NACHHALTIGwirtschaften

# Vorbilder aus der Natur: Sammlung von biologischen Vorbildern

Annex 2.2
Liste mit Referenzen, unselektiert [biological data base, Teil 1]

Phase 2: Recherche biologischer Vorbilder + wirksamer Prinzipien. Arbeitsergebnisse

P. Gruber

Berichte aus Energie- und Umweltforschung

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Liste mit Referenzen, unselektiert [biological data base, Teil 1]

Phase 2: Recherche biologischer Vorbilder + wirksamer Prinzipien.

Arbeitsergebnisse

Dr. Petra Gruber
transarch

Wien, Juni 2010

Ein Projektbericht im Rahmen des Programms

HAUS der Zukunft

im Auftrag des Bundesministeriums für Verkehr, Innovation und Technologie

# Vorwort

Der vorliegende Bericht dokumentiert die Ergebnisse eines Projekts aus dem Forschungs- und Technologieprogramm *Haus der Zukunft* des Bundesministeriums für Verkehr, Innovation und Technologie.

Die Intention des Programms ist, die technologischen Voraussetzungen für zukünftige Gebäude zu schaffen. Zukünftige Gebäude sollen höchste Energieeffizienz aufweisen und kostengünstig zu einem Mehr an Lebensqualität beitragen. Manche werden es schaffen, in Summe mehr Energie zu erzeugen als sie verbrauchen („Haus der Zukunft Plus“). Innovationen im Bereich der zukunftsorientierten Bauweise werden eingeleitet und ihre Markteinführung und -verbreitung forciert. Die Ergebnisse werden in Form von Pilot- oder Demonstrationsprojekten umgesetzt, um die Sichtbarkeit von neuen Technologien und Konzepten zu gewährleisten.

Das Programm *Haus der Zukunft Plus* verfolgt nicht nur den Anspruch, besonders innovative und richtungsweisende Projekte zu initiieren und zu finanzieren, sondern auch die Ergebnisse offensiv zu verbreiten. Daher werden sie in der Schriftenreihe publiziert und elektronisch über das Internet unter der Webadresse **www.HAUSderZukunft.at** Interessierten öffentlich zugänglich gemacht.

DI Michael Paula
Leiter der Abt. Energie- und Umwelttechnologien
Bundesministerium für Verkehr, Innovation und Technologie

# Recherche biologischer Vorbilder für Materialien, Strukturen, Systeme und Prozesse

## 1.1. Übertragung der Funktionsmatrix auf biologische Parameter

Die Prinzipienmatrix der Fassadentechnologie aus Phase 1 wurde in eine Serie von "Biologised Questions" übersetzt. Technische Zielsetzungen und komplexe Grundfragen wurden in Hinblick auf eine sinnvolle Suche in der Biologie zusammengefasst oder aufgeteilt und vereinfacht um eine Lösungsfindung nicht zu sehr einzuschränken. Bei der Übertragung war die Klärung von Begriffen in den verschiedenen Disziplinen und Sprachen notwendig (z.B. "generate energy" - wurde von Grundlagenforschern in der Physik und Bauphysikern unterschiedlich interpretiert).

Die breite Herangehensweise aus der Fassadentechnologie war eine Herausforderung an den weiteren Verlauf des Projekts. Die Menge an Fragestellungen und die entsprechende Menge an Lösungsvorschlägen erforderte die Einführung von zusätzlichen Selektionsparametern um einerseits die Bearbeitbarkeit zu gewährleisten, andererseits aber das Ziel - die Erstellung einer Grundlagenstudie, in der die wichtigsten Felder aus der Fassadentechnologie bearbeitet sein sollten - nicht zu gefährden.

Die Zuordnung der biologischen Phänomene zu den Funktionen aus der Fassadentechnologie war aufgrund der Multifunktionalität und des hohen Integrationsgrads nicht eindeutig. Vor allem die Bereiche "Ventilation" und "Cooling" sind nicht getrennt voneinander betrachtbar. Einige Phänomene wurden im Lauf der vertieften Recherche anders zugeordnet als zu Beginn. Trotzdem stellt die funktionelle Differenzierung und Analogiebildung die einzig sinnvolle Möglichkeit dar, Übertragungen vorzunehmen.

Die Differenzierung in "Materials" und "Systems" aus der Biologie, ein Zugang der sich in früheren Projekten bewährt hatte, hat sich für den Bereich der Fassadentechnologie als nicht zielführend erwiesen, weil die aufgefundenen Vorbilder aus der Natur aus relativ ähnlichen Grössenbereichen kommen. Es handelt sich bei den meisten Vorbildern um "Materialsysteme", die ihre Performance durch die Kombination ihrer Materialität an sich und ihrer auf mehreren Grössenskalen vorhandenen Struktur erhalten. Aus diesem Grund wurde auf eine diesbezügliche Differenzierung im Weiteren verzichtet.

Die "Biologised questions" sind in der Funktionsmatrix und den Recherchelisten aufgeführt, samt den Bereichen aus der Fassadentechnologie denen sie zugeordnet sind. Ergebnis dieses Schritts sind insgesamt 74 Fragestellungen aus den Hauptbereichen "Light, Energy, Conditioning (Humidity), Heat, Ventilate, Cool". Die fett hervorgehobenen Fragestellungen sind die für den jeweiligen Bereich wichtigsten und allgemeinsten, die für die Recherche verwendet wurden.

## 1.2. Recherchearbeit mittels Top Down Methode anhand festgelegter Struktur (Kewords,…),

Methode: Meta-Research – Suche nach Ergebnissen der Grundlagenforschung in den Life Sciences

Die verwendete Methode wird "Top down Bionik" oder "problem-based approach" genannt und bedeutet die gezielte Suche nach Lösungen in der Natur ausgehend von einer technischen Fragestellung. Dabei wurden Interviews, Literatur- und Datenbankrecherchen durchgeführt.

Die Recherche wurde anhand der "Biologised Questions" durchgeführt. Die Quellen waren: Internet Datenbank "AskNature" der Biomimicry Gruppe in den Vereinigten Staaten (öffentlich zugängliche Datenbank über "Strategien" der Natur mit derzeit 1285 Einträgen), halbstrukturierte Experteninterviews (siehe Annex 2_3), persönliche Informationen der Konsulenten Speck und Jeronimidis, persönliche Informationen der Arbeitsgruppe Speck in Freiburg, das persönliche Archiv von Gruber basierend auf den Bionik-Studentenarbeiten der Abteilung für Hochbau und Entwerfen von 2001-2007 und die gezielte Suche in Überblickswerken der Bionik. Die InterviewpartnerInnen wurden aus der Community der BionikforscherInnen und auf Empfehlung der Konsulenten ausgewählt, und zum Grossteil bei einem Forschungsaufenthalt der Autorin an der Universität Freiburg im Jänner 2010 befragt.

Die grosse Menge an Fragestellungen wurde für die Experteninterviews zu einer bewältigbaren Anzahl von Themen zusammengefasst, und im Lauf des Interview erst weiter detailliert. Die Interviewpartner haben viele ähnlich Phänomene genannt, die aus der bekannten Bionik-Literatur stammen.

Die erste Zusammenstellung von Vorbildern aus der Natur wurde zusammen mit den Konsulent/innen für die weitere Bearbeitung gefiltert. Für manche Fragestellungen, wie z.B. "transmit light with minimal loss of intensity" sind in der gegenwärtigen biologischen Grundlagenforschung keine Informationen zu finden. Viele Fragestellungen haben sich aufgrund der Zusammenhänge der Phänomene als redundant herausgestellt. Manche Fragestellungen waren zu allgemein um eine spezifische Antwort zu finden. Insgesamt wurden 243 Vorbilder aus der Natur identifiziert und den Fragestellungen aus der Fassadentechnologie in allen fünf Bereichen zugeordnet.

