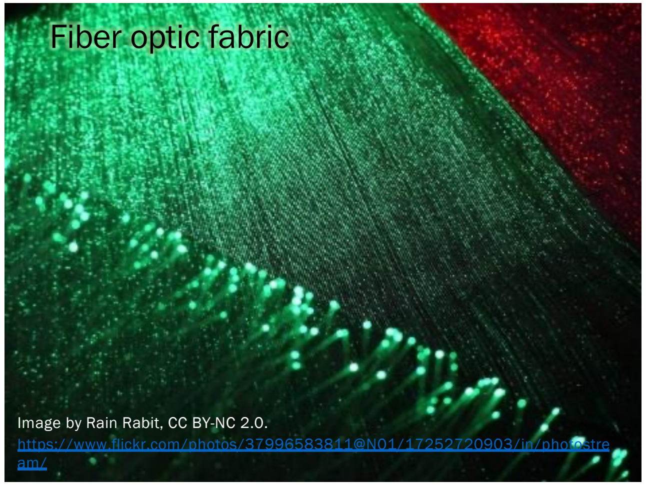
smart
textile

Passive smart textiles
SENSE



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Active smart textiles

SENSE & REACT

smart textile

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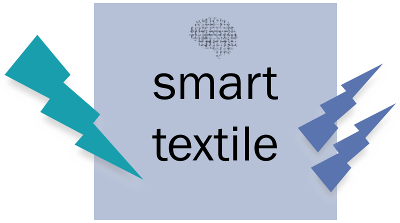
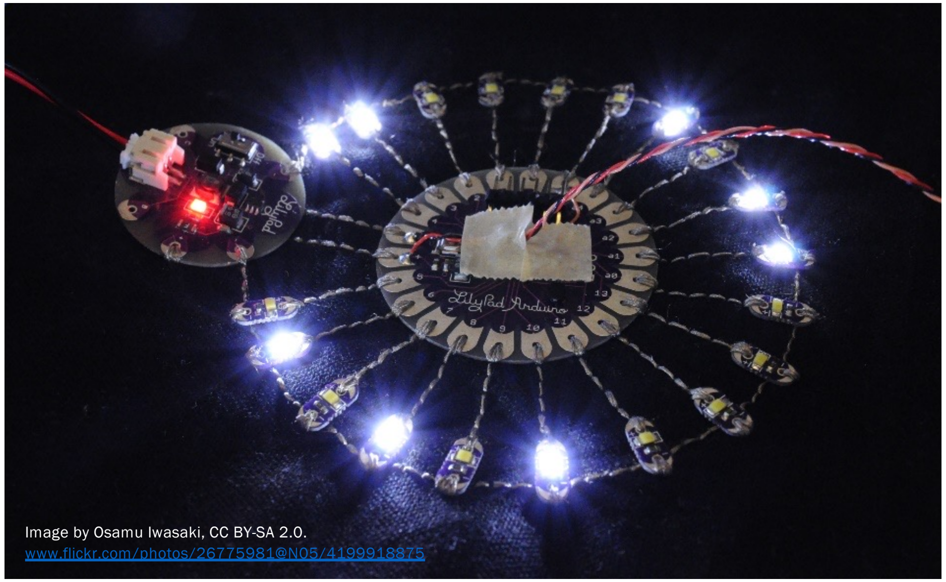
Very smart textiles

(or *Ultra Smart Textiles*)

SENSE, REACT & ADAPT



A unit/part acting as the “brain”



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Integration level

textile value chain

fibre ▶ *spinning* ▶ **yarn** ▶ *weaving/knittng* ▶ **fabric** ▶ *finishing* ▶ **finished fabric** ▶ *joining* ▶ **garment**

At the spinning level
conductive fibre/filament/yarn
engineered/composite yarns
shape memory yarns
etc.

very high integration

At the weaving / knitting level
conductive fabrics
knitted shape memory structures
etc.

high integration

At the finishing level
chromoactive printings
conductive printings
thermoactive coatings
etc.

high-medium integration

At the joining level
e-textiles
embroidery
joining electrical components
etc.

medium-low integration

integration level

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Main smart materials

Advanced and intelligent textiles

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Main smart textiles

- Chromo-active
- Electro-active
- Shape memory
- e-textiles

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Chromo-active textiles

Main smart textiles

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Chromo-active textiles

Type	Stimulus	Response
Thermochromic	Temperature	Colour change
Photochromic	Light	
Electrochromic	Electricity	
Solvatochromic	Solvent's polarity	
Halochromic	pH	
Others	*Others*	

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Thermocromic textiles

Chromo-active textiles

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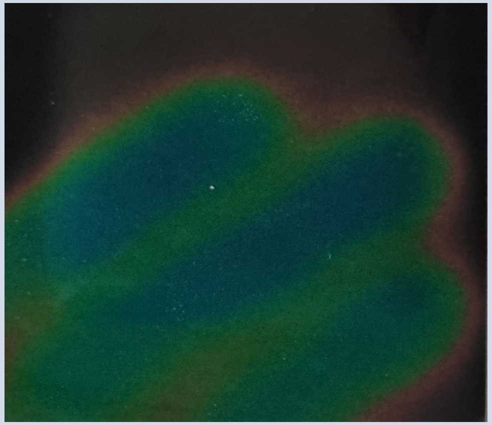
Thermochromic textiles

Liquid crystals

- based on changes in the structure



Leuco-dyes

- based on molecular rearrangement

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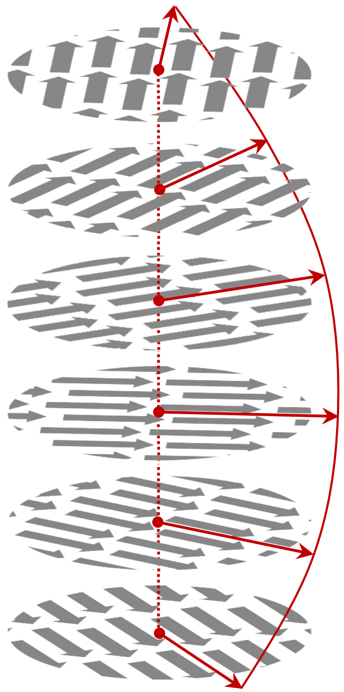
Thermochromic textiles

