

# Review of Integument

Engineering challenges and research paths for  
human-grown fur, scales, or feathers

## Report

Tilt Wolf, Lathreas, Rumi, MacDaRacc, Cam Cam,  
Birdy, Rakeela, Athamanatha Kitsune, and Zennith



freedom  
of form  
foundation

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# SECTION I: FUNCTIONAL, MATERIAL, MORPHOLOGICAL AND GENETIC PROPERTIES

# 1

## Properties of Fur

### Abstract

In order to faithfully reconstruct non-human fur from human hair, we must list all properties of fur that make it different from human hair. This chapter provides an overview of the relevant properties, as well as a comparison of fur between different species, ranging from pigmentation to geometry, and from mechanics to heat transport.

### 1.1 - Common fur coats require ensembles of strands with differing properties

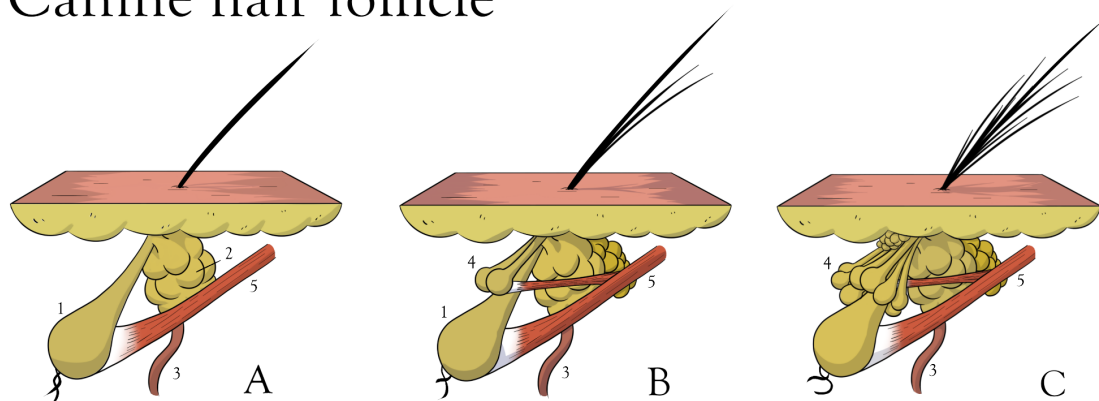
Humans generally only have one type of terminal hair occupying a single region of skin ([Otberg et al., 2004](#)). Although the hair follicle types on the scalp are indeed different from the smaller hairs on most other skin surfaces, populations of follicle types are not interspersed to form one complex fur coat, unlike with other animals. There may however be vellus hairs interspersed between fully developed hairs, which are barely visible under normal circumstances, unlike an undercoat, which is dense and clearly visible.

In many mammals, such as canines and felines, the apparent homogeneity of the hair population is not present: distinct populations of fur are interspersed to form a distinct **topcoat/overcoat**, consisting of primary (**guard**) hairs, and an **undercoat**, consisting of secondary (**down**) hairs, on the same patch of skin. The upper coat is the generally visible portion of a fur coat, pigmented and long-haired to aid in camouflage, to protect against cuts and abrasions, and to avoid sunburn. Below this layer, a more dense layer of thinner and shorter hairs make up the undercoat, which is more insulative and keeps the animal warm. The undercoat is generally less visible and does not contribute as much to the overall color of the fur, but does aid in keeping the upper coat upright and is essential for proper fur texture.

Often, a third distinct group of hair strands is categorized in fur coats. In addition to the guard and down hairs, this group is classified as an intermediate type, referred to as **awn** hair, or

sometimes referred to as lateral primary hair (as compared to the central variety, which represents the larger guard hairs). Awn hair grows alongside guard hairs — often clustered into a single follicular unit around a guard hair — and helps to provide structure to the coat ([Meyer 2009](#)). Whether or not the development of awn hairs distinct from guard hairs is necessary for realistic coat growth in transformed people is yet to be determined. Due to limitations of currently available models for fur on running visual simulations, we propose as a potential alternative a future experiment with model textiles to determine whether an intermediate hair is required for realism, and this can serve to inform on the engineering requirements for hair heterogeneity in future procedures. However, we are aware of limitations in the optical properties of artificial strands, and to circumvent this problem, we may opt for model textiles to be reconstituted from sheared real fur that has been ethically obtained.

## Canine hair follicle



**Figure 1.1:** Progression in growth of a canine hair follicle. **A:** At first, only the primary follicle is present. **B, C:** Over several months, secondary follicles arise, and other follicle-associated structures like the arrector pili and sebaceous glands become more extensive. **Legend:** 1, primary hair follicle. 2, sebaceous gland. 3, sweat duct. 4, secondary hair follicles. 5, arrector pili. Adapted from [Singh B. Veterinary Anat 5ed. p347](#). By Fenris, 2024.