# Zusammenstellung der Rechercheergebnisse

Liste mit Referenzen, unselektiert

| **count** | | **biologised question** | **phenomenon** | **references** | **functional or main principl** | **detailed principle** | **comment** | **select 1** | **select 2** |
|---|---|---|---|---|---|---|---|---|---|
| 1 | **1** | change/filter/control wavelength/colour spectrum | Eyes see in various wavelengths: birds | www.asknature.org [11/2009] | transmit light at maximum | signal transmission and conversion | | | |
| 2 | **1** | change/filter/control wavelength/colour spectrum | Bacteria help sense far-red light: loosejaw | www.asknature.org [11/2009] | transmit light at maximum | selective pigmental light control | | | |
| 3 | **1** | change/filter/control wavelength/colour spectrum | selection of light wavelength by many deep sea creatures: corals, algae | Hibst University of Ulm | transmit light at maximum | selective pigmental light control | | | |
| 4 | **2** | transmit light with minimal loss of intensity/in full intensity | Optical systems in nature | | transmit light at maximum | light transfer by lensen and facets<br>light transfer by fibres and crystals<br>photonic structure | too general | | |
| 5 | **3** | direct/guide light | Leaves focus light: begonias | www.asknature.org [11/2009] | transmit light at maximum | light transfer by lensen and face | high potential | | |
| **6a** | **3** | direct/guide light | **Light transmission inside sponges** | Aizenberg J. et al.: Biological glass fibers: Correlation between optical and structural properties. Proc. Natl. Acad. Sci.U. S. A. 101, 3358–3363, 2004.<br>Brümmer F. et al.: Light inside sponges. Journal of Experimental Marine Biology and Ecology 367, 61–64, 2008.<br>Müller W.E.G. et al.: Novel photoreception system in sponges? Unique transmission properties of the stalk spicules from the hexactinellid Hyalonema sieboldi. Biosens. Bioelectron. 21, 1149-1155, 2005. | transmit light at maximum | light transfer by fibres and crystals | | x | x |
| **6** | **3** | direct/guide light | **Fibers guide light: venus flower basket** | asknature.org [12/2009]<br>Sundar V.C., Yablon A.D., Grazul J.L., Ilan M., Aizenberg J.: Fibre-optical features of a glass sponge. Nature 424(6951) 899-900, 2003.<br>Aizenberg J., Sundar V., Yablon A., Weaver J., Chen G.: Biological glass fibers: Correlation between optical and structural properties, Proceedings of the NAtional Academy of Sciences of the United States of America, Natl Acad Sciences, 2004, 101, 3358-3363, 2004. | transmit light at maximum | light transfer by fibres and cryst | high potential | x | x |
| **7** | **3** | direct/guide light | **Brittlestar calcite microlenses guide light** | Aizenberg J. et al.: Calcitic microlenses as part of the photoreceptor system in brittlestars, Nature 412, 819-822, 23 August 2001.<br>Vukusic P., Samble J. R.: Photonic structures in biology, Nature 424, 852-855, 14 August 2003. | transmit light at maximum | photonic structure | high potential | x | x |
| 8 | **3** | direct/guide light | Lenses in eyes | | transmit light at maximum | light transfer by lensen and face | too general | | |
| **9** | **3** | direct/guide light | **Facets in insects** | Goldsmith T.H., Philpott D.E.: The Microstructure of the Compound Eyes of Insects, J. Biophysic. and Biochem. Cytol., Vo1. 3, No. 3, 1957.<br>Nilsson D.-E., Kelber A.: A functional analysis of compound eye evolution, Arthropod Structure & Development 36 373-385, 2007.<br>Land M.F.: The optical structures of animal eyes, Current Biology Vol 15 No 9, R322, 2005.<br>Davis J.D. et al: A bio-inspired apposition compound eye machine vision sensor system, Bioinsp. Biomim. 4, 2009. | transmit light at maximum | light transfer by lensen and face | general but high potenti | x | x |
| 10 | **3** | direct/guide light | Crustacean optical systems | | transmit light at maximum | light transfer by lensen and face | too general | | |
| 11 | **3** | direct/guide light | Butterfly scales - structural colours | Ingram A.L. Parker A.R: A review of the diversity and evolution of photonic structures in butterflies, Phil. Trans. R. Soc. B 2008 363, 2465-2480 | transmit light at maximum | photonic structure | high potential | | |
| 12 | **3** | direct/guide light | Feathers - reflectivity and structure | Kinoshita S. et al: Physics of structural colors, 2008 Rep. Prog. Phys. 71 076401 | transmit light at maximum | photonic structure | high potential | | |
| 13 | **3** | bundle light | Complex structures focus reflected light: lobster | www.asknature.org [12/2009]<br>Yahya H.: Design in Nature. London: Ta-Ha Publishers Ltd. 180 p. 2002.<br>Land M.F.: Eyes with mirror optics J. Opt. A: Pure Appl. Opt. 2 R44 2000.<br>Cronin T.W., Jinks R.N.: Ontogeny of Vision in Marine Crustaceans, AMER. ZOOL., 41:1098–1107, 2001.<br>Vogt K.: Die Spiegeloptik des FluBkrebsaugesJ. Comp. Physiol. 135, 1-19, 1980. | transmit light at maximum | light transfer by lensen and face | high potential | x | |
| 14 | **3** | **use light effectively** | Eyes increase photosensitivity and direct light: javelin spookfish | www.asknature.org [11/2009]<br>Wagner, H.J.et al.: A Novel Vertebrate Eye Using Both Refractive and Reflective Optics, Current Biology 19, 108–114, January 27, 2009 | transmit light at maximum | light transfer by lensen and face | insufficient reference | | |
| 15 | **3** | **use light effectively** | Photosynthesis in low-light conditions: taeniophyllum orchid | www.asknature.org [11/2009] | transmit light at maximum | ? | not applicable | | |
| 16 | **3** | **use light effectively** | Pigment cells absorb incidental light: insects | www.asknature.org [11/2009] | transmit light at maximum | selective pigmental light control | high potential | | |
| 17 | **3** | **use light effectively** | Eye structure enhances night vision: vertebrates | www.asknature.org [11/2009] | transmit light at maximum | photonic structure | high potential | | |
| 18 | **3** | **use light effectively** | Focusing mechanism enhances vision: Tokay gecko | www.asknature.org [11/2009] | transmit light at maximum | ? | insufficient reference | | |
| 19 | **3** | **use light effectively** | Hunting in the dark: piranha | www.asknature.org [11/2009] | transmit light at maximum | signal transmission and conversion | | | |
| 20 | **3** | **use light effectively** | Pigment enhances light absorption: tropical plants | www.asknature.org [11/2009] | transmit light at maximum | selective pigmental light control | high potential | | |
| 21 | **3** | **use light effectively** | Structures maximize light absorption: plants | www.asknature.org [11/2009] | transmit light at maximum | ? | too general | | |
| 22 | **3** | **use light effectively** | Optimizing exposure to sunlight: stony corals | www.asknature.org [11/2009] | transmit light at maximum | ? | not applicable | | |
| 23 | **3** | **use light effectively** | Eyes see in the dark: oilbird | www.asknature.org [11/2009] | transmit light at maximum | signal transmission and conversion | | | |
| **24a** | **3** | **use light effectively** | **Lotus surfaces - matt but translucent surface** | Barthlott W., Neinhuis C.: Purity of the sacred lotus, or escape from contamination in biological surfaces, Planta 1997;202,1–8, 1997.<br>Schulte A.J. et al.: Biomimetic replicas: Transfer of complex architectures with different optical properties from plant surfaces onto technical materials, Acta Biomaterialia 5 1848–1854, 2009.<br>Fuerstner R, Barthlott W, Neinhuis C, et al.: Wetting and self-cleaning properties of artificial superhydrophobic surfaces, Langmuir, Volume: 21, Issue: 3, 956-961, FEB 1 2005.<br>Koch K. et al.: Multifunctional surface structures of plants: An inspiration for biomimetics, Progress in Materials Science 54, 137–178, 2009. | transmit light at maximum | photonic structure<br>reflective structure | high potential | x | x |

| count | | biologised question | phenomenon | references | functional or main principl | detailed principle | comment | select 1 | select 2 |
|---|---|---|---|---|---|---|---|---|---|
| **24** | **3** | **use light effectively** | **Eyes are anti-reflective: elephant hawk-moth** | asknature.org [12/2009]<br>Huang Y.F. et al.: Improved broadband and quasi-omnidirectional anti-reflection properties with biomimetic silicon nanostructures, Nature Nanotechnology, Vol.2, Issue 12, pp770-774, 2007.<br>Mirotznik MS, Good B, Ransom P, et al.: Iterative Design of Moth-eye antireflective surface at millimeter wave frequencies, Microwave and Optical Technology Letters, Volume: 52, Issue: 3, Pages: 561-568, 2010.<br>Vukusic, P. & Sambles, J. R. Photonic structures in biology Nature, 424, 852-855, 2003<br>Vukusic, P.: Natural photonics, Physics World, February 2004 35-39, 2004.<br>Linn N.C. et al.: Self-assembled biomimetic antireflection coatings, APPLIED PHYSICS LETTERS 91, 101108 2007.<br>Stavenga D.G. et al.: Light on the moth-eye corneal nipple array of butterflies, Proc. R. Soc. B 273, 661–667 2006. | transmit light at maximum | photonic structure<br>reflective structure | high potential | x | x |
| 25 | **3** | **use light effectively** | Wing scales aid thermoregulation: green birdwing butterfly | www.asknature.org [11/2009] | transmit light at maximum | photonic structure | high potential | | |
| 26 | **3** | **use light effectively** | Araceae: light is transmitted through leaves, then reflected by pigments at the bottom back to photosynthesizing cells | | transmit light at maximum | reflective structure | insufficient reference | | |
| 27 | **3** | **use light effectively** | Intensify photosynthetic activity by increasing density of chlorophyll on surface - dark green leaves of understorey rainforest plants | | transmit light at maximum | ? | | | |
| 28 | **4** | generate light | Moving cilia create iridescence: comb jellies | www.asknature.org [11/2009] | transmit light at maximum | bioluminescence | biochemistry excluded | | |
| 29 | **4** | generate light | Light generated chemically: firefly | www.asknature.org [11/2009] | transmit light at maximum | bioluminescence | biochemistry excluded | | |
| 30 | **4** | generate light | Luciferin molecules create bioluminescence: Pyrophorus beetle | www.asknature.org [11/2009] | transmit light at maximum | bioluminescence | biochemistry excluded | | |
| 31 | **4** | generate light | Enzyme produces red bioluminescence: railroad worm | www.asknature.org [11/2009] | transmit light at maximum | bioluminescence | biochemistry excluded | | |
| 32 | **4** | generate light | Lure attracts prey: anglerfish | www.asknature.org [11/2009] | transmit light at maximum | bioluminescence | biochemistry excluded | | |
| 33 | **4** | generate light | Light used for instant signaling: comb jellies" | www.asknature.org [11/2009] | transmit light at maximum | bioluminescence | biochemistry excluded | | |
| 34 | **4** | generate light | Bioluminescence in plants | | transmit light at maximum | bioluminescence | biochemistry excluded | | |
| 35 | **4** | generate light | Light trap for insects – Arisaema, Aristolochia | | transmit light at maximum | bioluminescence | biochemistry excluded | | |
| 36 | **4** | generate light | Bioluminescence of marine organisms | AWI Christian Hamm, Bremen Antonia Kesel, Helmholtz Institute | transmit light at maximum | bioluminescence | biochemistry excluded | | |
| **37a** | **5** | disperse/scatter light | **Davidia involucrata, or Cornus florida colour: change by layered system** | Sun J.F., Gong Y.B., Renner S.S. et al.: Multifunctional bracts in the dove tree Davidia involucrata (Nyssaceae : Cornales): Rain protection and pollinator attraction, AMERICAN NATURALIST, Volume: 171, Issue: 1, 119-124, JAN 2008.<br>Weiss M.R.: Floral colour changes as cues for pollinators, Nature vol 354, 227-229, 21 November | transmit light selectively | photonic structure | high potential | x | x |
| **37** | **5** | disperse/scatter light | **Scales create brilliant white: Cyphochilus beetles (reflection)** | asknature.org [12/2009]<br>Vukusic P., Hallam B., Noyes J.: Brilliant Whiteness in Ultrathin Beetle Scales. Science. 315(5810): 348, 2007.<br>Seago A.E. et al.: Gold bugs and beyond: a review of iridescence and structural colour mechanisms in | transmit light selectively | photonic structure | high potential | x | x |
| 38 | **6** | disperse/scatter light | Wing scales diffract and scatter light: Morpho butterflies | www.asknature.org [11/2009] | transmit light selectively | photonic structure | high potential | | |
| 39 | **6** | change/control transmission factor/transmittance/transparency | Pigment filters excessive light: balloonfish | www.asknature.org [11/2009]<br>Yahya H.: Design in Nature. London: Ta-Ha Publishers Ltd. 180 p. 2002. | transmit light selectively | selective pigmental light control | high potential | x | |
| 40 | **6** | change/control transmission factor/transmittance/transparency | Pigments in plants filter specific light spectra | | transmit light selectively | selective pigmental light control | too general | | |
| 41 | **6** | change/control reflectance/reflectivity | Body surfaces reflect light to create colors: jewel beetles | www.asknature.org [11/2009] | transmit light selectively | photonic structure | high potential | | |
| 42 | **6** | change/control reflectance/reflectivity | Microscopic plates produce interference colors: copepods | www.asknature.org [11/2009] | transmit light selectively | ? | insufficient reference | | |
| **43** | **6** | change/control reflectance/reflectivity | **Humidity changes exoskeleton color: Hercules beetle** | asknature.org [12/2009]<br>Hinton H.E., Jarman G.M.: Physiological colour change in elytra of hercules beetle, dynastes-hercules, Journal of Insct Physiology, Volume: 19, Issue: 3, Pages: 533-&, 1973.<br>Rassart M. et al.: Diffractive hygrochromic effect in the cuticle of the hercules beetle Dynastes hercules, New Journal of Physics, Volume: 10, Article Number: 033014, 2008.<br>Rassart M., Simonis P., Bay A., et al.: Scale coloration change following water absorption in the beetle Hoplia coerulea (Coleoptera) Physical Review E 80 3 Part 1, SEP 2009. | transmit light selectively | photonic structure | high potential | x | x |
| 44 | **6** | change/control reflectance/reflectivity | Rapid color change used for protection: cuttlefish | www.asknature.org [11/2009] | transmit light selectively | selective pigmental light control | high potential | | |
| 45 | **6** | change/control reflectance/reflectivity | Red pigment protects against UV rays: snow algae | www.asknature.org [11/2009] | transmit light selectively | selective pigmental light control | | | |
| **46** | **6** | change/control reflectance/reflectivity | **Optical structure and function of the white filamentary hair covering the edelweiss bracts** | asknature.org [12/2009]<br>Attenborough D.: The Private Life of Plants: A Natural History of Plant Behavior. London: BBC Books. 320 p. 1995.<br>Vigneron J.P. et al.: Optical structure and function of the white filamentary hair covering the edelweiss bracts, Physical Review E, Volume: 71, Issue: 1 Article Number: 011906, Part 1, 2005. | transmit light selectively | photonic structure | high potential | x | x |
| 47 | **6** | change/control reflectance/reflectivity | Birds eggs reflect most of the near infrared, use pigments other than melanin | 449–460.<br>Bakken et al 1978 | transmit light selectively | selective pigmental light control | | | |