Liquid crystals

- Organic materials in a stable intermediate phase between a solid and a liquid
- Molecules have a certain degree of orientation order
- Cholesteric liquid crystals present thermochromism



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Thermochromic textiles

Liquid crystals

- Helical arrangement characterised by the distance of one full helical rotation (pitch length)
- The colour depends on the light that is reflected
- Reflected light is governed by pitch length
- Pitch length is temperature dependant

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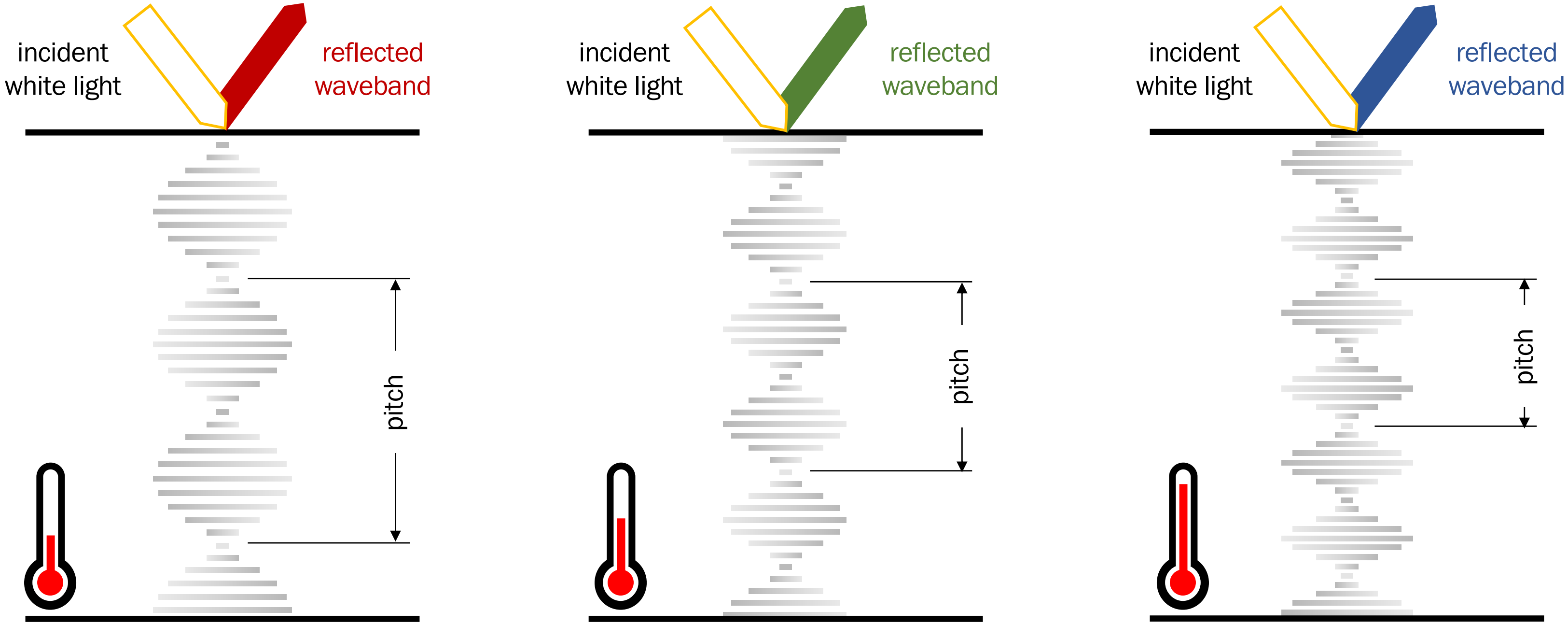
Thermochromic textiles

Liquid crystals



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Thermochromic textiles

Leuco dyes

- Based on molecular rearrangements of organic compounds
- Leuco dyes are pH sensitive dye-based indirect **systems** that change pH value due to heating
- Require the interaction of three components:
  - organic colour former (leuco dye)
  - developer (proton donor)
  - organic solvent
- Microencapsulated to have all components enclosed

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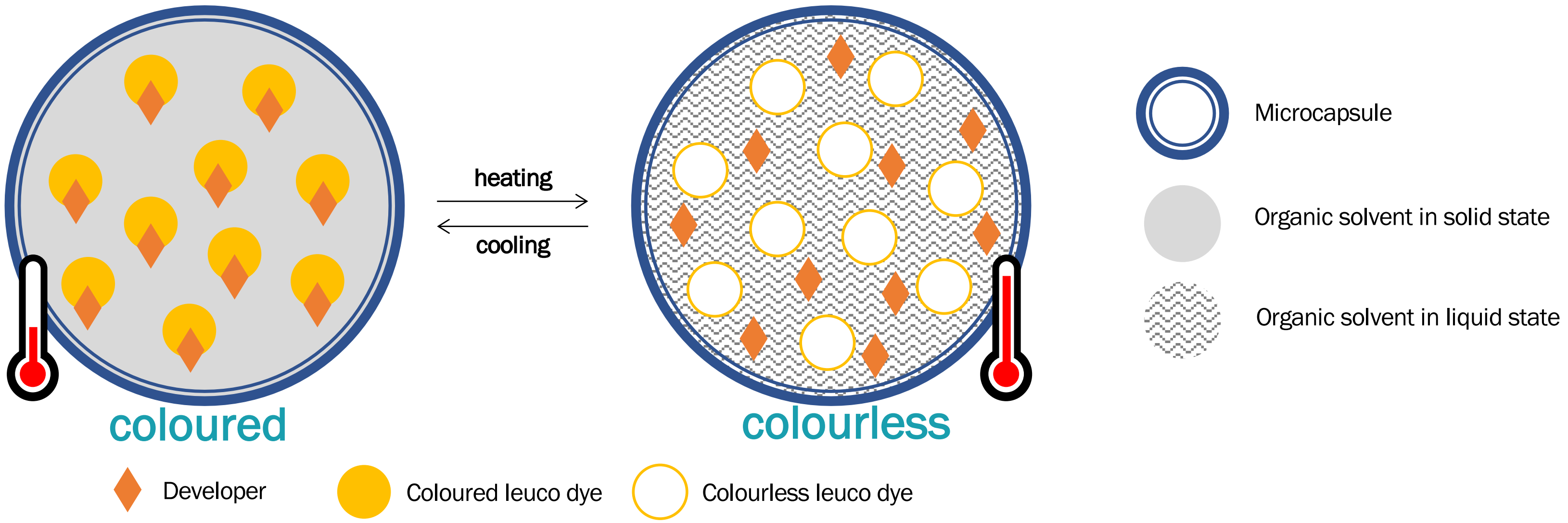
Thermochromic textiles