### 1.1.1 - Top coat and undercoat across species

An ensemble of these hair types emerge from a single **follicular unit**. In many species, including felines and canines, a follicular unit often consists of a single guard hair follicle, several awn hair follicles, and many downy hair follicles that surround each awn hair. The number of secondary hairs per follicular unit differs between species, as shown in **Table 1.1**. However, the exact distinction between down, awn, and guard hairs is sometimes not clearly defined in various types of existing research. As such, down and awn hairs are often simply grouped together as secondary hairs or otherwise intermediate forms ([Singh B. Veterinary Anat 5ed. p345](#)), and even the distinction between awn and guard hairs can differ from author to author.



Table 1.1: Composition of hair types in a single follicular unit		
Species	Region	Guard : Awn : Down Ratio
Rabbit ( <i>Leporidae</i> )		1 : 2-4 : 20-50 ( <a href="#">Diribarne et al., 2012</a> )
Cat ( <i>Felis catus</i> )	Dorsal	1 : 2 : 6-8 ( <a href="#">Zanna et al., 2015</a> )
	Ventral	1 : 2 : 28-32 ( <a href="#">Zanna et al., 2015</a> )
		1 : 6 (guard : down) ( <a href="#">Meyer 2009</a> )
Dog ( <i>Canis familiaris</i> )		1 : 3 (guard : down) ( <a href="#">Meyer 2009</a> )
Sheep ( <i>Ovis aries</i> )		3 : 15-16 (guard : down) ( <a href="#">Meyer 2009</a> )
Sheep (merino)		3 : 40-60 (guard : down) ( <a href="#">Meyer 2009</a> )
Goat ( <i>Capra hircus</i> )		3 : 3-6 (guard : down) ( <a href="#">Meyer 2009</a> )
Goat(Angora)		3 : 15-40 (guard : down) ( <a href="#">Meyer 2009</a> )
Goat (Cashmere)		3 : 8-22 (guard : down) ( <a href="#">Meyer 2009</a> )
Cow ( <i>Bos taurus</i> )		1 : 2 (guard : down) ( <a href="#">Meyer 2009</a> )
Laboratory mice & rats		1 : 2 (guard : down) ( <a href="#">Meyer 2009</a> )
Marsupials		0 : 1 : 0 ( <a href="#">Crittter Care Wildlife</a> ) Mixed ( <a href="#">Alibardi, 2004</a> )
Humans		1 : 0 : 0 ( <a href="#">Meyer 2009</a> )

In contrast, human hair is analogous to primary hair follicles only — there are no secondary hair follicles in humans. Since humans do not possess such secondary hairs, reconstructing a convincing fur coat out of human hair follicles is challenging. Distinct populations,

representative of guard, awn, and down hairs (or at the very least, guard and down hairs), must be produced and arranged in a distribution mimicking that of a realistic fur coat. It is therefore essential to describe methods of recreating viable hair follicles reminiscent of secondary hair follicles, arranged around primary hair follicles, within humans. Different types of secondary hairs, e.g. awn versus downy, might need to be considered on a species-specific basis.

The main differentiating factor between primary, secondary, and other types of hair is the hair strand thickness and length. Primary hairs are thicker (150–600  $\mu\text{m}$  diameter) than secondary hairs (70–200  $\mu\text{m}$  diameter), and therefore serve different functions ([Meyer 2009](#)). This gives a clear target for manipulation of hair follicles to faithfully resemble those of fur, and will be the focus of the rest of this chapter.

### 1.1.2 - Hair follicles in different animal species differ in width and length

Different animal species have fur of varying textures and appearances, which come about from different coat compositions.

Longer hairs can be produced by differing growth times in the hair cycle — a hair that spends more time growing (i.e., in the [anagen phase](#)) before it is shed, given equal growth rates, will end up longer, and a coat made up of many of these hairs will be longer on average as well. This varies across many different factors, including genetic background, age, sex, body region, hormonal influence, neurogenic stimulation, and nutrition ([Welle & Wiener, 2016](#)).

For example, the hair on the average human's arms spends less time growing than the hair on the scalp before it is shed and a new hair grows in its place — this is what makes arm hair shorter than scalp hair. The distribution of hair length around the body is sufficiently explained by the variation in length of hair cycle and mean growth rate on different sites of the body (internal data, see [here](#)).

Wider follicles produce thicker hairs, which impart different volume and texture than thinner hairs ([Chi et al., 2013](#)). Some animals, such as the boar, have distinct and recognizable coats due to the coarseness of their fur, which is made bristly in part by the width of the hair.

### 1.1.3 - Whiskers, used for mechanoreception, are a separate type of hair

Beyond the hairs that make up a fur coat, other types of more specialized hairs exist, such as whiskers – also known as **vibrissae**. Vibrissae are thick, tough, and long hair strands used for mechanoreception: they are typically present on the front of the face to provide additional sensory perception to the individual regarding its immediate frontal surroundings ([Singh B. Veterinary Anat 5ed. p346](#)). For example, some rodents sense the size of a hole or opening with their vibrissae to tell if it is large enough to pass through before attempting to do so and getting stuck.