| count | | biologised question | phenomenon | references | functional or main principl | detailed principle | comment | select 1 | select 2 |
|---|---|---|---|---|---|---|---|---|---|
| **48a** | **6** | change/control reflectance/reflectivity | **Glassnails** | Hausdorf B.: Phylogeny and biogeography of the Vitrinidae (Gastropoda : Stylommatophora), ZOOLOGICAL JOURNAL OF THE LINNEAN SOCIETY, Volume: 134, Issue: 3, 347-358, MAR 2002<br>www.weichtiere.at [05/2010] | transmit light selectively | ? | high potential | x | x |
| **48** | **6** | change/control reflectance/reflectivity | **Desert snails reflect most of the suns direct infrared** | Vogel S.: Living in a physical world IV: Moving heat around. Journal of Biosciences, 30, 449–460, 2005.<br>Yom-Tov Y.: Body temperature and light reflectance in two desert snails; Proc. Malacol. Soc. London 39 319–326, 1971. | transmit light selectively | photonic structure<br>reflective structure | high potential | x | x |
| 49 | **6** | change/control reflectance/reflectivity | Iridae, iridescent red algae: cuticle structure relfects infrared | Vogel S.: Living in a physical world IV: Moving heat around. Journal of Biosciences, 30, 449–460, 2005.<br>Gerwick, W.H. and Lang N.J.: Structural, chemical and ecological studies on iridescence in Iridaea | transmit light selectively | photonic structure | high potential | x | |
| 50 | **6** | change/control reflectance/reflectivity | Iridescent effects of plants, not a surface characteristic - UV protection | | transmit light selectively | photonic structure | | | |
| 51 | **6** | change/control reflectance/reflectivity | Elaphoglossum - Iridescence | | transmit light selectively | photonic structure | | | |
| 52 | **6** | change/control reflectance/reflectivity | Rapateaceae: Stegolepis hitchcockii - iridescence | | transmit light selectively | photonic structure | insufficient reference | | |
| 53 | **6** | change/control reflectance/reflectivity | Silver moss: UV protection by hair | | transmit light selectively | photonic structure | | | |
| 54 | **6** | change/control reflectance/reflectivity | UV protection of alpine plants | | transmit light selectively | photonic structure | high potential | | |
| 55 | **6** | change/control reflectance/reflectivity | Pollination mechanisms – UV patterning of leaves, combination of pattern and structure | | transmit light selectively | reflective structure<br>selective pigmental light control | high potential | | |
| 56 | **6** | change/control reflectance/reflectivity | Chameleons: temperature induced colour change | Walton M., Bennett A.F.: Temperature-dependent Color Change in Kenyan Chameleons, Physiological Zoology 66(2):270-287,1993.<br>Clusella-Trullas S. et al.: Testing the thermal melanism hypothesis: a macrophysiological approach, Functional Ecology, Volume 22, Issue 2 , Pages232 - 238, 2007.<br>Clusella-Trullas S. et al.: Thermal melanism in ectotherms, Journal of Thermal Biology 32, 235–245, | transmit light selectively | selective pigmental light control | high potential | x | |
| **57** | **6** | change/control reflectance/reflectivity | **Hairy leaves of desert plants - reflect and generate convection** | Koch K. et al.: Multifunctional surface structures of plants: An inspiration for biomimetics, Progress in Materials Science 54 137–178, 2009.<br>Jones H.G., Rotenberg E.: Energy, radiation and temperature regulation in plants. Encyclop. of Life Sci. John Wiley & Sons; 2001. p. 1–8. 2001.<br>Ehleringer J.R., Bjorman O.: Pubescence and leaf spectral characteristics in desert shrub, Encelia-farinosa, Oecologia, Volume: 36, Issue: 2, Pages: 151-162, 1978.<br>Haworth M., McElwain J.: Hot, dry, wet, cold or toxic? Revisiting the ecological significance of leaf and cuticular micromorphology, Palaeogeography, Palaeoclimatology, Palaeoecology 262 79–90, 2008. | transmit light selectively | reflective structure<br>convection system | high potential | x | x |
| 58 | **7** | generate sunshade | Screen protects symbiotic algae from light: giant clam | www.asknature.org [11/2009] | transmit light selectively | selective pigmental light control | | | |
| 59 | **7** | generate sunshade | Sweat protects skin: hippopotamus | www.asknature.org [11/2009]<br>Saikawa, Y.; Hashimoto, K.; Nakata, M.; Yoshihara, M.; Nagai, K.; Ida, M.; Komiya, T.: The red sweat of the hippopotamus. Nature. 429(6990): 363.<br>Galasso, V; Pichierri, F.: Probing the molecular and electronic structure of norhipposudoric and hipposudoric acids from the red sweat of hippopotamus amphibius: A DFT Investigation. Journal of Physical Chemistry A. 113(11): 2534-2543. 2009. | transmit light selectively | selective pigmental light control | high potential | | |
| 60 | **7** | generate sunshade | Iridescent thin layer provides photoprotection: understory rainforest plants | www.asknature.org [11/2009]<br>Lee, D; Kelley, J; Richards, JH.: Blue Leaf Iridescence as a By-product of Photoprotection in Tropical Rainforest Understory Plants. Botanical Society of America. 2008. | transmit light selectively | photonic structure | high potential | | |
| 61 | **7** | generate sunshade | Branches protected from the sun: quiver tree" | www.asknature.org [11/2009] | transmit light selectively | photonic structure | insufficient reference | | |
| 62 | **7** | generate sunshade | Cactus shape delivers sunshade | | transmit light selectively | static shading structure | high potential | | |
| 63 | **7** | generate sunshade | Negative phototropism in plants | | transmit light selectively | non-reversible actuation system | | | |
| 64 | **7** | avoid light | Cactus hides from the sun: mescal cactus | www.asknature.org [11/2009] | transmit light selectively | reversible actuation system | | | |
| 65 | **7** | avoid light | Mound passively heats/cools: compass termite | www.asknature.org [11/2009] | transmit light selectively | static shading structure | high potential | | |
| 66 | **7** | avoid light | Adaptation by turgor movements (wilting) | | transmit light selectively | reversible actuation system | insufficient reference | | |
| 67 | **7** | avoid light | Behavioural adaptations of organisms | | transmit light selectively | behavioural adaptation | too general | | |
| 68 | **8** | react/adapt to changing light conditions | Leaves change colors under different lighting: Selaginella ferns | www.asknature.org [11/2009] | transmit light selectively | photonic structure | high potential | | |
| 69 | **8** | react/adapt to changing light conditions | Leaves transmit long-distance signals: Arabidopsis | www.asknature.org [11/2009] | transmit light selectively | signal transmission and conversi | biochemistry excluded | | |
| 70 | **8** | react/adapt to changing light conditions | Pigments cells respond to hormones: African clawed frog | www.asknature.org [11/2009]<br>Karlsson A.M. et al: Biosensing of opioids using frog melanophores, Biosensors and Bioelectronics Volume 17, Issue 4, April 2002, Pages 331-335 | transmit light selectively | signal transmission and conversion<br>selective pigmental light control | high potential | | |
| 71 | **8** | react/adapt to changing light conditions | Heliotaxis (growth movement towards sun direction), i.e. sunflower | | transmit light selectively | non-reversible actuation system | too general | | |
| **72** | **8** | react/adapt to changing light conditions | **Leaf orientation controls sun exposure: plants (Opening and closing of leaves - Heliconia)** | Attenborough D.: The Private Life of Plants: A Natural History of Plant Behavior. London: BBC Books. 320 p. 1995.<br>Koller D.: Light-driven leaf movements, Plant, Cell and Environment 13, 615-632 Plants and the Environment 1990.<br>Herbert T. J.: Geometry of Heliotropic and Nyctinastic Leaf Movements American Journal of Botany, Vol. 79, No.5 , pp. 547-550 May, 1992.<br>Schleicher S. et al.: Abstraction of bio-inspired curved-line folding patterns for elastic foils and membranes in architecture, Design and Nature 2010. in press<br>Lienhard J.: Elastic architecture: nature inspired pliable structures, Design and Nature 2010. in press<br>Poppinga S.: Plant movements as concept generators for deployable systems in architecture, Design and Nature 2010. in press | transmit light selectively | reversible actuation system | high potential | x | x |