Leuco dyes



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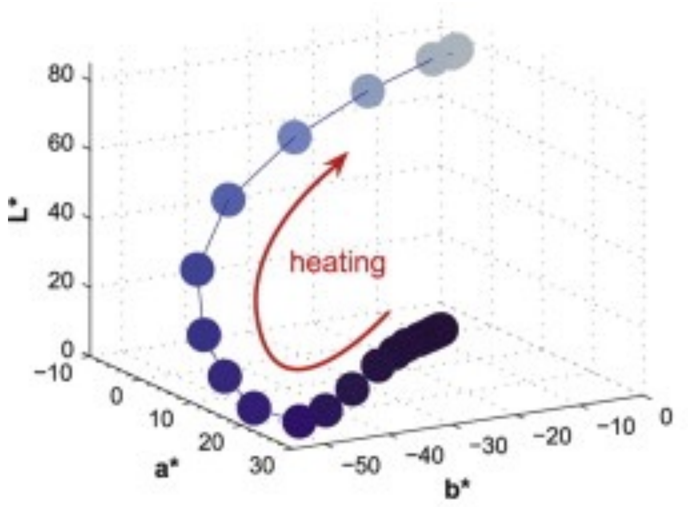
Thermochromic textiles



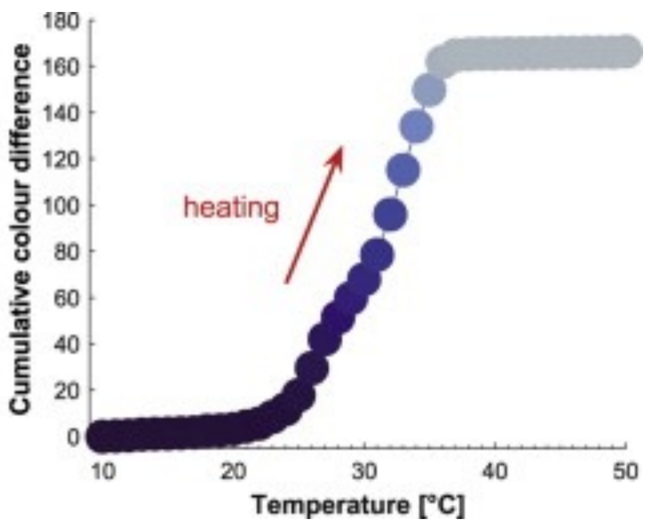


Image credits: O. Panák, M. Držková and M. Kaplanová, *Insight into the evaluation of colour changes of leuco dye based thermochromic systems as a function of temperature*, Dyes and Pigments, 120 (2015), 279-287. doi: 10.1016/j.dyepig.2015.04.022. Available at https://www.sciencedirect.com/science/article/pii/S0143720815001448

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Thermochromic textiles

- Liquid crystals and thermochromic leuco dyes present the form of microcapsules
- Are not applied by exhaustion or impregnation methods, are applied but by printing or coating processes and using adequate binders
- Thermochromic polymeric filaments are obtained by mass-colouration (thermochromic microcapsules added during polymerization)
- Possible to integrate this smart function at fibre-level and at fabric-level

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Thermochromic textiles

Performance properties:

- Colorimetric properties:
  - Activation temperature or switching temperature
  - Colouration/discolouration hysteresis
- Colour strength: generally, is low.
  - Dark background required for liquid crystals
  - Limited amount of colorant for leuco dyes (pastel shades)
- Fastness of thermochromic system to light, washing, rubbing, etc.
  - Photo-chemical fading in leuco dyes
  - Low affinity for the fibre of microencapsulated thermochromics results

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Uses of thermochromic textiles

- Aesthetic purposes
  - workout t-shirts and sweaters
  - toys
- Functional applications:
  - healthcare sector
  - babies' clothes to detect fever
  - facemasks to detect fever
  - military camouflage uniforms