Vibrissae are thicker and more stiff than other hairs. Vibrissae are unique from most other hairs in that their follicles are surrounded in a *blood sinus* — a fluid-filled cavity that conducts and amplifies mechanical stimuli — that is highly innervated with sensory nerve fibers ([Singh B. Veterinary Anat 5ed. p346](#)).

Additional mechanosensitive, specialized guard hairs called **tylotrich** are also distributed across the body of at least dogs and cats, and these hairs also have blood sinuses (though smaller than those of vibrissae) ([Singh B. Veterinary Anat 5ed. p346](#)).

#### 1.1.4 - Modeling of distribution of hair follicles

Although fur is commonly divided into guard, awn, and down fur, natural variation between the duration of growth between different hair strands within each population may cause the strand length of the populations of hairs to overlap, resulting in a simplification of the overall hair coat into a single, normally distributed population.

To assess the effect of such natural variation, we have modelled the distribution of hair lengths of the three populations under the influence of different degrees of natural variation between individual follicles. Although the mean lengths of each population can be found readily in the literature, the standard deviation of each population is not known, to our knowledge. As such, the natural spread, i.e. the noise in the hair cycle duration, is a non-fixed parameter. With large natural variation between individual strands, it becomes possible to treat the fur coat as a single, diffuse population of hair lengths. If the natural variation is low, it must be modeled as three well-defined population peaks. This has implications for whether we need to produce distinct methods for different distinct populations of hair to grow, or whether a noisier method leading to a diffuse population would be sufficient. For these simulations, we have used parameters described in **table 1.2**.

∞ Length distribution of fur.ipynb

Table 1.2: Numerical Parameters of Hair Growth		
Parameter	Value	Reference
Growth rate (all phases, dog)	2.2 mm/week (forehead, summer) 2.6 mm/week (forehead, winter) 5.0 mm/week (shoulder, summer) 4.1 mm/week (shoulder, winter) 3.4 mm/week (flank, summer) 2.8 mm/week (flank, winter)	<a href="#">Gunaratnam &amp; Wilkinson, 1983</a>
Anagen:Telogen Ratio (human scalp)	90% anagen : 1% catagen : 9% telogen	<a href="#">Burg et al., 2017</a>
Anagen:Telogen Ratio (dog, plucked hairs, weighted averages)	18.4% anagen : 70.2% telogen : 11.4% broken-off roots	<a href="#">Diaz et al., 2004</a>



## 1.2 - Fur strands can be recreated in humans by changing select properties of hair

Just as between species, hair strands in animals differ in width and length within the same individual. Hair length is a function of the length of anagen phase of the hair cycle — how much time it spends growing — as well as the speed of hair strand extrusion, both of which vary by species, sex, and region of body ([Gray's Anatomy 42nd ed p 154](#); [Singh B. Veterinary Anat 5ed, p345](#)). Hair width is in turn controlled by the width of the hair follicle itself, and the hair angle is controlled by the growth direction of a hair follicle. More such properties are relevant for faithfully reconstructing fur from human hairs, which we have summarized below.

Some properties have a high impact on the overall quality of a fur coat, such as the strand density (amount of strands per unit area), whereas others, such as strand eccentricity, only play a subtle role in the overall appearance of a coat. Even so, we include all of these relevant parameters in **Table 1.3** for completeness. In practice, we can strategically decide to only tackle the most important subset of these properties first, so as to lower the time required for developing an initial treatment. As such, we have included a column stating the overall priority for our research. Please note that this priority list is not set in stone, and can be shifted based on new insights such as interest from the community.

This selection constitutes the properties we deem to be sufficient to faithfully reconstruct fur that is indistinguishable from fur in the target animal. We will elaborate on the selected parameters in the following sections.

Table 1.3: Relevant Geometrical Parameters of Fur		
Parameter	Main Far-field Effect	Overall priority
Strand density	Coat thickness, fluffiness, volume, brightness, saturation	Essential
Strand length	Coat thickness	Essential
Hair growth angle	Coat directionality, volume	High
Strand diameter	Coat fluffiness, coarseness	High
Cuticle scale roughness	Light diffusivity, saturation	Medium
Strand tapering shape	Coat fluffiness, coarseness	Medium
Strand curl	Coat volume, coarseness	Low
Strand flatness (eccentricity)	Highlight angles; may also affect curl	Low
Medullary index	Overall coat brightness, highlight angles, light diffusivity, and saturation	Low

### 1.3 - Different species have unique hair strand morphology, density, and distribution

Hair strand density is highly variable between species, as well as between regions on the body, summarized in **Table 1.4**. Humans have far fewer hair follicles on most skin regions (14-32 per cm<sup>2</sup>, including vellus hairs, in areas of the body other than the scalp) ([Otberg et al., 2004](#)) than animals such as dogs or cats (507 and 702 per cm<sup>2</sup>, respectively), and even more thinly furred species such as the Rhesus macaque have 340 per cm<sup>2</sup> ([Otberg et al., 2004](#), [Mangelsdorf et al., 2013](#)). Some measurements for cats and dogs place the density much higher, at 1,500 to 4,000 per cm<sup>2</sup> for dogs, and 6,000 to 10,000 per cm<sup>2</sup> for cats, which is two orders of magnitude greater than humans.