| count | | biologised question | phenomenon | references | functional or main principl | detailed principle | comment | select 1 | select 2 |
|---|---|---|---|---|---|---|---|---|---|
| 73 | **8** | react/adapt to changing light conditions | Opening and closing of flowers according to light | | transmit light selectively | reversible actuation system | high potential | | |
| 74 | **8** | react/adapt to changing light conditions | Climbing plants move to places with better light conditions, diverse adapatations to increase yield, i.e. Goose Grass Gallium aparinae | | transmit light selectively | non-reversible actuation system | | | |
| 75 | **8** | react/adapt to changing light conditions | Change of morphology in climbing plants - also triggered by light conditions | | transmit light selectively | ? | | | |
| 76 | **8** | react/adapt to changing light conditions | Adaptation in metabolism - shadow and sunny plants | | transmit light selectively | metabolic adaptation | biochemistry excluded | | |
| 77 | **8** | react/adapt to changing light conditions | Adaptation in metabolism - different photosynthesis compensation point in shadow and sunny leaves of the same tree | | transmit light selectively | metabolic adaptation | biochemistry excluded | | |
| 78 | **8** | react/adapt to changing light conditions | Plants sense sun/shadow by detecting wavelength chemically - phytochrom changes with wavelength | | transmit light selectively | signal transmission and conversi | biochemistry excluded | | |
| 79 | **8** | react/adapt to changing light conditions | Algae contain different accessory pigments capturing light for photosynthesis in different depths of water, where different wavelenths of light are available | | transmit light selectively | selective pigmental light control | too general | | |
| 80 | **8** | maintain constant light conditions | Flowers follow sun: snow buttercups | www.asknature.org [12/2009]<br>Sherry, RA; Galen, C.: The mechanism of floral heliotropism in the snow buttercup, Ranunculus adoneus. Plant, cell and environment. 21(10): 983-993,1998.<br>Eleringer J., Forseth, I.: Solar tracking by plants, Science, Vol.210, Dec.1980. | transmit light selectively | reversible actuation system (?) | high potential | x | |
| 81 | **8** | maintain constant light conditions | Solar tracking of plants | | transmit light selectively | reversible actuation system | too general | | |
| 82 | **8** | maintain constant light conditions | Phototropism of plants | | transmit light selectively | non-reversible actuation system | too general | | |
| 83 | **9a** | avoid overheating from thermal radiation | Gular fluttering dissipates heat: nightjars | www.asknature.org [11/2009] | avoid overheating from thermal radiation<br>protect from heat | heat dissipation area | high potential | | |
| 84 | **9a** | avoid overheating from thermal radiation | Organism tolerates heat and desiccation: lichen | www.asknature.org [11/2009] | avoid overheating from thermal radiation<br>protect from heat | metabolic adaptation | biochemistry excluded | | |
| 85 | **9a** | avoid overheating from thermal radiation | Managing high temperatures: tenrecs | www.asknature.org [11/2009] | avoid overheating from thermal radiation<br>protect from heat | metabolic adaptation | biochemistry excluded | | |
| 86 | **9a** | avoid overheating from thermal radiation | Postural control of solar irradiation in insects and lizards | Vogel S. Living in a physical world IV: Moving heat around. Journal of Biosciences, 2005, 30, 449–460.<br>Heinrich 1996 | avoid overheating from thermal radiation<br>protect from heat | behavioural adaptation | | | |
| 87 | **9a** | avoid overheating from thermal radiation | Ground squirrel (Xerus inauris) uses tail as parasol | Vogel S. Living in a physical world IV: Moving heat around. Journal of Biosciences, 2005, 30, 449–460.<br>Bennet et al 1984 | avoid overheating from thermal radiation<br>protect from heat | behavioural adaptation | | | |
| 88 | **9a** | avoid overheating from thermal radiation | Transpiration – protects from overheating | | avoid overheating from thermal radiation<br>protect from heat | evaporation system | too general | | |
| 89 | **9a** | avoid overheating from thermal radiation | Cushion shaped plant populations – create microclimate, moss, adaptation in formation | Cavieres L.A. et al.: Microclimatic modifications of cushion plants and their consequences for seedling survival of native and non-native herbaceous species in the high andes of central Chile, ARCTIC ANTARCTIC AND ALPINE RESEARCH, Volume: 39, Issue: 2, Pages: 229-236, 2007<br>Badano EI et al.: Assessing impacts of ecosystem engineers on community organization: a general approach illustrated by effects of a high-Andean cushion plant, OIKOS, Volume: 115, Issue: 2, | avoid overheating from thermal radiation<br>protect from heat | group organisation | | x | |
| 90 | **9a** | avoid overheating from thermal radiation | Desert animals - snail | | avoid overheating from thermal radiation<br>protect from heat | ? | high potential | | |
| 91 | **9a** | avoid overheating from thermal radiation | Change of surface/volume ratio | | avoid overheating from thermal radiation<br>protect from heat | geometric adaptation | too general | | |
| 92 | **9a** | avoid overheating from thermal radiation | Metabolic adaptation | | avoid overheating from thermal radiation<br>protect from heat | metabolic adaptation | too general | | |
| 93 | **9a** | avoid overheating from thermal radiation | Heat stress leads to wilting of mimosa | | avoid overheating from thermal radiation<br>protect from heat | ? | insufficient reference | | |
| **94** | **3** | direct/guide light | **Crystals draw sunlight into plant: window plants** | asknature.org [12/2009]<br>Vogel S. Living in a physical world V. Maintaining temperature. Journal of Biosciences, 30, 2005, 581–590.<br>Turner J.S. et al: Thermal ecology of an embedded dwarf succulent from southern Africa (Lithops spp: Mesembryanthemaceae), Journal of Arid Environment 24: 361-385, 1993<br>Egbert K.J et al..: The influence of epidermal windows on the light environment within the leaves of | transmit light at maximum | geometric adaptation<br>thermal coupling to environment<br>? | high potential | x | x |
| 95 | **10** | transmit light and absorb thermal radiation | Lithops – window cells | | avoid overheating from thermal radiation<br>protect from heat | geometric adaptation<br>thermal coupling to environment | high potential | | |

| **count** | | **biologised question** | **phenomenon** | **references** | **functional or main principl** | **detailed principle** | **comment** | **select 1** | **select 2** |
|---|---|---|---|---|---|---|---|---|---|
| 96 | **10** | transmit light and absorb thermal radiation | Mesembryanthemum cristallinum - liquid filled bladders | | avoid overheating from thermal radiation<br>protect from heat | geometric adaptation<br>thermal coupling to environment | high potential | | |
| 97 | **11** | generate low thermal conductivity by material | Waxy coating protects from heat and drought: euphorbia | www.asknature.org [11/2009] | insulate | reflective coating (?) | high potential | | |
| 98 | **11** | generate low thermal conductivity by material | Succulent surface waxes – new hypothesis suggests protection from heat by melting of waxes | | insulate | reflective coating (?) | high potential | | |
| 99 | **11** | generate low thermal conductivity by material | Internal insulation with subcutaneous fat layers | | insulate | fat layer insulation system | | | |
| 100 | **11** | generate low thermal conductivity by material | Penguins | | insulate | fat layer insulation system | | | |
| 101 | **11** | generate low thermal conductivity by material | Seals | | insulate | fat layer insulation system | | | |
| 102 | **12** | **insulate (material and structure characteristics)** | Tolerance to heat, cold and high-light stress: Borya nitida, a poikilohydrous angiosperm, in the hydrated state | www.asknature.org [11/2009] | insulate | ? | insufficient reference | | |
| 103 | **12** | **insulate (material and structure characteristics)** | Relationship provides thermal protection: hot springs panic grass, fungus | www.asknature.org [11/2009]<br>Redman R. S. et al: Thermotolerance Generated by Plant/Fungal Symbiosis, Science 22 November 2002 298: 1581 | insulate | symbiotic system | high potential | | |
| 104 | **12** | **insulate (material and structure characteristics)** | Strategy: Dense covering protects from cold: snow lotus | www.asknature.org [11/2009] | insulate | air keeping (porous) structure | high potential | | |
| 105 | **12** | **insulate (material and structure characteristics)** | Group organization protects from the cold: emperor penguins | www.asknature.org [11/2009] | insulate | group organisation | | | |
| 106 | **12** | **insulate (material and structure characteristics)** | External insultation with fur - similar conduction as air | Vogel S. Living in a physical world IV: Moving heat around. Journal of Biosciences, 2005, 30, 449–460. | insulate | air keeping (porous) structure | high potential | | |
| 107 | **12** | **insulate (material and structure characteristics)** | External insulation with feathers | | insulate | air keeping (porous) structure | high potential | | |
| 108 | **12** | **insulate (material and structure characteristics)** | Chinese silk tree (Albizzia julibrissin) direct leaves down for not freezing -- avoid radiative cooling | Vogel S. Living in a physical world IV: Moving heat around. Journal of Biosciences, 2005, 30, 449–460.<br>Campbell and Garber 1980 | insulate | reversible actuation<br>thermal coupling to environment | high potential | | |
| 109 | **12** | **insulate (material and structure characteristics)** | Rhododendron: leaf curling in winter - avoid freezing by creating microclimate | | insulate | reversible actuation | | | |
| 110 | **12** | **insulate (material and structure characteristics)** | Common mullein - hairs create insulation microclimate | | insulate | air keeping (porous) structure | high potential | | |
| 111 | **12** | **insulate (material and structure characteristics)** | Sequoiadendron - bark is insulating, also against forest fires | Tributsch H, Fiechter S.: The material strategy of fire-resistant tree barks, HIGH PERFORMANCE STRUCTURES AND MATERIALS IV Book Series: WIT TRANSACTIONS ON THE BUILT ENVIRONMENT, Volume: 97, Pages: 43-52, 2008.<br>Gignoux J., Clobert J., Menaut J.C.: Alternative fire resistance strategies in savanna trees. Oecologia. 110(4): 576-583, 1997.<br>Bauer G. et al.: Insulation capability of the bark of trees with different fire adaptation, internal paper Plant Biomechanics Group Freiburg, 2010. | insulate | air keeping (porous) structure | high potential | x | |
| 112 | **12** | generate low thermal conductivity by structure | Fur provides insulation: polar bear | www.asknature.org [11/2009] | insulate | air keeping (porous) structure | high potential | | |
| 113 | **12** | generate low thermal conductivity by structure | Compacted leaves form efficient heat insulation: grass tree | www.asknature.org [11/2009] | insulate | air keeping (porous) structure | high potential | | |
| 114 | **12** | generate low thermal conductivity by structure | Down feathers insulate: king eider | www.asknature.org [11/2009] | insulate | air keeping (porous) structure | high potential | | |
| 115 | **12** | generate low thermal conductivity by structure | Underhairs provide insulation: merino sheep" | www.asknature.org [12/2009]<br>Foy, Sally; Oxford Scientific Films. 1982. The Grand Design: Form and Colour in Animals. Lingfield, Surrey, U.K.: BLA Publishing Limited for J.M.Dent & Sons Ltd, Aldine House, London. 238 p.<br>Maia ASC et al.: Effect of temperature and air velocity on the thermal insulation of the fleece of sheep in climatic chamber, REVISTA BRASILEIRA DE ZOOTECNIA-BRAZILIAN JOURNAL OF ANIMAL SCIENCE, Volume: 38 Issue: 1, Pages: 104-108, 2009<br>Ye Z, Wells CM, Carrington CG, et al: Thermal conductivity of wool and wool-hemp insulation, INTERNATIONAL JOURNAL OF ENERGY RESEARCH, Volume: 30, Issue: 1, Pages: 37-49, 2006 | insulate | air keeping (porous) structure | high potential | x | |
| 116 | **12** | generate low thermal conductivity by structure | Cellular structures | | insulate | air keeping (porous) structure | too general | | |
| 117 | **13a** | **avoid heat loss** | Change in behaviour | Campbell, Biology, Spektrum Verlag | avoid heat loss | behavioural adaptation | too general | | |
| 118 | **13a** | **avoid heat loss** | Poikilothermia as a strategy | Campbell, Biology, Spektrum Verlag | avoid heat loss | metabolic adaptation | too general | | |
| 119 | **13a** | **avoid heat loss** | Dolphins pass heat from artery to vein before it can escape through flippers | Schmidt-Nielson 1997 | avoid heat loss | countercurrent heat system | high potential | | |
| **120** | **13a** | **avoid heat loss** | **Aquatic birds pass heat from artery to vein before it can escape through feet** | Vogel S. Living in a physical world V: Maintaining temperature, 30, 581–590, 2005.<br>Schmidt-Nielsen K.: Animal physiology Adaptation and Environment, Cambridge University Press, 1975.<br>Mitchell J.W., Myers G.E.: An analytical model of the countercurrent heat exchange phenomena, | avoid heat loss | countercurrent heat system | high potential | x | x |
| 121 | **13** | exchange air without heat loss | Desert rodents - countercurrent exchange in nasal passages | Vogel S. Living in a physical world V: Maintaining temperature, 2005, 30, 581–590.<br>Schmidt-Nielsen 1972 | avoid heat loss | countercurrent heat system | high potential | | |
| 122 | **13** | avoid air exchange | Gas transport in vascular plants | | avoid heat loss | breathable structures | high potential | | |

