Chapter 7
Brief Information to Biological Structures

The abstracted and compiled information in the following 50 sections originates in textbooks, original publications, and reference articles. Some data originate in the data collection of Flindt (1986). Much information is also taken from v. Frisch (1974), Freude (1982), and the Finnish collaboration “Animal Architecture” (1995).

7.1 Biological Building Materials (Outline)

1 Endogenous Materials
1.1 Secretions
1.1.1 Threads without Foreign Materials
1.1.2 Threads with Foreign Materials
1.1.3 Not Thread-like, without Foreign Materials
1.1.4 Not Thread-like, with Foreign Materials
1.2 Excretions
1.3 Skin Formations
2 Exogenous Materials
2.1 Plant Origin
2.2 Animal Origin
2.3 Inorganic Materials
2.4 Anthropogenic Materials
3 Substrates for Hollowed Structures
3.1 Organic
3.1.1 Plant Origin
3.1.2 Animal Origin
3.2 Inorganic
3.2.1 Stone, Earth
3.2.2 Ice, Snow
(Outline according to Freude (1982). The author gives examples for each on pages 177–179 for his outline points.)

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7.2 Beaver Structures

Water lodges of beavers (*Castor fiber*) are built from up to 4-m-long sticks and twigs that are woven over and between one another. The structure is then hollowed out from the inside so that an inner den emerges. This den is completely sealed with mud, stones, and fine plant fibers, except for the uppermost portion, which serves as air ventilation. The beaver prefers trees with thicknesses of about 12 cm, which it chops into pieces and transports away. The dams are generally not taller than 1.5 m.

7.3 Beaver Dams

Beaver dams stall the water. The water level is controlled by the removal and addition of twigs. The longest known beaver dam is 1200 m long. "In the Voronezh region in Russia, the largest dam is 120 m long, 1 m tall, and 60–100 cm wide. In the USA the beavers build dams in the swamps of the Mississippi of several hundred meters in length. On the Jefferson River (Montana, USA) lies possibly the largest of all dams. One can walk along it for 700 m. A horseman could not break in" (v. Frisch).

7.4 Badger Structures

The structures of the badger *Meles meles* have the diameter of about 10–30 m and reach up to 5 m in depth. The chambers are laid out in up to three levels on top of one another and connected with passageways that lead to several exits. Large structures can be up to 100 m in total tunnel length with 40–50 openings.

7.5 Tunnel Systems of Steppe Marmots

The passage system reaches depths of 2–3 m, occasionally 7 m, and has one or two exits, a den, and a chamber for excrement. The den is particularly soft padded in very cold regions (most clearly with the Siberian black-capped marmot that winters in permafrost soils). Entire families remain there, curled up and snuggled next to one another, for their hibernation. The body temperature amounts then to only 5 ℃. To hinder further sinking of the temperature in the den, individuals will occasionally wake up and generate metabolic heat.

7.6 Scrubfowl Mounds

The scrubfowl *Megapodius freycinet*, despite its partridge size, can build nest mounds with a diameter of up to 12 m and a height of up to 5 m, the dimensions of largest structures that have been observed with this species of fowl. Smaller scrubfowls that live on volcanic islands use geothermal warmth by building mounds with loose, warm volcanic soil.

7.7 Storage Chambers of Moles

Moles, *Talpa europaea*, gather stockpiles of partially eaten and therefore immobilized earthworms; in one instance, 1200 earthworms with a total mass of over 2 kg were counted in one storage chamber.

7.8 Storage Chambers of Hamsters

The female European hamster, *Cricetus cricetus*, gathers up to 15 kg of grain supplies for winter, in certain cases actually up to 50 kg.

7.9 Spherical Structures of the Ovenbird

Ovenbirds of the family Furnarius build up to 10-kg heavy nests from around 2000 mud clumps, with each individually weighing up to 5 g. The diameter amounts to about 25 cm; the diameter-to-wall thickness ratio is about 7.5:1.

7.10 Mortar Structures of the Potter Wasp

Potter wasps of the species *Polybia singularis* finish their thick-walled “ceramic” nests with slits on the sides as entrances and can reach up to 30 cm in length and 1.5 kg in mass.

7.11 Weaver Bird Nests

The weaver bird *Philetairus socius* completes communal nests that can be up to 9 m wide and around 2 m thick.

7.12 Tallest Ant Mounds

In Finland, an above ground structure of the red wood ant *Formica rufa* was observed. Its height was 2 m and base diameter was close to 6 m.