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Photocromic textiles

Chromo-active textiles

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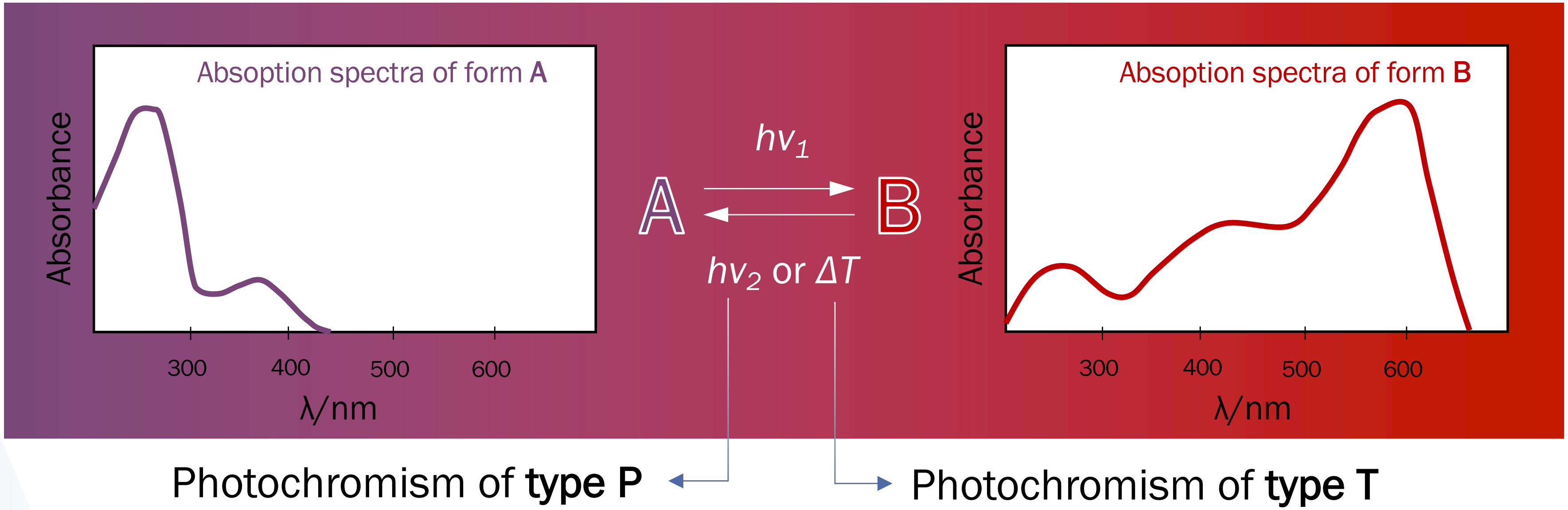
Photochromic textiles

- **Photochromism = reversible light-induced colour change**



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Photochromic textiles

Performance properties:

- Good photochromic absorption and efficiency
  - capable to reveal clear colour changes with minimum concentration
  - good level of optical absorption under light irradiation (intensity, colour and band shape)
- High coloration-bleaching speed
  - fast change between colourless and coloured states
  - low half-time
- Good stability
  - resistance to photodegradation with prolonged UV exposure
  - minimal variation of the photochromic response with temperature
  - minimal loss of performance over time of coloration-bleaching cycles (fatigue)

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Photochromic textiles

- Photochromic effect in textiles is achieved with a variety of commercial photochromic dyes, pigments, and even microcapsules
- Applied over fabrics and yarns by dyeing, printing or coating processes
- Some photochromic compounds can present technical difficulties or poor effects due to lack of compatibility with textile processes
- Possible to produce mass-coloured photochromic fibres, hence to integrate this smart function at fibre-level and at fabric-level

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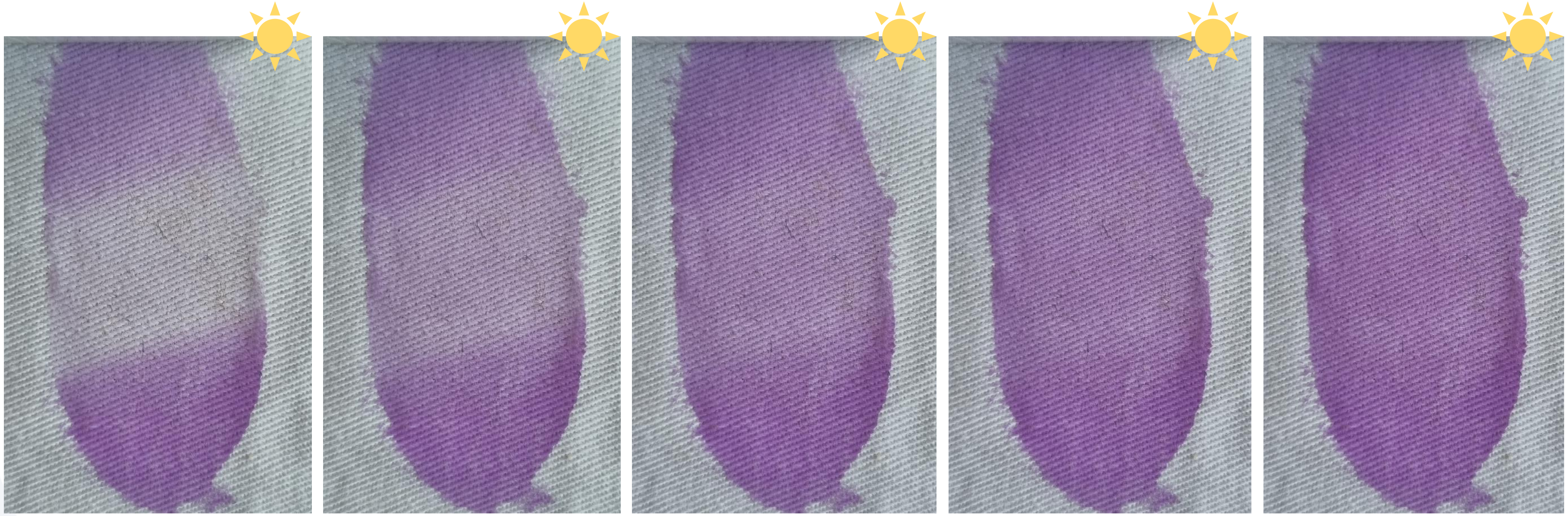
Photochromic textiles



Time of light exposure in the central zone (after partial light blocking)

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Uses of photochromic textiles

- UV-exposure indicators and UV protection (cosmetic and medical fields)
- Military protection and camouflage systems
- Aesthetic purposes:
  - promotional apparel (T-shirts, caps, tote bags)
  - embroidery decorations
- Authentication systems in logos and brand names to prevent duplication
- Future technological applications:
  - textiles for optical information recording/storage.
  - use of photochromic compounds to obtain textiles with tuneable surface-wettability