| count | | biologised question | phenomenon | references | functional or main principl | detailed principle | comment | select 1 | select 2 |
|---|---|---|---|---|---|---|---|---|---|
| 123 | **13** | avoid air exchange | Diver in nature - mechnisms to close respiration passage | | avoid heat loss | control air flow | added potential | | |
| 124 | **15a** | **use thermal inertia<br>generate heat storage** | Clay in buildings of termites | | use thermal inertia<br>generate heat storage | gas transport system by geometry<br>air keeping (porous) structure | high potential | | |
| 125 | **15a** | **use thermal inertia<br>generate heat storage** | Advantage of large animals, thermal inertia | | use thermal inertia<br>generate heat storage | geometric adaptation | too general | | |
| 126 | **15** | store thermal energy locally | Dolphins - phase change material in blubbers | 449–460.<br>Dunkin et al 2005 | use thermal inertia<br>generate heat storage | phase transition | high potential | | |
| 127 | **15** | store thermal energy locally | Bombardeer beetle - storage of chemical energy | | use thermal inertia<br>generate heat storage | evaporation system (?) | | | |
| 128 | **15** | store heat (material aspect) | Internal storage with subcutaneous fat layers | | use thermal inertia<br>generate heat storage | fat layer insulation system | high potential | | |
| 129 | **15** | store heat (material aspect) | External with stored food | | use thermal inertia<br>generate heat storage | behavioural adaptation | | | |
| 130 | **17** | **control heat storage and dissipation (time)** | Blood vessels regulate temperature: vertebrates | www.asknature.org [11/2009] | use thermal inertia<br>generate heat storage | heat dissipation area | high potential | | |
| 131 | **17** | **control heat storage and dissipation (time)** | Thermodynamics of poikilothermic organisms - skin and tissue | | use thermal inertia<br>generate heat storage | metabolic adaptation | too general | | |
| 132 | **17** | **control heat storage and dissipation (time)** | Vasodilatiation and vasoconstriction of capillaries in human skin | | use thermal inertia<br>generate heat storage | heat dissipation area | high potential | | |
| 133 | **17** | **control heat storage and dissipation (time)** | Bumble bees have counter-current heat flow mechanisms that prevent heat loss | Vogel S. Living in a physical world V: Maintaining temperature, 2005, 30, 581–590.<br>Heinrich B 1996 The thermal warriors: Strategies of insect survival (Cambridge, MA: Harvard University Press) | use thermal inertia<br>generate heat storage | countercurrent heat system | high potential | | |
| 134 | **17** | **control heat storage and dissipation (time)** | Iguanas heat faster in the sun than they cool | 449–460.<br>Turner 1987 | use thermal inertia<br>generate heat storage | metabolic adaptation | | | |
| 135 | **17** | generate constant thermal conditions | Leaves optimize internal state: mangrove | www.asknature.org [11/2009] | use thermal inertia<br>generate heat storage | geometric adaptation<br>reversible actuation | high potential | | |
| 136 | **17** | generate constant thermal conditions | Foam provides thermal and moisture control: spittlebug | www.asknature.org [11/2009] | use thermal inertia<br>generate heat storage | air keeping (porous) structure | high potential | | |
| 137 | **17** | generate constant thermal conditions | Internal thermostat regulates temperature: skunk cabbage | www.asknature.org [11/2009]<br>Ito K. et al.: Temperature-triggered periodical thermogenic oscillations in skunk cabbage (Symplocarpus foetidus) PLANT AND CELL PHYSIOLOGY, Volume: 45, Issue: 3, Pages: 257-264, MAR | use thermal inertia<br>generate heat storage | thermogenic system | biochemistry excluded | | |
| 138 | **17** | generate constant thermal conditions | Nest kept warm: mallee fowl | www.asknature.org [11/2009]<br>Tributsch, H. 1984. How life learned to live. Cambridge, MA: The MIT Press. 218 p. | use thermal inertia<br>generate heat storage | behavioural adaptation | | | |
| 139 | **17** | generate constant thermal conditions | Coat changes with the seasons: rock squirrel | www.asknature.org [11/2009]<br>WALSBERG G.E. et al: SEASONAL ADJUSTMENT OF SOLAR HEAT GATN IN A DESERT MAMMAL BY ALTERING COAT PROPERTIES INDEPENDENTLY OF SURFACE COLORATION, Journal of Experimental Biology 142, 387-400 (1989) 387, 1989 | use thermal inertia<br>generate heat storage | air keeping (porous) structure - adaptive | high potential | | |
| 140 | **17** | generate constant thermal conditions | Mechanisms help thermoregulation: bumblebees | www.asknature.org [11/2009]<br>Heinrich, B. 1976. Heat exchange in relation to blood flow between thorax and abdomen in bumblebees. Journal of Experimental Biology. 64(3): 561-585. | use thermal inertia<br>generate heat storage | countercurrent heat system | high potential | | |
| 141 | **17** | generate constant thermal conditions | Varying response thresholds aid hive thermoregulation: honeybee | www.asknature.org [11/2009]<br>Jones, J. C.; Myerscough, M. R.; Graham, S.; Oldroyd, B. P. 2004. Honey Bee Nest Thermoregulation: Diversity Promotes Stability. American Association for the Advancement of | use thermal inertia<br>generate heat storage | behavioural adaptation<br>group organisation | | | |
| 142 | **17** | generate constant thermal conditions | Collective body heat warms nest: wood ants | www.asknature.org [11/2009] | use thermal inertia<br>generate heat storage | behavioural adaptation<br>group organisation | | | |
| 143 | **17** | generate constant thermal conditions | Countercurrent heat exchange in dolphins, legs of wading birds and many other organisms | Vogel S. Living in a physical world V: Maintaining temperature, 2005, 30, 581–590. | use thermal inertia<br>generate heat storage | countercurrent heat system | too general | | |
| 144 | **17** | generate constant thermal conditions | Metabolic adaptation | | use thermal inertia<br>generate heat storage | metabolic adaptation | too general | | |
| 145 | **17** | generate constant thermal conditions | Piloerection in furs and feathers | | use thermal inertia<br>generate heat storage | air keeping (porous) structure<br>reversible actuation system | high potential | | |
| 146 | **17** | generate constant thermal conditions | Adaptive thermogenesis in hummingbirds | Proc. IMechE Vol. 223 Part C: J. Mechanical Engineering Science JMES1563 A gaze into the crystal ball: biomimetics in the year 2059<br>Bicudo, J. et al: Adaptive thermogenesis in hummingbirds. J. Expl Biol., 2002, 205, 2267–2273. | use thermal inertia<br>generate heat storage | thermogenic system | biochemistry excluded | | |
| 147 | **17** | generate constant thermal conditions | Adaptive thermogenesis in sphinx moths | Proc. IMechE Vol. 223 Part C: J. Mechanical Engineering Science JMES1563 A gaze into the crystal ball: biomimetics in the year 2059<br>Casey,T.M. Flight energetics in sphinx moths: heat production and heat loss in Hyleslineata during free flight. J. Expl Biol., 1976, 64(3), 545–560. | use thermal inertia<br>generate heat storage | thermogenic system | biochemistry excluded | | |
| 148 | **17** | generate constant thermal conditions | Organisms in extreme environments: desert, arctic | | use thermal inertia<br>generate heat storage | | too general | | |
| 149 | **18a** | **generate permeability to air<br>ventilate with heat recovery** | Respiration of organisms in cold climates | | generate permeability to air<br>ventilate with heat recovery | breathable structure | too general | | |
| 150 | **18** | generate ventilation by structure | Aerating device delivers oxygen: mangroves | www.asknature.org [11/2009] | generate permeability to air<br>ventilate with heat recovery | breathable structure | high potential | | |

Gefördert vom Programm „Haus der Zukunft Plus“

| **count** | | **biologised question** | **phenomenon** | **references** | **functional or main principl** | **detailed principle** | **comment** | **select 1** | **select 2** |
|---|---|---|---|---|---|---|---|---|---|
| 151 | **18** | generate ventilation by structure | Tracheal system delivers oxygen efficiently: fly | www.asknature.org [12/2009]<br>Yahya H.: Design in Nature. London: Ta-Ha Publishers Ltd. 180 p. 2002.<br>Lehmann F.O., Heymann N.: Unconventional mechanisms control cyclic respiratory gas release in flying Drosophila, JOURNAL OF EXPERIMENTAL BIOLOGY, Volume: 208, Issue: 19, Pages: 3645-3654, 2005. | generate permeability to air ventilate with heat recovery | breathable structure | high potential | x | |
| 152 | **18** | generate ventilation by structure | Fluid protects eggs: birds | www.asknature.org [12/2009]<br>Yahya H.: Design in Nature. London: Ta-Ha Publishers Ltd. 180 p. 2002.<br>Tributsch H.: How life learned to live. Cambridge, MA: The MIT Press. 218 p., 1984. | generate permeability to air ventilate with heat recovery | breathable structure | high potential | x | |
| **153a** | **18** | generate ventilation by structure | **Sea sponge - water stream through organism** | Ruppert E.E., Fox R.S., Barnes, R.D.: Invertebrate Zoology (7 ed.). Brooks / Cole. pp. 76–97 2004.<br>Leys S.P.: The Choanosome of Hexactinellid Sponges, Invertebrate Biology, Vol. 118, No. 3, pp. 221-235, 1999.<br>Leys S.P. et al.: The biology of glass, ADVANCES IN MARINE BIOLOGY, VOL 52 Book Series: ADVANCES IN MARINE BIOLOGY, Volume: 52, 1-145, 2007.<br>Stegmaier T. et al.: Bionic developments based on textile materials for technical applications, Abbott A., Ellison M.: Biologically Inspired Textiles, CRC Press 2009.<br>Brümmer F. et al.: Light inside sponges, Journal of Experimental Marine Biology and Ecology 367 61–64, 2008.<br>Peacock T., Bradley E.: Going with (or Against) the Flow, SCIENCE VOL 320 6 JUNE 2008. | generate permeability to water | breathable structure | high potential | x | x |
| 153 | **18** | generate ventilation by structure | Skin acts as membrane: sea snake | Vogel S.: Comparative Biomechanics: Life's Physical World. Princeton: Princeton University Press. 580 p., 2003. | generate permeability to air ventilate with heat recovery | breathable structure | high potential | | |
| 154 | **18** | generate heat recovery (by structure) | Counter-current heat exchange in the respiratory passages: Effect on water and heat balance | www.asknature.org [11/2009]<br>Schmidt-Nielsen K. et al: Counter-current heat exchange in the respiratory passages: Effect on water and heat balance, Respiration Physiology, Volume 9, Issue 2, Pages 95-309 (May 1970), Pages 263-276 | generate permeability to air ventilate with heat recovery | countercurrent heat system | high potential | | |
| 155 | **18** | generate heat recovery (by structure) | An Analytical Model of the Counter-Current Heat Exchange Phenomena | www.asknature.org [11/2009]<br>MITCHELL J.W. et al: AN ANALYTICAL MODEL OF THE COUNTERCURRENT HEAT EXCHANGE PHENOMENA, Biophysical Journal, Volume 8, Issue 8, August 1968, Pages 897-911 | generate permeability to air ventilate with heat recovery | countercurrent heat system | high potential | | |
| **156** | **20** | ventilate passively | **Ventilated nests remove heat and gas: mound-building termites** | Gould J.L., Gould C.G.: Animal architects: building and the evolution of intelligence, 2007.<br>Turner J.S.: The Externded Organism. The Physiology of Animal-Built Structures, 2000.<br>Turner J.S.: Termite mounds as organs of extended physiology, no date, www.esf.edu/efb/turner/termite/termhome.htm [12/2009]<br>Turner J.S.: Architecture and morphogenesis in the mound of Macrotermes michaelseni (Sjöstedt) (Isoptera: Termitidae, Macrotermitinae) in northern Namibia, Cimbebasia 16: 143-175, 143, 2000.<br>Perna A.et al.: The structure of gallery networks in the nests of termite Cubitermes spp. revealed by X-ray tomography, Naturwissenschaften 95:877–884, 2008. | generate permeability to air ventilate with heat recovery | gas transport system by geomet | high potential | x | x |
| 157 | **20** | ventilate passively | Titan arum - shape of the flower is adapted to dispersal of scent, pollination strategy | Barthlott W. et al: A torch in the rain forest: thermogenesis of the Titan arum (Amorphophallus titanum). Plant Biology 11: 499, 2008. | generate permeability to air ventilate with heat recovery | gas transport system by geometry<br>thermogenic system | high potential | | |
| 158 | **20** | generate/use air pressure difference or temperature difference for ventilation | Burrow shape creates ventilation: prairie dog | www.asknature.org [11/2009] | generate permeability to air ventilate with heat recovery | gas transport system by geomet | high potential | | |
| 159 | **20** | generate/use air pressure difference or temperature difference for ventilation | Stems move air: Phragmites australis | www.asknature.org [12/2009]<br>van der Valk, A.: The Biology of Freshwater Wetlands. Oxford: Oxford University Press. 173 p. 2006.<br>Colmer T.D.: Long-distance transport of gases in plants: a perspective on internal aeration and radial oxygen loss from roots. Plant, cell and environment. 26(1): 17-36, 2003. | generate permeability to air ventilate with heat recovery | breathable structure | high potential | x | |
| 160 | **20** | generate/use air pressure difference or temperature difference for ventilation | Pressure makes air move: black mangrove | www.asknature.org [11/2009] | generate permeability to air ventilate with heat recovery | breathable structure | high potential | | |
| 161 | **20** | generate/use air pressure difference or temperature difference for ventilation | Underground burrows | | generate permeability to air ventilate with heat recovery | gas transport system by geomet | too general | | |
| 162 | **20** | generate/use air pressure difference or temperature difference for ventilation | Termite mounds | | generate permeability to air ventilate with heat recovery | gas transport system by geomet | too general | | |
| **163a** | **22** | change/control air flow | **Birds - passive mechanisms for laminar flow control** | Bechert D.W., Bruse M., Hage W., et al.: Fluid mechanics of biological surfaces and their technological application, Naturwissenschaften, Volume: 87, Issue: 4, 157-171, Apr. 2000.<br>Meyer R. et al.: Separation Control by Self-Activated Movable Flaps, AIAA Journal vol.45 no.1 (191-199) 2007. | generate permeability to air ventilate with heat recovery | control air flow | high potential | x | x |
| 163 | **22** | change/control air flow | Stomata of plants | Koch K. et al.: Multifunctional surface structures of plants: An inspiration for biomimetics, Progress in Materials Science 54 137–178, 2009.<br>Roth-Nebelsick A : Computer-based studies of diffusion through stomata of different architecture, ANNALS OF BOTANY, Volume: 100, Issue: 1, Pages: 23-32, Published: JUL 2007.<br>Collatz G.J. et al.: Physiological and environmental regulation of stomatal conductance, photosynthesis and transpiration: a model that includes a laminar boundary layer, Agricultural and Forest Meteorology Volume 54, Issues 2-4, Pages 107-136, April 1991. | generate permeability to air ventilate with heat recovery | control air flow | high potential | x | |