7.13 Stockpiles of the Harvester Ant

Harvester ants of the genus *Messor* can fetch 20,000 grains for a nest in a single day. The nest can reach up to 3 m deep and up to 50 m in extent. The nests can contain thousands of storage chambers, sometimes with several kilograms of grains.

7.14 Structures of Compass Termites

The “tower” structures of compass termites reach a height of 3.7 m, a length of 3 m, and a width of about 1 m, whose direction is exactly north–south.

7.15 Elongated Termite Structures

The South African termites of the genus *Odontotermes* form regular, wave-like structures of 2 m height and up to 11 m length, which run in distances of around 50 m through the landscape.

7.16 Earth Mounds of Less Organized Termites

The termite *Cornitернes cumulans* of South Africa builds approximately egg-shaped, underground nests with diameters up to 40 cm, which stands on stilts and is thereby thermally insulated. Later an earth dome is built on top of the nest, inside of which the nest is gradually relocated. Eventually, an overground termite structure that can measure up to 1.6 m tall with a base of 1 m emerges.

7.17 Largest Termite Structures

The maximum height measurements are around 9 m. A large termite mound weighs around 12 tons. Termite passages to groundwater sources can be up to 40 m long. In the Karakum Desert of Central Asia, termites can build shafts to groundwater of up to 200 m in length. “Geologists can take advantage of this by studying the excavation materials for the search of earth minerals deep underground” (Freude).

7.18 Nest of the Goldcrest

The exterior of the nest of the goldcrest *Regulus regulus* consists of weaving materials, moss, and lichen, about 7 g of weaving materials and 4 g of moss or lichen per nest. The goldcrest additionally collects the egg cocoons of spiders (along with the young spiders) as well as the cocoons of certain wasps and caterpillars, and builds an outer layer with them. The middle layer contains loosely packed moss stems with or without the addition of lichens. The inner cushion layer consists of small feathers or animal hairs. In one particular case, 2818 moss stems (total 3.1 g), 1422 lichen pieces (3.5 g), and 2674 feathers (1.8 g) were counted in one nest. The three-layered nest connects structural stability to thermoinsulation.

7.19 Tree Frog Nests

The Brazilian tree frog *Hyla faber* builds a 10-cm tall and 30-cm-diameter nest with his large forelimbs, in which it lays its eggs.

7.20 Foam Nest of the Green Flying Frog

This frog, *Rhacophorus reinwardtii*, is on the one hand well known due to its broad webbed feet, which allow it to more or less glide at length from tree tops to the forest floor, and on the other hand, for its foam nest structures. The several centimeter thick nest dries on the outer surface, which causes it to become brown and unnoticeable. The interior is made damp so that a small pond forms for the eggs and eventual tadpoles.

7.21 Egg Raft of the Purple Snail

Sea snails of the genus *Janthina* build foam rafts, on the underside of which they secure their egg cocoons. The air bubbles are adhered to a spiral band of with a length of 12 cm and width of 2 cm. Up to 500 cocoons with a total of 250,000 eggs can be adhered to the underside. The foam nests are also known from other snails, insects (praying mantises), some fishes, as well as tree frogs.

7.22 Honeycombs of the Honeybee

A honeycomb with an area of 37 cm × 22.5 cm can be built from merely 40 g wax; however it can contain no less than 1.8 kg honey.

7.23 Precise Constructions of the Honeybee

Wax glands of the bee workers secrete wax flakes of about 0.5 mm thick and 1.5 mm long, and each weighs 0.25 mg. The bees can build about 80,000 cells with 1 kg wax. The cell depth is 12 mm and breadth is 5.2 mm; the diameters of the cells have a margin of error of only 0.05 mm. The space between two parallel honeycomb strands amounts to only 9.5 mm; nevertheless the bees still have good mobility on the honeycomb. No less than 8.6 honeycombs are situated on 1 cm^2. The thickness of the honeycomb walls amounts to an average 0.073 ± 0.002 mm for workers and 0.092 for queens. The necessary sensors lie in the antennae and at the ends of the mandibles.

7.24 Temperature Differential in Bee Colonies

Bee wax is most workable at temperatures of 34–35 ℃; however, the larvae can tolerate nest temperatures of only 37 ℃, and at 45 ℃ the mature bees also die. The temperature differential, inside of which their lives are possible, amounts therefore to barely 2 ℃. In too hot weather, the bees ventilate the hive at the entrance hole (“fanning”) and spray water around for evaporative cooling. In too cold weather and longer frost periods, the bees crowd themselves closely together and generate then no less than 0.1 kW of warmth per kilogram of bee mass.