From these measurements, it is clearly necessary to add additional follicles to produce a realistic result for fur, such as through induced hair follicle neogenesis, transplantation of follicles after growth *in vitro*, etc.

**Table 1.4: Average hair densities for various animals and humans**

Species	Region	Infundibular Density (hair exit point count)	Hair Density (hair count)	Source
Human ( <i>Homo sapiens</i> ) - Transplant/Hair Loss Patients, races unreported	Scalp		124 - 200 per cm <sup>2</sup> (Photo) <sup>†</sup>	<a href="#">Jimenez &amp; Ruifernández, 1999</a>
Human ( <i>Homo sapiens</i> ) - Women age 13-84, races unreported	Scalp		316 per cm <sup>2</sup> (histology; derived from source table 1) <sup>†</sup>	<a href="#">Sinclair et al., 2005</a>
Human ( <i>Homo sapiens</i> )	Forehead	292 per cm <sup>2</sup> (CSSB*)		<a href="#">Otberg et al., 2004</a>
Human ( <i>Homo sapiens</i> )	Non-scalp body	14 - 32 per cm <sup>2</sup> (CSSB*)		<a href="#">Otberg et al., 2004</a>
Rhesus macaque ( <i>Macaca mulatta</i> )	Scapula	297 per cm <sup>2</sup> (CSSB*)	340 per cm <sup>2</sup> (Photo) <sup>†</sup>	<a href="#">Mangelsdorf et al., 2013</a>
Dog (Beagle) ( <i>Canis lupus familiaris</i> )	Scapula	367 per cm <sup>2</sup> (CSSB*)	507 per cm <sup>2</sup> (Photo) <sup>†</sup>	<a href="#">Mangelsdorf et al., 2013</a>
			1,500 - 4,000 per cm <sup>2</sup> (histology)	<a href="#">Meyer, 2009</a>

Cat (Domestic Shorthair) ( <i>Felis catus</i> )	Scapula	627 per cm <sup>2</sup> (CSSB*)	702 per cm <sup>2</sup> (Photo) <sup>†</sup>	<a href="#">Mangelsdorf et al., 2013</a>
			6,000 - 10,000 per cm <sup>2</sup> (histology)	<a href="#">Meyer, 2009</a>
Mouse ( <i>Mus musculus</i> )	Scapula	5045 per cm <sup>2</sup> (CSSB*)	6220 per cm <sup>2</sup> (Photo) <sup>†</sup>	<a href="#">Mangelsdorf et al., 2013</a>
Rat (Wistar Sprague-Dawley)	Scapula	1598 per cm <sup>2</sup> (CSSB*)	1500 per cm <sup>2</sup> (Photo) <sup>†</sup>	<a href="#">Mangelsdorf et al., 2013</a>
Rabbit (German domestic) ( <i>Oryctolagus cuniculus</i> )	Scapula	1728 per cm <sup>2</sup> (CSSB*)	2034 per cm <sup>2</sup> (Photo) <sup>†</sup>	<a href="#">Mangelsdorf et al., 2013</a>
Guinea pig (English cavy)	Scapula	1282 per cm <sup>2</sup> (CSSB*)	1032 per cm <sup>2</sup> (Photo) <sup>†</sup>	<a href="#">Mangelsdorf et al., 2013</a>
Pig (German Landrace) ( <i>Sus domesticus</i> )	Ear	22 per cm <sup>2</sup> (CSSB*)	24 per cm <sup>2</sup> (Photo) <sup>†</sup>	<a href="#">Mangelsdorf et al., 2013</a>
			10 - 40 per cm <sup>2</sup>	<a href="#">Meyer, 2009</a>
Sheep ( <i>Ovis aries</i> )			5000 - 7000 per cm <sup>2</sup>	<a href="#">Meyer, 2009</a>
Goat ( <i>Capra hircus</i> )			1200 - 1800 per cm <sup>2</sup>	<a href="#">Meyer, 2009</a>
Cow ( <i>Bos taurus</i> )			600 - 2500 per cm <sup>2</sup>	<a href="#">Meyer, 2009</a>
Horse ( <i>Equus ferus caballus</i> )	Trunk		1000 -1500 per cm <sup>2</sup>	<a href="#">Meyer, 2009</a>

\* = Cyanoacrylate skin surface biopsy (CSSB)

† = Digital Photography

+ = Calculated from data in Sinclair et al., 2005 using table 1: 4mm diameter punch biopsies (0.12566 cm<sup>2</sup>) with an average of 39.679 hairs per punch



Hair also varies by length, an essential parameter to regulate. For some species, such as humans, hair length varies greatly by body site, with scalp hair having a maximum length of about 100 cm in most people ([Robbins, 2006](#)). Body hair is more variable and sex-specific, but an upper value could be taken for male pubic hair. In contrast, fur length when measured for guard hairs (top coat) ranges greatly between breeds for cats and dogs, at 2.54 cm and 3.19 cm on average, respectively ([Sato et al., 2006](#)).