| count | | biologised question | phenomenon | references | functional or main principl | detailed principle | comment | select 1 | select 2 |
|---|---|---|---|---|---|---|---|---|---|
| 164 | **22** | change/control air flow | CAM plants can keep stomata closed in hot periods of the day, timebased control of ventilation, crassulaceae | | generate permeability to air ventilate with heat recovery | control air flow | high potential | | |
| 165 | **22** | change/control air flow | Lenticells | | generate permeability to air ventilate with heat recovery | control air flow | high potential | | |
| 166 | **22** | change/control air flow | Timebased control of ventilation - impact ventilation | Lighton J.R.B., Lovegrove B.G.: Temperature-Induced Switch From Diffusive to Convective Ventilation in the Honeybee Journal of Experimental Biology 154,509-516, 1990.<br>Woodman J.D., Cooper P.D., Haritos V.S.: Neural regulation of discontinuous gas exchange in Periplaneta americana, JOURNAL OF INSECT PHYSIOLOGY, Volume: 54, Issue: 2, Pages: 472-480, 2008. | generate permeability to air ventilate with heat recovery | control air flow | high potential | x | |
| 167 | **22** | provide constant air flow | Insect wings - vortices act like ball bearing generating laminar flow | | generate permeability to air ventilate with heat recovery | control air flow | added potential | | |
| 168 | **24a** | **generate cooling generate temperature change** | Carotid rete cools brain: Thomson's gazelle | www.asknature.org [12/2009]<br>Taylor, C.R.; Lyman, C.P. 1972. Heat storage in running antelopes: independence of brain and body temperatures. American Journal of Physiology. 222: 114-117.<br>Taylor, C.R.; Roundtree, V. 1973. Temperature regulation in running cheetah: a strategy for sprinters. American Journal of Physiology. 224: 848-851.<br>Baker, M.A.; Hayward, J.N. 1968. The influence of the nasal mucosa and the carotid rete upon hypothalamic temperature in sheep. Journal of Physiology. 198: 561-579.<br>Mitchell J. et al.: Thermoregulatory anatomy of pronghorn (Antilocapra americana) Eur J Wildl Res (2009) 55:23–31 | generate cooling generate temperature change | countercurrent heat system | high potential | x | |
| 169 | **24a** | **generate cooling generate temperature change** | Thermoregulation in Turkey Vultures. Vascular Anatomy, Arteriovenous Heat Exchange, and Behavior | www.asknature.org [11/2009] | generate cooling generate temperature change | heat dissipation area | high potential | | |
| 170 | **24a** | **generate cooling generate temperature change** | Changes in metabolism | | generate cooling generate temperature change | metabolic adaptation | too general | | |
| 171 | **24a** | **generate cooling generate temperature change** | Bees - ventilation of beehive by flapping of wings | | generate cooling generate temperature change | behavioural adaptation | | | |
| 172 | **24** | cool by radiation | Bill used as heat exchanger for thermoregulation: toco toucan | www.asknature.org [12/2009]<br>Tattersall, GJ; Andrade, DV; Abe, AS. 2009. Heat exchange from the toucan bill reveals a controllable vascular thermal radiator. Science. 325(5939): 468-470. | generate cooling generate temperature change | heat dissipation area | high potential | x | |
| 173 | **24** | cool by radiation | Large ears used to cool off: jackrabbit | www.asknature.org [11/2009] | generate cooling generate temperature change | heat dissipation area | high potential | | |
| 174 | **24** | cool by radiation | Large ears aid cooling: elephant | www.asknature.org [11/2009] | generate cooling generate temperature change | heat dissipation area | high potential | | |
| **175** | **24** | cool by radiation | **Jackrabbit (Lepus spp) uses well vascularised ears to cool off** | www.asknature.org [11/2009]<br>Foy S.: Oxford Scientific Films. The Grand Design: Form and Colour in Animals. Lingfield, Surrey, U.K.: BLA Publishing Limited for J.M.Dent & Sons Ltd, Aldine House, London. 238 p., 1982.<br>Vogel S.: Living in a physical world IV: Moving heat around. Journal of Biosciences, 30, 449–460, 2005.<br>Schmidt-Nielsen K.: Desert animals: Physiological problems of heat and water, Oxford, UK: Oxford University Press 1964.<br>Hill R.W. Veghte J.H.: Jackrabbit ears: surface temperatures and vascular responses, Science, Vol | generate cooling generate temperature change | heat dissipation area | high potential | x | x |
| **176** | **25** | cool by structured systems | **Shape shades and enhances heat radiation: cactus** | www.asknature.org [12/2009]<br>Tributsch H.: How life learned to live. Cambridge, MA: The MIT Press. 218 p. 1984.<br>Lewis D.A., Nobel P.S.: Thermal Energy Exchange Model and Water Loss of a Barrel Cactus, Ferocactus acanthodes, Plant Physiol. 60, 609-616,1977. | generate cooling generate temperature change | static shading structure | high potential | x | x |
| **177** | **25** | cool by structured systems | **Cuticle acts as cooling mechanism: Oriental hornet** | asknature.org [12/2009]<br>Ishay JS, Plotkin M, Ermakov NY, et al.The thermogenic center in social wasps, Journal of Electron Microscopy, Volume: 55 Issue: 1, Pages: 41-49 2006.<br>Heinrich B.: Heat echange in relation to blood flow between thorax and abdomen in bumblebees, J. exp. Biol., 64, 561-383, 1967. | generate cooling generate temperature change | heat exchange system | high potential | x | x |
| 178 | **25** | cool by structured systems | Tubes help cool muscles, transport gases: insects | www.asknature.org [11/2009] | generate cooling generate temperature change | heat exchange system<br>evaporation system | high potential | | |
| **179** | **25** | cool by structured systems | **Fractal systems for effective cooling** | Hermann M.: Bionische Ansätze zur Entwicklung energieeffizienter Fluidsysteme für den Wärmetransport, Dissertation Universität Karlsruhe 2005 | generate cooling generate temperature change | fractal system | added potential | x | x |
| 180 | **25** | cool by structured systems | Symbiosis of plants and insects - cooling of animal buildings | | generate cooling generate temperature change | ? | too general | | |
| 181 | **26** | cool by evaporation/evapotranspiration | Elevated leaves reduce evaporation: quiver tree | www.asknature.org [11/2009] | generate cooling generate temperature change | geometric adaptation | insufficient reference | | |
| 182 | **26** | cool by evaporation/evapotranspiration | Round shape reduces water loss: pebble plants | www.asknature.org [11/2009] | generate cooling generate temperature change | geometric adaptation | insufficient reference | | |