7.25 Spider Webs

Communal nests, fabricated by thousands of species of spider, for example *Araneus sermoniferous* and *Ulocerus republicanus*, reach 100 m in width.

7.26 Thickness of Spider Silk

A large, mature spider can produce silk which is 0.010–0.012 mm in diameter. Cribellate spiders weave around 50,000 silk threads of only 0.002 mm in diameter into one single thread.

7.27 Egg Containers of the Sac Spider

With silk threads the sac spider *Agroeca brunnea* builds an egg container of about 0.6 cm width and with a bell-shaped form, in which around 50 eggs can be accommodated. It is covered with earth and clay clumps that dry to form a solid outer layer.

7.28 Silkworm Cocoons

Silkworms have been used by humans for at least 5000 years. For the construction of a pupa cocoon, the larvae handle up to 4 km of self-produced silk in single threads of around 1 km in length, of which about 70 % is usable.

7.29 Nest Structures of the Swift

Swifts of the species *Panyptila cayennensis* from Central and South America build a tubular nest of about 60 cm in length with an opening on the bottom. The nests are built in 6 months with animal hairs, plant fibers, and feathers, mixed with a saliva secretion, onto an overhanging bluff or rock formation.

7.30 Dung Balls of the Scarab Beetle

The Egyptian scarab beetle *Scarabaeus sacer* weighs only 2 g, but can roll dung balls with the size of a fist and mass of 40 g.

7.31 Coral Reefs

The largest structure built by any animal is represented by the Barrier Reef in north-eastern Australia, with a total length of over 2000 km. The coral colonies there produce no less than 4 tons of limestone material per square kilometer in 1 day.

7.32 Sand Coral Reefs

Bristle worms of genus *Sabellaria* build closely snuggled together, organ-like tubes known as “sand coral reefs” on the North Sea shore. On the island of Norderney, a 60 m long reef with about a half meter height emerged within 2 years, in which one breakwater was sheeted with around 75 million tubes. Similarly, tall reefs are built by the tropical genus *Phragmatopoma* with heights of up to 1 m.

7.33 Fishing Nets

Many South American caddisflies produce nets with a tiny mesh dimension of 3–20 µm. A net with 1.5 cm diameter contains around 2,000,000 meshes.

7.34 Storage Hideaways

The eastern European house mouse species, known as the steppe mouse *Mus musculus spicilegus,* constructs hideaways inside of which two-to-six mice together collect 5–7 kg of seeds and these are then covered with earth. Below these hideaways they build their nests of 60–120 cm in diameter and up to 50 cm in height.

7.35 Path Constructions

Leaf-cutter ants of species *Atta sexdens* maintain up to 200-m-long path free of vegetation from the nest. The width of the path is up to 7 cm and can lead through formerly dense grass areas.

7.36 Bowers of the Bowerbird

In the course of a year, the bowerbird *Prionodura newtoniana*, although only blackbird sized, builds “two stems with giant, bristly towers, one 2 m and the other up to 2.70 m tall; the just under one meter space in between is transformed into a dance floor” (Animal Architecture).

7.37 Regulating Humidity

Termites of genus *Macrotermes* maintain a humidity level within 89–99 %. To reach water in dry regions, they build up to 40-m-long passages to groundwater, in some cases possibly up to 200 m in length.

7.38 Gas Exchange

Turtles leave air holes for the exchange of gases for their eggs that they bury in the sand. Many water-dwelling worms and caddis fly larvae drive water through their structures by either a muscle-driven vibration of their appendages or the pump-like movement of their abdomen. Nest-building fishes, for example, the stickleback *Gasterosteus aculeatus*, accomplish circulation through their nests with fin movements. African lungfish of the genus *Protopterus* build for the summer a mud cocoon that is dried out on the interior and whose upper lid is kept porous for gas circulation. For high tide, the Malaysian crab *Mictyris longicarpus* builds a sandcastle structure that contains an air chamber in which it resides. The prairie dog *Cynomys ludovicianus* uses, as stated previously, pressure differences "according to the Bernoulli principle" for the forced air circulation of its structures.