Male body hair length in humans is therefore at least roughly comparable to common fur types, but because of variation between body sites, and a need for global uniformity rather than sex-driven distribution patterns, it is our opinion that hair length regulation will likely still be a necessary parameter to control.

Table 1.5: Hair length across species			
Species	Type	Strand Length	Source
Human ( <i>Homo sapiens</i> )	Vellus	1-2 mm	<a href="#">Brannon, 2022</a> <a href="#">Meyer, 2009</a>
	Terminal (scalp)	~100 cm	<a href="#">Robbins, 2006</a>
Dog ( <i>Canis lupus familiaris</i> )	Primary (guard)	8.5 - 66.0 mm (mixed breed)	<a href="#">Sato et al., 2006</a>
		11 - 141 mm (various breeds)	
	Primary (guard)	Up to 100 mm (breed-dependent)	<a href="#">Teerink, 2004</a>
	Intermediate (awn)		
Cat ( <i>Felis catus</i> )	Primary (guard)	7.5 - 49.0 mm (mixed breed)	<a href="#">Sato et al., 2006</a>
		20 - 131 mm (various breeds)	
		40 mm	<a href="#">Teerink, 2004</a>
	Intermediate (awn)	30 mm	
Rabbit ( <i>Leporidae</i> )	Primary (guard)	25-35 mm	<a href="#">Teerink, 2004</a>

Hair width is also a major variable, both within and between species, with strands ranging from 20-150  $\mu$ m in width depending on species and study ([Teerink, 2004](#)). It is important to note, however, that the following width data in **Table 1.6** is complicated by the difficulty in categorizing hair strands — some estimates will refer to all strands, some refer only to topcoat, etc., and these categories themselves may be defined by different thresholds for different authors. As such, predictions arising from these data must be validated, either through computational modelling or artificial textiles, for example.

It should also be noted that for humans specifically, while distinct follicular units composed of grouped primary and secondary hair follicles do not exist, there is still a large amount of heterogeneity in hair morphology based on body site. Clinically, scalp hair is considered thick when it ranges in diameter from 90 to 110  $\mu\text{m}$ , medium from 50 to 80  $\mu\text{m}$ , and thin from 30 to 40  $\mu\text{m}$  ([de Lacharrière et al., 2001](#)). Similarly, 60-84  $\mu\text{m}$  is the cited overall range for terminal scalp hair in a different study ([Headington, 1984](#)).

**Table 1.6: Hair width across species**

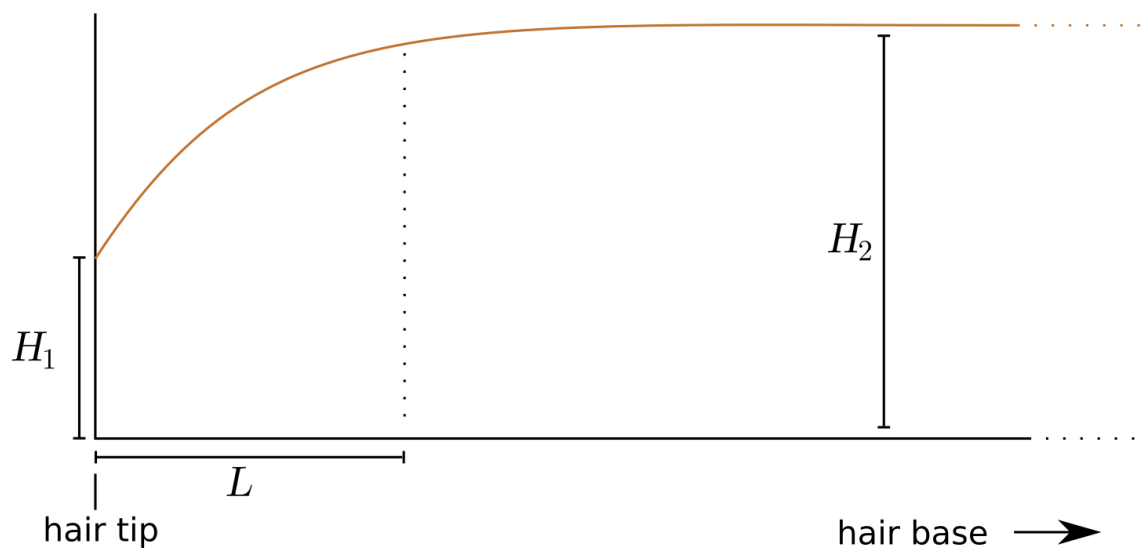
Species	Type	Bulb Diameter	Strand Diameter	Source
Human ( <i>Homo sapiens</i> )	Vellus		16 - 43 $\mu\text{m}$	<a href="#">Mangelsdorf et al., 2006</a>
			4 - 30 $\mu\text{m}$	<a href="#">Meyer, 2009</a>
	Terminal (Scalp)	134 $\mu\text{m}$	63 $\mu\text{m}$	<a href="#">Klam et al., 1983</a>
			52 - 83 $\mu\text{m}$	<a href="#">Birch et al., 2001</a>
Non-human animals (generally)	Primary (guard)	150–600 $\mu\text{m}$		<a href="#">Meyer, 2009</a>
	Secondary (down)	70–200 $\mu\text{m}$		
Dog ( <i>Canis familiaris</i> )	Primary (guard)	450 $\mu\text{m}$		<a href="#">Meyer, 2009</a>
	Secondary (down)	120 $\mu\text{m}$		
	Primary (guard)		20 $\mu\text{m}$	<a href="#">Teerink, 2004</a>
	Intermediate (awn)			
Cat ( <i>Felis catus</i> )	Primary (guard)	150 $\mu\text{m}$		<a href="#">Meyer, 2009</a>
	Secondary (down)	70 $\mu\text{m}$		
	Primary (guard)		90-100 $\mu\text{m}$	<a href="#">Teerink, 2004</a>
	Intermediate (awn)			
Rabbit ( <i>Leporidae</i> )	Primary (guard)		125-150 $\mu\text{m}$	<a href="#">Teerink, 2004</a>