| count | | biologised question | phenomenon | references | functional or main principl | detailed principle | comment | select 1 | select 2 |
|---|---|---|---|---|---|---|---|---|---|
| 183 | **26** | cool by evaporation/evapotranspiration | Skin is a multifunctional material: human | www.asknature.org [11/2009] | generate cooling<br>generate temperature change | heat exchange system<br>evaporation system | too general | | |
| 184 | **26** | cool by evaporation/evapotranspiration | Air scoops provide cooling: ants | www.asknature.org [11/2009] | generate cooling<br>generate temperature change | evaporation system | insufficient reference | | |
| **185** | **26** | cool by evaporation/evapotranspiration | **Evaporation from skin in larger animals as humans, cattle, etc.** | Vogel S.: Living in a physical world IV: Moving heat around. Journal of Biosciences, 30, 449–460, 2005.<br>Nilsson G. E.: Measurement of water exchange through skin, Med. & Biol. Eng. & Comput. 15,209 218, 1977. | generate cooling<br>generate temperature change | evaporation system | high potential | x | x |
| 186 | **26** | cool by evaporation/evapotranspiration | Respiratory evaporation of dogs, goats, rabbits and birds | Vogel S. Living in a physical world IV: Moving heat around. Journal of Biosciences, 2005, 30, 449–460.<br>Crawford 1962, Crawford and Kempe 1971 | generate cooling<br>generate temperature change | evaporation system | high potential | | |
| **187** | **26** | cool by evaporation/evapotranspiration | **Evaporation cooling of leaves** | Vogel S.: Living in a physical world IV: Moving heat around. Journal of Biosciences, 30, 449–460 2005.<br>Vogel S.: Leaves in the lowest and highest winds: temperature, force and shape, Tansley review, New Phytologist, Volume 183 Issue 1, Pages 13 - 26, 29 Apr 2009.<br>Vogel S.: The lateral thermal conductivity of leaves, Canadian Journal of Botany-Revue Canadienne de Botanique, Volume: 62, Issue: 4, 741-744,1984.<br>Sherwood B.I. et al.: Relative Importance of Reradiation, Convection, and Transpiration in Heat Transfer from Plants,Plant Plysiol. 42, 631-640 1967.<br>Kerstiens G.: Cuticular water permeability and its physiological significance, Journal of Experimental | generate cooling<br>generate temperature change | evaporation system<br>convection system | high potential | x | x |
| **188a** | **26** | cool by evaporation/evapotranspiration | **Desert plant surfaces - boundary layer increasing convection cooling** | Koch K. et al.: Multifunctional surface structures of plants: An inspiration for biomimetics, Progress in Materials Science 54 137–178 2009.<br>Althawad A.M.,Grace J.: Water use by the desert cucurbit Citrullus colocynthis (L.) Schrad. Oecologia, 70 (3), 475-480, 1986.<br>Roth-Nebelsick A.: Computer-based analysis of steady-state and transient heat transfer of small-sized leaves by free and mixed convection, Plant, Cell and Environment 24, 631–640, 2001.<br>VOGEL J.: Convective Cooling at Low Airspeeds and the Shapes of Broad Leaves, Exp. Bot. 21: 91-101, 1970.<br>Schuepp P.H.: Leaf boundary layers, Tansley Review No. 59 New Phytol. 125, 477-507, 1993.<br>Benz B.W., Craig E.M.: Foliar trichomes, boundary layers, and gas exchange in 12 species of | generate cooling<br>generate temperature change | evaporation system | high potential | x | x |
| 188 | **26** | cool by evaporation/evapotranspiration | Labiates - essential oil for evaporation cooling | | generate cooling<br>generate temperature change | evaporation system | high potential | | |
| **189** | **27** | cool by generating thermal boundary layers | **Plants in arid climates - position of stomata adapted to climate lower than leaf surface** | Koch K. et al.: Multifunctional surface structures of plants: An inspiration for biomimetics, Progress in Materials Science 54 137–178, 2009.<br>Roth-Nebelsick A.: Stomatal Crypts Have Small Effects on Transpiration: A Numerical Model Analysis, Plant Physiology, Vol. 151, pp. 2018–2027, December 2009. | generate cooling<br>generate temperature change | geometric adaptation | high potential | x | x |
| 190 | **27** | cool by generating thermal boundary layers | Trachea section shows irregularities - creating local turbulences in flow, similar to ball bearings to increase flow | | generate cooling<br>generate temperature change | geometric adaptation | added potential | | |
| 191 | **27a** | maintain/control specific moisture contents | Nasal turbinates reduce water loss: northern elephant seal | asknature.org<br>Huntley A.C.: The contribution of nasal countercurrent heat exchange to water balance in the Northern elephant seal, Mirounga Angustirostris, MIROUNGA ANGUSTIROSTRIS, J. exp. Biol. 113, 447-454, 447, 1984.<br>Lester Christopher W.,Costa Daniel P.: Water conservation in fasting northern elephant seals | generate cooling<br>generate temperature change | countercurrent heat system | high potential | x | |
| 192 | **27a** | maintain/control specific moisture contents | Waxy coat controls moisture loss: cockroach | www.asknature.org [11/2009]<br>Wigglesworth, V. B.: Transpiration Through the Cuticle of Insects. Journal of Experimental Biology. 21(3): 97-114, 1945. | generate cooling<br>generate temperature change | evaporation system | insufficient reference | | |
| 193 | **27a** | maintain/control specific moisture contents | Desert shrub: low-energy water removal | Gebeshuber et al.: A gaze into the crystal ball: biomimetics in the year 2059, Proc. IMechE Vol. 223 Part C: J. Mechanical Engineering Science JMES1563, 2010.<br>Vogel, S. Comparative biomechanics: life's physical world, PrincetonUniversity Press, Princeton, USA p. 113, 2003.<br>Schlesinger W.H.,Gray J.T.,Gill D.S., Mahall B.E.: Ceanothus megacarpus chaparral: a synthesis of ecosystem processes during development and annual growth. Bot. Rev., 48(1), 71–117 1982. | generate cooling<br>generate temperature change | fluid harvesting system | high potential | x | |
| **194** | **27a** | maintain/control specific moisture contents | **Water management in camel nasal surfaces** | asknature.org [12/2009]<br>Schmidt-Nielsen K., Schroter R. C., Shkolnik A.: Desaturation of exhaled air in camels. Proc. R. Soc. B, 211(1184), 305–319 1981.<br>Schmidt-Nielsen K. et al.: Counter-current heat exchange in the respiratory passages: Effect on water and heat balance, Respiration Physiology 9, 263-276, 1970.<br>Gallardo P. et al: Distribution of aquaporins in the nasal passage of Octodon degus, a South-American desert rodent and its implications for water conservation. Rev. chil. hist. nat. [online]. vol.81, n.1, pp. 33-40, 2008. | generate cooling<br>generate temperature change | evaporation system (?) | high potential | x | x |
| **195** | **27a** | maintain/control specific moisture contents | **Pine needles, cloud forest, harvest water from air** | Limm E.B. et al.: Foliar water uptake: a common water acquisition strategy for plants of the redwood forest, Oecologia 161:449–459, 2009.<br>Gorb S. (ed.): Pull, Push and Evaporate: The Role of Surfaces in Plant Water Transport,Chapter III Transport Roth-Nebelsick A., Springer 2009.<br>Sarsour J. et al.: Bionische Entwicklung textiler Flächengebilde zur Wassergewinnung aus Nebel, Bionik: Patente aus der Natur 2008. | generate cooling<br>generate temperature change | fluid harvesting system | high potential | x | x |
| **196** | **27a** | maintain/control specific moisture contents | **Aireal roots harvest water from air - Velamen radicum specialised tissue** | Gorb S. (ed.): Pull, Push and Evaporate: The Role of Surfaces in Plant Water Transport,Chapter III Transport Roth-Nebelsick A., Springer 2009. | generate cooling<br>generate temperature change | fluid harvesting system | high potential | x | x |
| 197 | **27a** | maintain/control specific moisture contents | Water collection devices - bromelias funnel shaped rosettes | | generate cooling<br>generate temperature change | fluid harvesting system | high potential | | |
| 198 | **27a** | maintain/control specific moisture contents | Conifers - pines adapted form, structure and positioning of stomata to avoid water loss | | generate cooling<br>generate temperature change | evaporation system (?) | high potential | | |

| count | | biologised question | phenomenon | references | functional or main principl | detailed principle | comment | select 1 | select 2 |
|---|---|---|---|---|---|---|---|---|---|
| 199 | **27a** | maintain/control specific moisture contents | Leaf curling in poikilohydric plants to avoid dehydration | | generate cooling<br>generate temperature change | reversible actuation system | insufficient reference | | |
| 200 | **28a** | **generate energy** | Energy conversion | LaVan, D. A. and Cha, J. N. Approaches for biological and biomimetic energy conversion. PNAS, 2006, 103(14), 5251–5255. | generate energy | ? | too general | | |
| 201 | **28a** | **generate energy** | Plant physiology | | generate energy | photosynthesis | biochemistry excluded | | |
| 202 | **28** | use solar radiation | Pigments 'photosynthesize' without CO2: Halobacteria | www.asknature.org [11/2009] | generate energy | photosynthesis | biochemistry excluded | | |
| 203 | **28** | use solar radiation | Photosynthesis: plants | www.asknature.org [11/2009] | generate energy | photosynthesis | biochemistry excluded | | |
| 204 | **28** | use solar radiation | Wing scales aid thermoregulation: green birdwing butterfly | www.asknature.org [11/2009] | generate energy | photonic structure | high potential | | |
| 205 | **28** | use solar radiation | Creating energy from sunlight: plants | www.asknature.org [11/2009] | generate energy | photosynthesis | biochemistry excluded | | |
| 206 | **28** | use solar radiation | Leaves convert photons to energy: spinach" | www.asknature.org [11/2009] | generate energy | photosynthesis | biochemistry excluded | | |
| 207 | **28** | use solar radiation | LAI leaf area index - predicts photosynthetic production, is inverse proportional to light interception | | generate energy | photosynthesis | biochemistry excluded | | |
| 208 | **28** | adapt the energy generation by solar radiation to changing need (day, season) | Nest maximizes solar heat absorption: wood ants | www.asknature.org [11/2009] | generate energy | behavioural adaptation<br>group organisation | | | |
| 209 | **29** | generate energy in places without direct solar radiation | Heterotrophy - sourcing of chemical energy | | generate energy | non solar energy sourcing | biochemistry excluded | | |
| 210 | **29** | generate energy in places without direct solar radiation | Radiosynthesis: melanin in micro-organisms captures high-energy electromagnetic radiation as a source of supplying metabolic energy | Proc. IMechE Vol. 223 Part C: J. Mechanical Engineering Science JMES1563 A gaze into the crystal ball: biomimetics in the year 2059<br>Dadachova E. et al: A. Ionizing radiation changes the electronic properties of melanin and enhances the growth of melanized fungi. PLoS ONE., 2007, 2, e457. | generate energy | non solar energy sourcing | biochemistry excluded | | |
| 211 | **29** | generate energy in places without direct solar radiation | Soldanella plant, photosynthesis below snow cover | | generate energy | photosynthesis | biochemistry excluded | | |
| 212 | **29** | generate energy | Vibration creates heat: honeybee | www.asknature.org [11/2009] | generate energy | thermogenic system | biochemistry excluded | | |
| 213 | **29** | generate energy | Shivering produces heat: mammals | www.asknature.org [11/2009] | generate energy | thermogenic system | biochemistry excluded | | |
| 214 | **29** | generate energy | Shivering muscles produce heat: Arctic bumblebees | www.asknature.org [11/2009] | generate energy | thermogenic system | biochemistry excluded | | |
| 215 | **29** | generate energy | Microbial fuel cells: Geobacter sulfurreducens | Proc. IMechE Vol. 223 Part C: J. Mechanical Engineering Science JMES1563 A gaze into the crystal ball: biomimetics in the year 2059<br>Reguera, G., McCarthy, K. D., Mehta, T., Nicoll, J.S., Tuominen, M. T., and Lovley, D. R. Extracellular electron transfer via microbial nanowires. Nature, 2005, 435(7045), 1098–1101. | generate energy | non solar energy sourcing | biochemistry excluded | | |
| 216 | **29** | generate energy | Oxidation of molecular hydrogen: bacteria | Proc. IMechE Vol. 223 Part C: J. Mechanical Engineering Science JMES1563 A gaze into the crystal ball: biomimetics in the year 2059<br>Spear, J. R.,Walker, J. J.,McCollom,T. M., and Pace, N. R. Hydrogen and bioenergetics in the Yellowstone geothermal ecosystem. Proc. Natl Acad. Sci. USA, 2005, 102(7), 2555–2560. | generate energy | non solar energy sourcing | biochemistry excluded | | |
| 217 | **29** | generate energy | Create heat by increasing metabolic turnover | | generate energy | metabolic adaptation | biochemistry excluded | | |
| 218 | **29** | generate energy | Arum and other plants - thermogenesis | | generate energy | thermogenic system | biochemistry excluded | | |
| 219 | **30** | use osmosis for energy production/conversion | Energy is converted from chemical stored form into mechanical energy - muscles | | generate energy | chemical energy processing | biochemistry excluded | | |
| 220 | **30** | use osmosis for energy production/conversion | Osmotic processes in plants | | generate energy | ? | too general | | |
| 221 | **30** | use selective permeable membranes for energy production/conversion | Cell membranes | | generate energy | ? | too general | | |
| 222 | **32** | produce energy by organisms | Processing of energy in organims | | generate energy | ? | too general | | |
| 223 | **33** | produce energy by chemical processes | Energy transfers in photosynthetic process: green sulphur bacteria | www.asknature.org [11/2009] | generate energy | photosynthesis | biochemistry excluded | | |
| 224 | **33** | produce energy by chemical processes | Flower creates heat: philodendron | www.asknature.org [11/2009] | generate energy | thermogenic system | biochemistry excluded | | |
| 225 | **33** | produce energy by chemical processes | Electron flow generates heat: sacred lotus | www.asknature.org [11/2009] | generate energy | thermogenic system | biochemistry excluded | | |
| 226 | **33** | produce energy by chemical processes | Chemical heat production: thermogenic plants species of elephant foot, lily, and philodendron | Proc. IMechE Vol. 223 Part C: J. Mechanical Engineering Science JMES1563 A gaze into the crystal ball: biomimetics in the year 2059<br>Nagy K. A. et al: Temperature regulation by the inflorescence of philodendron. Science, 1972, 178(4066), 1195–1197.<br>Lamprecht I. et al: Flower ovens: thermal investigations on heat producing plants. Thermochim. Acta, 2002, 391(1-2), 107–118.<br>Schwartz S. et al: Chemical Sciences Roundtable, National Research CouncilBioinspired Chemistry for Energy: A Workshop Summary to the Chemical Sciences Roundtable. | generate energy | thermogenic system | biochemistry excluded | | |
| 227 | **34** | use earth to produce energy (geothermal energy, gravitation, magnetic fields) | Heat earthing by desert rodent, antelope ground squirrel (Ammospermophilus leucurus), use of burrows to cool off | Vogel S. Living in a physical world IV: Moving heat around. Journal of Biosciences, 2005, 30, 449–460.<br>Chappell and Bartholomew 1981 | generate energy | thermal coupling to environment | high potential | | |