7.39 Vertebrate Temperature Regulation

Occupied nests of the weaver bird of the species *P. socius* maintain an internal temperature of 20 ℃ over exterior temperatures in environments such as the Kalahari Desert of South Africa, where during winter the temperatures at night can fall up to −10 ℃. Snow hares and redpolls build snow dens in igloo style, inside of which the temperature is 7–8 ℃ higher than the external temperature. Australian "thermometer birds" of the species *Leipoa ocellata* build large nests out of decomposing plant material whose warmth incubates the eggs. By heaping an earthen mound on top of the eggs, the interior temperature remains at a constant 34 ± 1 ℃ independent from the exterior climate.

7.40 Temperature Regulation by Insects

Wasps can maintain 30 ℃ in the breeding chamber of their nests. When it becomes too cold, the worker bees generate warmth with muscle vibrations; when it becomes too hot, evaporating water is released in the nest. Honeybees maintain a temperature of 35 ℃ within their honeycomb structures, as the wax is easier to work with at this temperature. Red forest ants of the species *F. rufa* provide numerous ventilation openings for their nests, which they seal shut during nights and cold weather by plugging them with their heads. The slope of the mounds is regulated by the worker ants so that it acts as an ideal collector of sunlight. In springtime, the ants warm themselves on the exterior of their mounds and then return to the interior where they "digitally" radiate their warmth.

7.41 Sizes of Populations of Colony-Forming Insects

Sizes of populations of colony-forming insects are as follows: paper wasps 140 individuals, bumblebees up to 2000, hornets up to 1500, yellow meadow ants up to 20,000, honeybees up to 80,000, army ants and leaf-cutter ants 100,000–600,000, red wood ants up to 800,000, and termites of the genus *Bellicositermes* up to 3,000,000.

7.42 Leaf Surfaces of Plants

An average apple tree has around 20,000 leaves with a median surface area of each leaf of 18 cm^2 and therefore 32 m^2 of total surface area. A large beech possesses 450 m^2 of total leaf surface area.

7.43 Maximum Heights of Trees

Maximum heights of trees are: sycamore 40 m, ash 50 m, pine 48 m, coconut palm 32 m, silver fir 75 m, sequoia 132 m, and giant eucalyptus 152 m.

7.44 Maximum Trunk Diameters of Trees

Maximum trunk diameters of trees are: field maple 0.7 m, pine 1.0 m, spruce 2.0 m, red beech 2.0 m, fir 3.0 m, sequoia 11.0 m, and baobab 15.0 m.

7.45 Slenderness of Plants

Slenderness is described here as the quotient of the height and the base diameter.

Baobab (20 m): 2.5
Giant sequoia (135 m): 11
Fir (70 m): 42
Spruce (60 m): 60
Sunflower (4 m): 100
Bamboo (40 m): 133
Sugarcane (6 m): 200
Rye stalk (1.5 m): 500

For comparison: The TV tower in Stuttgart (200 m): 19. (The "thickening" of taller structural system results from the Barba-Kick law of "proportional resistance", where the diameter *d* is not directly proportional to a height *h*, but to the product $h\sqrt{h}$).

7.46 Specific Masses of Wood

As the lightest wood variety, balsa wood weighs 0.18 g cm^{-3}, pine 0.49 g cm^{-3}, buckeye 0.57 g cm^{-3}, pear tree 0.72 g $cm^{-3,}$ red beech 0.74 g cm^{-3}, rosewood 0.82 g cm^{-3}, and the heaviest wood, *Guaiacum* weighs 1.23 g cm^{-3}.

7.47 Elasticity Moduli of Biological Building Materials

The "most elastic" material of the animal kingdom, the protein Resilin, possesses the lowest E-Module of merely 0.002 GPa whereas spruce wood possesses the E-Module of 10 GPa. For comparison the E-Module of silicone rubber is 0.01 GPa whereas that of V2A steel is 200 GPa.

7.48 Elastic Efficiencies of Biological Stretching Elements

Resilin has the highest elastic efficiency of 96 %. In comparison, the elasticity efficiency of sheep tendons is 90 %.

7.49 Tensile Strength of Biological Building Materials

Coniferous wood, Class III, possesses a tensile strength of 90 N mm^{-2}; spider silk possesses a tensile strength of 500 N mm^{-2}. For comparison the tensile strength of hard PVC is 75 N mm^{-2}, that of structural steel ST 33 is 310 N mm^{-2}, and that of special spring steel is up to 3090 N mm^{-2}.

7.50 Root Depths of Plants

The depths of dandelion roots reach around 30 cm, over 1 m in case of silver thistle, just under 3 m in case of wheat and rapeseed, up to 10 m in case of forest trees, and up to 20 m in case of desert plants.