### 1.3.1 - Strand tapering shape across species

The thickness of hair strands has a big impact on the overall perceived density of fur. Thinner hairs will occupy less space for rays of light to bounce off of, and as such will appear fainter when viewed from a distance. So far, we have only covered hair strand thickness as a single parameter. However, hair strand thickness can vary greatly depending on whether it is measured at the tip of a hair, in the center, or at the base.

This difference becomes especially important in the case of agouti-patterned fur. In agouti-patterned fur, each fur strand consists of different bands with a different color. When one of those bands, however, has an overall smaller width, this means that the band's color will be less represented in the full fur coat. Furthermore, since the color has a transmissive component, Lambert-Beer's law can significantly affect the hue and brightness of the color. If this occurs consistently for every strand in the fur coat, this will yield a global color pattern that is different from what may be intended. To correct for those factors, strand geometry must be taken into account. This is explored in detail in section 1.5.

Although the width of individual hairs regularly fluctuates along the strand ([Yang et al., 2020](#)), hairs generally have a tendency to taper off at the tip. As such, hair strands are commonly modelled with three parameters: one describing the width at the tip ( $H_1$ ), one describing the width at the base ( $H_2$ ), and some parameter describing the shape of tapering ( $L$ ). This model is visualized in figure 1.2. Detailed measurements of the widths of several hair strands from various species can be found in the supplementary material of [Yang et al., 2020](#).



*Figure 1.2: General shape of fur strands. The parameters  $H_1$ ,  $H_2$ , and  $L$  depend on the species and type of hair.  $L$  is commonly around 3 cm (with some exceptions) for the hair of various species, regardless of length, although type (guard or down) was not specified ([Yang et al., 2020](#)). This suggests a constant 'startup' period during the growth of the tip of the hair, which later stabilizes into a more constant width as the hair continues to grow.*



## 1.4 - Realistic fur coloration requires careful patterning of human melanins

### 1.4.1 - Fur colors range from white, yellow, to brown and black by modulating melanocyte density and behaviour

There are many different conceivable fur coats, depending on the species. Individual points on a strand, however, can only have a limited range of colors, from white and yellow to brown and black. This is modulated by the density of melanocytes at each position along the strand, as well as by the amount of melanin synthesized and distributed by each individual melanocyte. Any colors outside of the main palette, as described in the next section, must be constructed through careful patterning of the strand, of groups of strands, and of an area section of fur. When designing the coloration of a mammal, it is important to keep this leveled nature of fur coloration in mind: the perceived color is a combination of many factors.

Colors along a fur coat are not uniform. Bellies of mammals are usually covered in light-coloured fur. Such a gradient of color can be alternated with Turing-like patterns, such as spots (e.g. on a leopard) or stripes (e.g. on a zebra). Each parcel of fur will have its own major average color. For example, a leopard's fur is a pale yellow, while its spots are black, and each spot is often covered with a faint white line. However, even more subtle differences exist, such as slight differences in shading (not shadows) achieved on a leopard's face, caused by tiny changes between the patterns on each individual hair in the region. This can be seen well in figure 1.3. To achieve this average coloration per area of fur, each strand too has a unique pattern to give rise to the exact color. In the subsequent sections, we will examine each of these color-producing mechanisms.