Gefördert vom Programm „Haus der Zukunft Plus“

| count | | biologised question | phenomenon | references | functional or main principl | detailed principle | comment | select 1 | select 2 |
|---|---|---|---|---|---|---|---|---|---|
| 228 | **34** | use earth to produce energy (geothermal energy, gravitation, magnetic fields) | Lithops combines thermal mass with surrounding soil to cool | Vogel S. Living in a physical world V: Maintaining temperature, 2005, 30, 581–590.<br>Turner and Picker 1993 | generate energy | thermal coupling to environment | high potential | | |
| 229 | **34** | use earth to produce energy (geothermal energy, gravitation, magnetic fields) | Bacteria and microorganisms living close to hot environments can make direct use of thermal energy | | generate energy | behavioural adaptation<br>metabolic adaptation | biochemistry excluded | | |
| 230 | **35a** | **transport energy without loss**<br>**distribute energy** | Storing carbon and energy: bacteria | www.asknature.org [11/2009] | transport energy without loss<br>distribute energy | chemical energy processing | biochemistry excluded | | |
| 231 | **37** | transport thermal energy | Blood system (distributing sugar) | | transport energy without loss<br>distribute energy | fluid transport system | | | |
| 232 | **37** | transport thermal energy | Convection of blood in humans | | transport energy without loss<br>distribute energy | fluid transport system | | | |
| 233 | **38** | transport fluids over long distances | Xylem conduits transport water: plants | www.asknature.org [11/2009] | transport energy without loss<br>distribute energy | fluid transport system | | | |
| 234 | **38** | transport fluids over long distances | Lianas, water transport system | (refer to Anita Roth-Nebelsick) | transport energy without loss<br>distribute energy | fluid transport system | | | |
| 235 | **38** | transport fluids over long distances | Phloem, transport of nutrients and sugar over whole plant | | transport energy without loss<br>distribute energy | fluid transport system | | | |
| 236 | **38** | transport fluids over long distances | Optimised nervature of leaves | | transport energy without loss<br>distribute energy | fluid transport system | | | |
| 237 | **38** | avoid thermal loss when transporting fluids | Lingual rete precools blood: gray whale | www.asknature.org [11/2009] | transport energy without loss<br>distribute energy | fluid transport system<br>countercurrent heat system | | | |
| 243 | | | | | | | 111 | 47 | 30 |
| | | colour code: | | | | | | | |
| | 🟨 | Light | | | | | | | |
| | 🟧 | Heat | | | | | | | |
| | ⬜ | Ventilation | | | | | | | |
| | 🟦 | Cooling | | | | | | | |
| | 🟪 | Energy | | | | | | | |

Gefördert vom Programm „Haus der Zukunft Plus“

# Bionische Evaluierungskriterien

## Selektionshilfen für finale Sammlung

# BIOSKIN - MODELS FOR ENERGY EFFICIENT FACADE SYSTEMS

| | 6a | 6 | 7 | 9 | 24a | 24 | 37a | 37 | 43 | 46 | 48a | 48 | 57 | 72 | 94 | 120 | 153a | 156 | 163a | 175 | 176 | 177 | 179 | 185 | 187 | 188a | 189 | 194 | 195 | 196 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Role model<br>Criteria (Importance/Intensity) | Light transmission inside sponges | Fibers guide light: venus flower basket | Brittlestar calcite microlenses guide light | Facets in insects | Lotus surfaces - matt but translucent surface | Eyes are anti-reflective: elephant hawk-moth | Davidia involucrata, or Cornus florida colour: change by layered system | Scales create brilliant white: Cyphochilus beetles (reflection) | Humidity changes exoskeleton color: Hercules beetle | Felt-like covering protects from cold: Edelweiss | Glassnails | Desert snails reflect most of the suns direct infrared | Hairy leaves of desert plants - reflect | Leaf orientation controls sun exposure: plants | Window cells allow sunlight into plant: window plants | Aquatic birds pass heat from artery to vein before it can escape through feet | Sea sponge - water stream through organism | Ventilation by structure: mound-building termites | Birds - passive mechanisms for laminar flow control | Large ears used to cool off: Jackrabbit | Shape shades and enhances heat radiation: cactus | Cuticle acts as cooling mechanism: Oriental hornet | Fractal systems for effective cooling | Evaporation from skin in larger animals as humans, cattle, etc. | Evaporation cooling of leaves | Desert plant surfaces - boundary layer influences convection cooling | Plants in arid climates - position of stomata adapted to climate lower than leaf surface | Water management in camel nasal surfaces | Trees harvest water from air | Aireal roots harvest water from air - Velamen radicum specialised tissue |
| **speed/timescale** | + | + | + | + | + | + | -<br>slow | + | -<br>slow | + | + | + | + | -<br>slow | + | +<br>medium | -<br>slow | +<br>medium | + | -<br>slow | -<br>slow | + | -<br>slow | -<br>slow | -<br>slow | -<br>slow | -<br>slow | -<br>slow | -<br>slow | -<br>slow |
| **reversibility** | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | - | ▨ | + | ▨ | ▨ | ▨ | ▨ | + | ▨ | ▨ | + | ▨ | ▨ | ▨ | ▨<br>static system | ▨ | ▨ | - | - | - | ▨ | ▨ | - | - |
| **light** | | | | | | | | | | | | | | + | | | | | | | | | | | | | | | | |
| transmission | + | + | + | + | 0<br>partial | + | + | - | 0 | 0 | + | - | - | ▨<br>light - only stimulus | + | ▨ | ▨ | ▨ | ▨ | ▨ | ▨<br>light - only stimulus | ▨ | | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |
| reflection | - | - | - | + | +<br>partial | + | 0<br>partial | + | + | + | - | +<br>infrared | + | ▨ | - | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ 0 | ▨ | | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |
| **thermal properties** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| conductivity | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | +<br>coupled with T | ▨ | - | - | - | ▨ | ▨ | + | ▨ | + | ▨ | + | + | + | + | + | + | + | 0 | + | ▨ | ▨ |
| reflectivity | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | + | + | - | - | + | ▨ | ▨ | + | ▨ | + | ▨ | + | + | + | + | + | + | + | 0 | 0 | ▨ | ▨ |
| **interesting material properties for technical applications** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| interesting material properties other than the following | - | - | - | +<br>optical properties | - | +<br>optical properties | + | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| non-hybrid design functionally graded materials | - | - | - | + | - | 0 | + | 0 | - | - | - | - | - | + | - | - | - | - | - | - | - | - | - | - | - | - | + | - | + | + |
| water content | - | - | - | + | - | + | + | - | + | - | - | - | - | + | - | + | - | - | - | + | + | + | + | + | + | - | + | + | + | + |
| **complexity*** | - | - | - | 0 | - | - | 0 | - | 0 | 0 | + | 0 | 0 | + | - | + | - | - | - | + | 0 | + | - | + | + | - | + | + | - | - |
| **scaleability** | - | - | - | - | - | - | +<br>limited | - | + | - | + | - | - | - | - | + | -<br>limited | + | +<br>limited | + | + | + | + | + | + | - | - | - | -<br>limited | -<br>limited |
| **multifunctionality** | - | +<br>structure | - | - | +<br>surface properties | - | - | 0<br>surface properties? | + | + | +<br>structure | +<br>structure | +<br>reflect and convection | + | - | + | + | + | + | + | + | + | +<br>fluid transport | + | + | +<br>surface properties | +<br>gas exchange | + | - | - |
| **sensing integrated** | - | -<br>sensing organ | -<br>sensing organ | -<br>sensing organ | - | -<br>sensing organ | - | - | -<br>passive mechan. | - | - | - | - | + | - | + | + | - | -<br>passive mechan. | + | - | + | + -<br>optional | + | + | 0 | + | + | - | - |
| **energy efficiency**** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | + | + | + | + | + | + | + | + | 0 | + | + | + | + | + | + | + | + | + | + | + | 0 | 0 |
| **innovative potential** | - | - | + | + | + | + | 0<br>layer tech. | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + |
| **adaptivity***** | - | - | - | +<br>pigment position | - | - | - | - | +<br>change but no adapt. | - | - | - | - | + | - | + | + | -<br>only by change | +<br>passive mechan. | + | - | + | - | + | + | - | + | + | -<br>passive mechan. | - |
| **decentrality** | + | + | + | + | + | + | + | + | + | + | ▨ | ▨ | + | + | + | + | + | ▨ | + | + | + | + | + | + | + | + | + | + | + | + |
| **transferability** | + | + | + | + | + | + | 0 | + | + | + | + | + | + | -<br>difficult | + | + | + | + | + | + | + | + | ▨ | + | + | 0 | + | 0<br>difficult | + | + |

| **Evaluation** | | **Comment** | |
|---|---|---|---|
| **+** | high/yes | * | complexity is interpreted as the presence of many interelating factors, that make a causal or linear interpretation impossible |
| 0 | neutral | ** | energy efficiency is present in all living systems - only effects that obviously influence energy balance directly are evaluated with + |
| - | low/no | *** | adaptivity is evaluated on an ontogenetic or individual level, evolutionary adaptation is present in all living systems |
| ▨ | irrelevant | | |

gefördert vom Programm "Haus der Zukunft Plus"