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Electro-active textiles

Main smart textiles

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Electro-active textiles

Type	Stimulus	Response
Pyroelectric *Thermoelectic*	Temperature	Electrical current
Photovoltaic	Solar radiation	
Piezoelectric	Mechanical	
Triboelectric	Friction	

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Piezoelectric textiles

Electro-active textiles

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Piezoelectric textiles

- When subjected to pressure or vibrations, generate an electrical signal of a limited magnitude and viceversa (the effect is reversible)
- Caused by of dipoles formed when mechanically deformed or impacted due to:
  - non-centrosymmetric crystal structure for metal-based
  - distribution of the polymer chains and its molecular orientation in the structure for polymer-based
- For textile applications, must present low density, high flexibility (i.e. to adapt to body curvatures), and low cost, i.e. piezopolymers like polyvinylidene fluoride (PVDF)

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Piezoelectric textiles

- PVDF and its copolymers are the most investigated owing to their thermal stability, good chemical resistance, good processability and good mechanical properties
- Due to its atom configuration PVDF is inherently polar
- PVDF molecular dipoles CF_2-CH_2 can arrange into various conformations, leading to five piezoelectric phases
- α-, β- and γ-phases the most relevant
- β-phase of PVDF is the phase mostly responsible of the piezoelectric effect

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Piezoelectric textiles

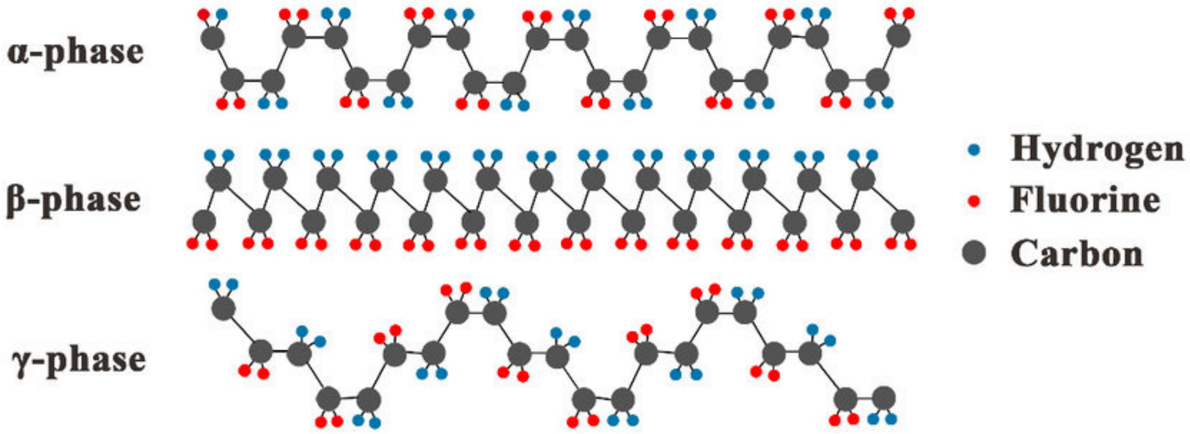

Image by: Ting Wu et al. CC BY 4.0 “A Flexible Film Bulk Acoustic Resonator Based on β-Phase Polyvinylidene Fluoride Polymer,” *Sensors*, vol. 20, no. 5, p. 1346, Feb. 2020.

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Piezoelectric textiles

The most common phase in PVDF is α-phase. Therefore, for an optimal piezoelectric effect, it is necessary to induce the β-phase.

Increasing of β-phase content can be done:

- **By orientation and polarization**
  1. Fibre stretching (orientation)
  2. Polarization with high electric field
     - contact mode (electrodes)
     - non-contact mode (high potential corona discharge)

  Polarization enhanced by high temperature, or by simultaneously stretching
- **By electrospinning**
  - Especially with doped PVDF solution:
    - electron donor doping: e.g. tri-ρ-tolyamine or TTA
    - hole donor doping: e.g. 2-(4-tert-butylphenyl)-5-(4-biphenylyl)-1,3,4-oxidiazole or Butyl-PBD

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Piezoelectric textile examples

- PVDF-based electrospun membranes:
  - Good sensibility
  - Low voltage signals
  - For sensors, not for energy harvesting

- PVDF-based knitted 3D spacers:
  - Outer layers (top and bottom electrodes) made with silver-coated polyamide multifilament
  - Spacer yarn of PVDF monofilament with around 80% β-phase content
  - Higher output power density and efficiency than 2D structures

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Triboelectric textiles

Electro-active textiles

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Triboelectric textiles

- Triboelectric effect occurs at the interface between the two of different materials in contact, when they generate friction via rubbing.
- An electrical charge transfers from one material to the other, producing a certain voltage.
- But to achieve this, have to be materials widely separated from the triboelectric series.

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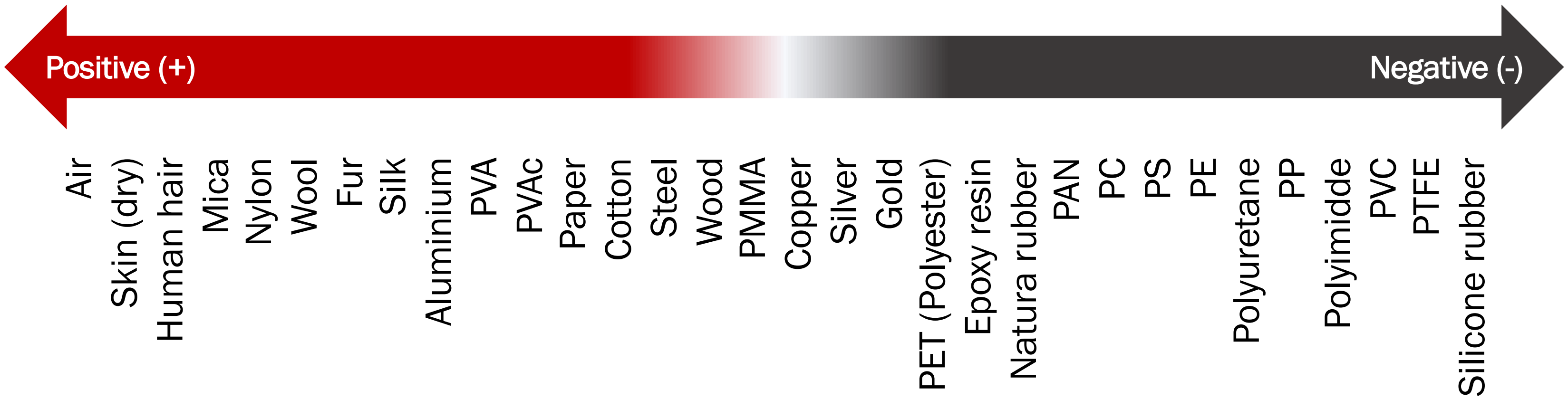
Triboelectric series



The higher the difference between both materials, the higher transfer during friction.