*Figure 1.3: A picture of an amur leopard, showing many sharp patterns (spots and stripes) and gradient patterns (various shadings on the nose, cheeks, head, and body), which together contribute to the look of a leopard. Picture by Colin Hines from wikimedia commons, licensed under CC-BY-SA 3.0.*

### 1.4.2 - The 'redness' of fur depends on the ratio of eumelanin to pheomelanin

There are two types of pigment in mammalian hairs: **eumelanin** and **pheomelanin**. Both have slightly different absorption spectra. Eumelanin is generally darker and grayish brown, whereas pheomelanin is lighter and reddish-brown. The absorption spectra of both are contrasted in figure 1.4. The mix between these pigments, their distribution, and their overall concentration broadly determines the final color of fur, although the geometric architecture of individual hairs can significantly modulate the intensity and saturation of the coat (see section 1.5 - "Strand geometry significantly affects color pattern and saturation of fur").

#### Relevant chemical parameters for the far field visual properties of hair and fur

According to the most commonly used visual models, only a few relevant chemical depositions should be taken into account for accurate fur reconstruction from hairs:

- **Total melanin concentration** - Determines darkness of the hair strand.
- **Eumelanin to pheomelanin ratio** - Determines 'yellowness' of the hair strand, but is a quite subtle effect.

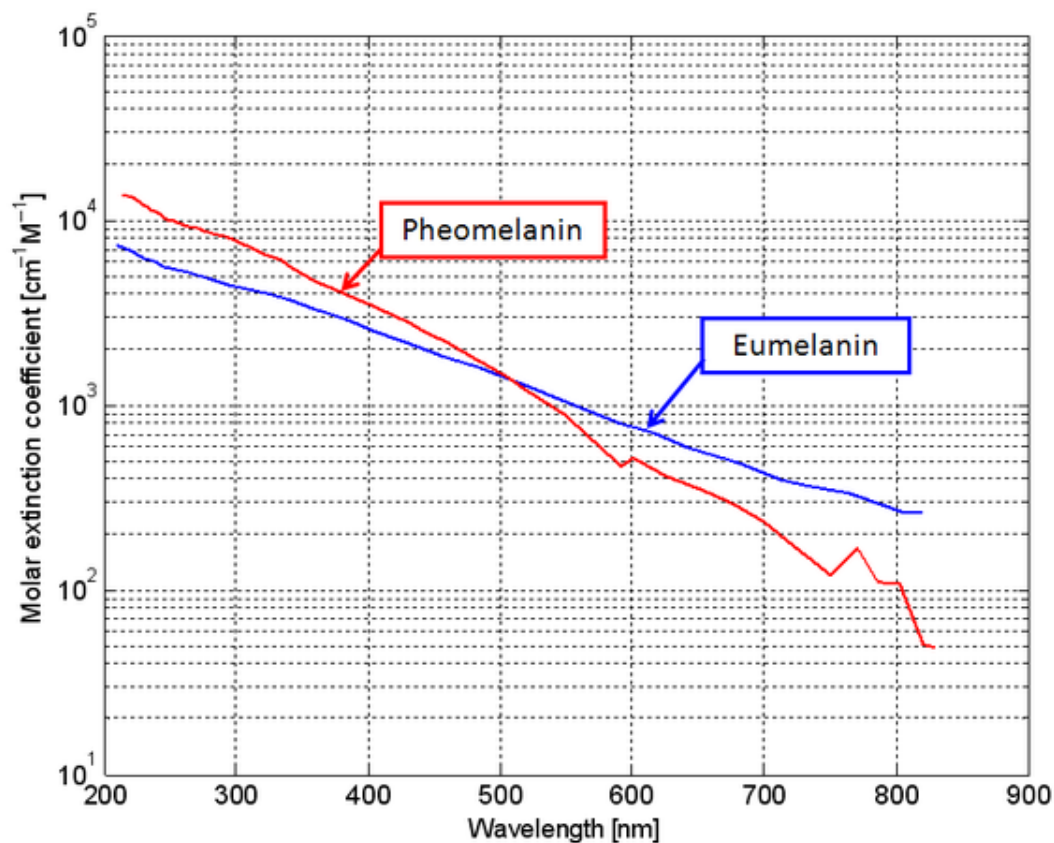


Figure 1.4: Molar extinction coefficients of eumelanin and pheomelanin. Indeed, there is only a subtle difference between the graphs. The graph of pheomelanin's extinction coefficient, however, is more skewed, leading to a more saturated brown/red coloration. Image credit: user Zhun310 from wikimedia commons, licensed under CC BY-SA 3.0.

Red foxes have a high ratio of pheomelanin to eumelanin in their fur, explaining their orange look, though they still do have detectable eumelanin. Silver foxes completely lack detectable pheomelanin, their fur instead only containing eumelanin ([Prasolova et al., 2002](#)). Interestingly, the total melanin concentration is highest in silver foxes, rather than red foxes ([Prasolova et al., 2002](#)). This is explained by the fact that the vibrancy of the color diminishes as more pigment is added, and for red foxes to have such a vibrant orange color, the total absorption of light must remain limited.