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Triboelectric textiles

- Triboelectric generators, with friction between two materials with opposite polarized triboelectric charges, can drive the electrons back and forth in the external circuit between the electrodes
- Conversion of mechanical energy into electrical energy
- A basic triboelectric generator is based on:
  - two electrification materials
  - conductive electrodes

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Triboelectric textile examples

- **Textile wearable triboelectric nano-generator for harvesting body motion energy, using polyester fabric (Dacron®) and polyamide 66 fabric (nylon). Long rectangular shaped elements from the two fabrics are fixed intercalated onto a cotton fabric base, and connected to the electrodes. Placed in the forearm, uses the mechanical energy to power an electroluminescent tube like lamp.**
  N. Cui, J. Liu, L. Gu, S. Bai, X. Chen, and Y. Qin, "Wearable Triboelectric Generator for Powering the Portable Electronic Devices," *ACS Appl. Mater. Interfaces*, vol. 7, no. 33, pp. 18225–18230, Aug. 2015.

- **Triboelectric nano-generator textiles from special core–shell yarns with stainless-steel conductive fibres as the core for electrodes, and polyurethane (Spandex®) dielectric fibres as the shell for triboelectrification. Yarns were woven and knitted to obtain fabrics, leading to positive results.**
  A. Yu et al., "Core–Shell-Yarn-Based Triboelectric Nanogenerator Textiles as Power Cloths," ACS Nano, vol. 11, no. 12, pp. 12764–12771, Dec. 2017.

- **Textile triboelectric nano-generator based on a printed array of carbon nanotube-based ink over a nylon fabric (the electrode), and a silk fabric as frictional material. The resulting textile device exhibited highly sensitive touch and gesture sensing performance.**
  R. Cao *et al.*, "Screen-Printed Washable Electronic Textiles as Self-Powered Touch/Gesture Tribo-Sensors for Intelligent Human–Machine Interaction," *ACS Nano*, vol. 12, no. 6, pp. 5190–5196, Jun. 2018.

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Shape memory textiles

Main smart textiles

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Shape memory alloys SMAs

Shape memory textiles

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Shape memory alloys - SMAs

- Some metals present certain shape transformation capabilities derived from phase transitions.
- Example: nickel-titanium alloys
- Phase transitions between austenitic and martensitic phases within a favourable temperature range.
  - **Martensite phase:** stable phase found at low temperature, generally as **twinned martensite**
    Can be deformed, generating **detwinned martensite**
  - **Austenite phase:** stable phase at high temperature
- Depending on the composition, the characteristic temperatures of the transition can be varied.

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Shape memory alloys - SMAs

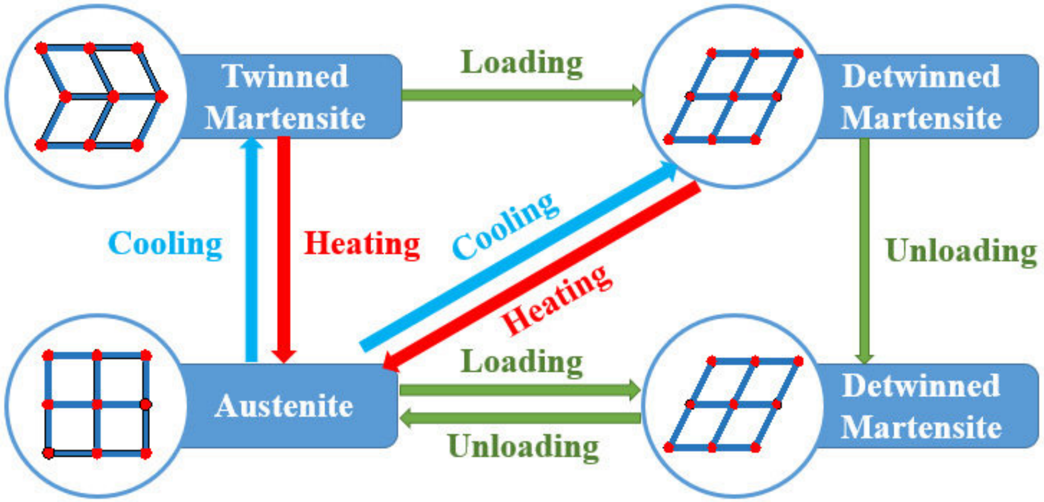

Image by: Ying-qi Jia, Zhou-dao Lu, Ling-zhi Li, Zhen-li Wu, CC BY 3.0 “A Review of Applications and Research of Shape Memory Alloys in Civil Engineering,” IOP Conf. Ser. Mater. Sci. Eng., vol. 392, p. 022009, Aug. 2018.

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Shape memory alloys - SMAs

One-way memory shape

Two-way memory shape

Supereleasticity

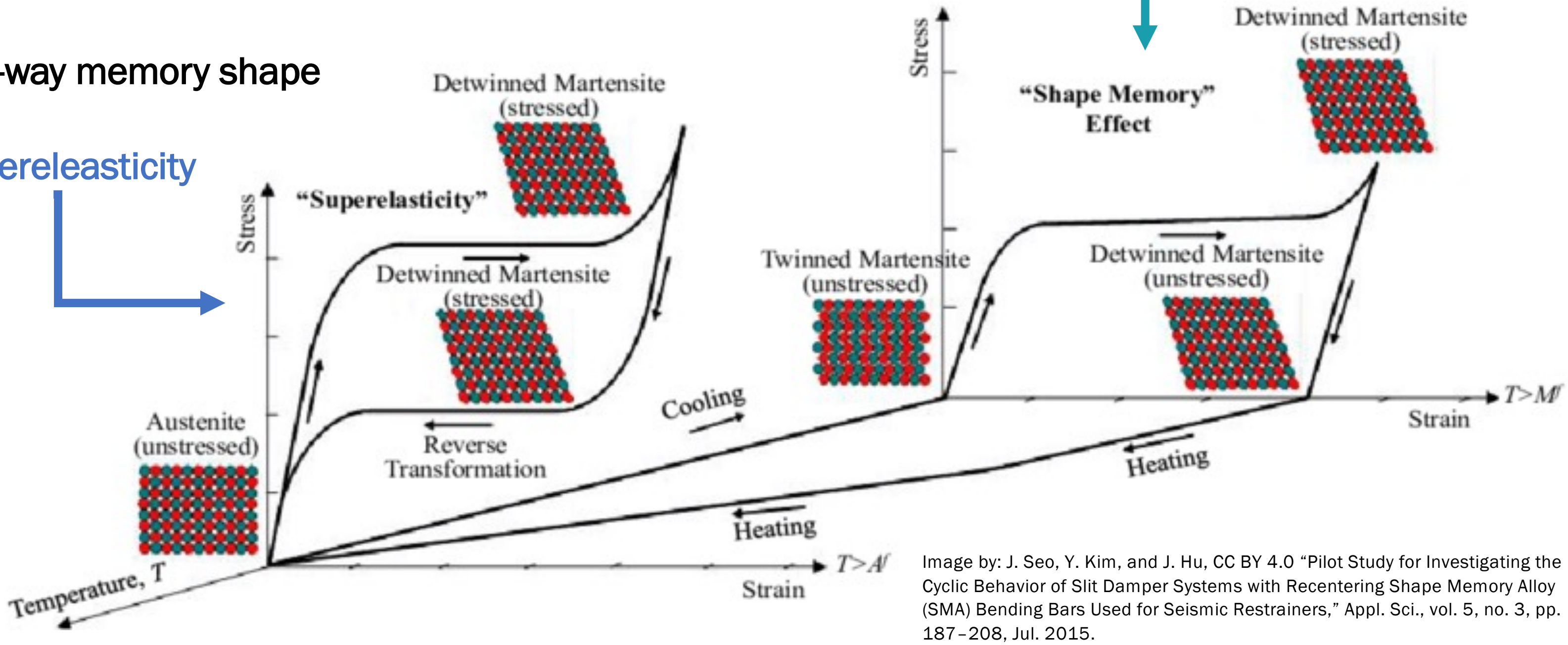

Image by: J. Seo, Y. Kim, and J. Hu, CC BY 4.0 "Pilot Study for Investigating the Cyclic Behavior of Slit Damper Systems with Recentering Shape Memory Alloy (SMA) Bending Bars Used for Seismic Restrainers," Appl. Sci., vol. 5, no. 3, pp. 187–208, Jul. 2015.

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Shape memory alloys - SMAs

- The use of SMAs for textile-based applications has been modestly studied in the literature
- Application examples:
  - actuators for some functional applications such as insulation improvement in protective clothing
  - other more conceptual than functional examples such as the Oricalco fabric from Grado Zero, or the adaptable top from Mariëlle Leenders
- Present certain potential in technical textile-based products, such as smart blinds and curtains or smart insulation solutions.

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Shape memory polymers SMPs

Shape memory textiles

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Shape memory polymers- SMPs

- Polymeric materials which can be deformed and fixed in a temporary shape
  - when exposed to an appropriate stimulus, they recover their original shape
  - change of shape is predefined and determined by the mechanical deformation leading to the temporary shape
- Trigger stimulus can be heat or light, but thermally-induced are most common:
  - irradiation with IR-light
  - application of electrical current
  - exposure to alternating magnetic fields
  - immersion in water

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Shape memory polymers- SMPs

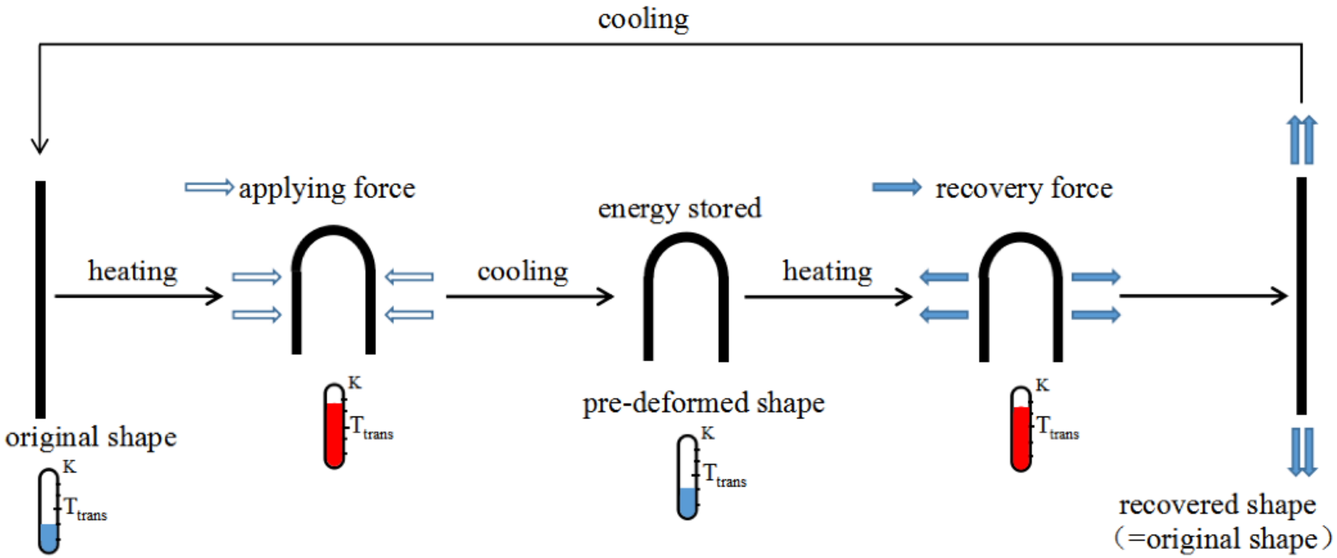

Image by: Z. Wang, J. Liu, J. Guo, X. Sun, and L. Xu, CC BY "The Study of Thermal, Mechanical and Shape Memory Properties of Chopped Carbon Fiber-Reinforced TPI Shape Memory Polymer Composites," Polymers (Basel)., vol. 9, no. 11, p. 594, Nov. 2017.

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Shape memory polymers- SMPs

- Based on the formation of a phase-separated morphology, where one of the two phases acts as a molecular switch.
- Two different segments:
  - *switching* or *soft segment:* temporarily fixes the programmed shape by a glass transition, crystallization, or reversible bonds
  - *permanent* or *hard segment:* responsible for retaining the original shape of the whole SMP. This hard segment can be attained through chemical cross-linking in the polymer network, incorporation of interpenetrating networks, or crystalline phases.
- Shape recovery typically takes place when heating over the transition temperature (T_{trans}), which switches-off the soft segments.
- Depending on the polymeric system, the T_{trans} can be a glass transition temperature (T_g) or a melting temperature (T_m).

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Shape memory polymers- SMPs

Use of SMPs for smart textiles:

- In thermal and moisture control in garments, allowing a better water vapour and heat transfer.
- In shape-adaptable garments, capable to enlarge and adapt to the wearer shape and size almost without applying pressure.
- SMPs coatings to avoid/eliminate deformation derived for the use, wrinkles, etc.
- Smart wettability/smart cleaning, being able to adapt between hydrophobic and hydrophilic behaviour

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e-textiles

Main smart textiles

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e-textiles

- Textile systems that contain one or more electronic components with the aim to fulfil one or more functions (textile sensors, actuators, electrically conductive fibres/textiles and other components)
- Great potential in wearable electronics, especially designed to be worn close to the body, while being flexible, lightweight, adaptable to the user activity and comfortable

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e-textiles

- Electronic devices require of many components to create systems with sensing, processing, actuation, communication and energy harvesting and storage abilities. The potential of e-textile lies in that many of these components could be achieved with e-textiles, for example:
  - Connectors, such as textile connexion cables
  - Batteries and energy harvesting components, such as triboelectric nanogenerators and rechargeable batteries
  - Sensors, such as touch (capacitance) sensors
  - Actuators, such as electroluminescent light emitting printings or heating textiles
  - Antennas, to communicate the wearable with an external device such as a mobile phone.
- Many of those components require conductive layers. Therefore, textile conductors are a basic need for e-textiles.

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Conductive textiles

- Can be achieved with conductive fibres or conductive printing pastes and inks, mainly
- Conductive fibres can be used for the production of yarns and fabrics
  - Yarns can have different constructions, twisting, etc.
  - Fabrics can be either woven or knitted fabrics.
- Conductive threads can also be used in embroidery

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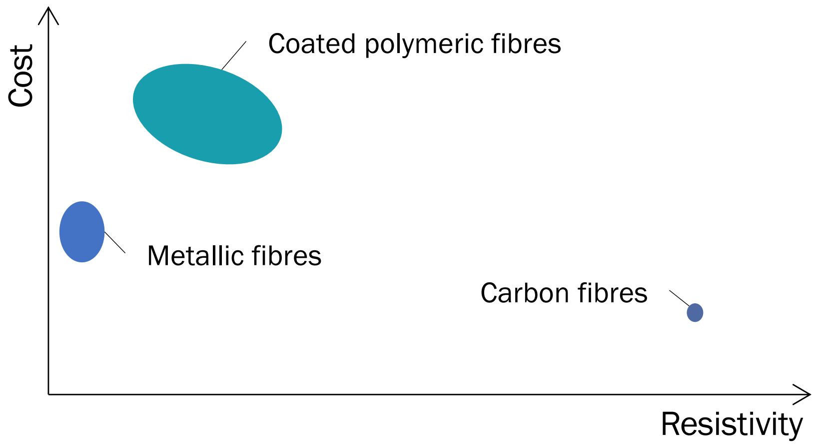
Conductive textiles



- **Metal fibres**: stainless steel, copper, silver, brass or aluminium obtained by drawing
- **Coated conductive polymer fibres**: polymeric fibres (like polyamide fibres) coated with metals, galvanic substances or metallic salts
- **Composite conductive polymer fibres**: polymeric matrix with conductive particles

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Conductive textiles

- Conductive printing pastes consist of a dispersion of highly conductive particles (carbon, silver, silver/silver chloride, gold, copper, graphene…) and binders (i.e. suitable resins such as PES or epoxy) in an organic or inorganic solvent.
- In the case of the inks, the viscosity of the solution must be lower, this meaning that the conductive particles must be of a very fine diameter, and the binders controlled (or even eliminated to be applied in a separated process).
- Printing pastes are often applied by screen-printing techniques, while inks are intended for inkjet printing.

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Aplications

Advanced and intelligent textiles

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Applications

- Potential applications in all the technical textile sectors
- However, there are 5 main sectors, according to European CONTEXT project (European Network to connect research and innovation efforts on advanced Smart Textiles):
    - *Medical*
    - *Personal protection*
    - *Transportation*
    - *Leisure*
    - *Building*

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CRNS - Centre de Recherche en Numérique de Sfax
Tunisia

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