Domestic dogs have a wide variety of pigment hues and color patterns, all arising from the mix of eumelanin and pheomelanin. Dogs such as Nova Scotia Duck-Tolling Retrievers commonly have vibrant golden-brown fur, caused by a medium amount of pheomelanin and eumelanin. Irish Setters are marked by a deep red-brown coat, caused by a relatively high concentration of pheomelanin (higher than in red foxes) ([Slavney et al., 2021](#)).

The color can be estimated with a simple Lambert-Beer model of absorbance. One such model has been used substantially in recent computer graphics efforts, and we can plot different values for absorbance (at arbitrary scaling) using the absorbance parameters used in [d'Eon et al., 2011](#). We have displayed this plot in figure 1.5. (Our implementation can be reviewed in `fur pigment graph.ipynb`.)

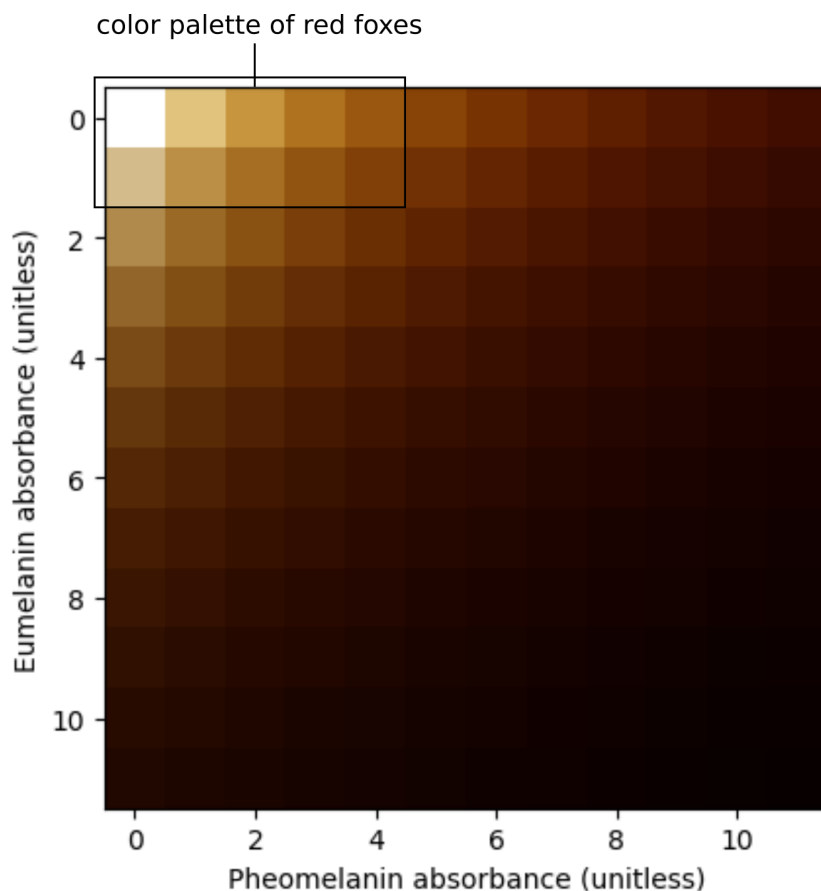


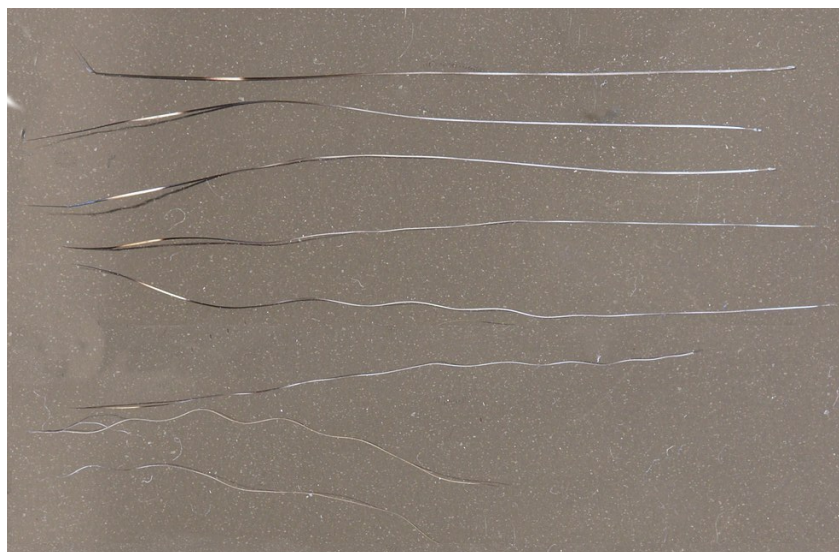
Figure 1.5: Visual coloration of eumelanin vs pheomelanin absorbance. Red foxes obtain their orange color by using low concentrations of melanin, and having a high pheomelanin-to-eumelanin ratio. See `fur pigment graph.ipynb` for implementation details.



This graph allows us to estimate the required concentrations of pigment inside hair strands for various types of fur coat. However, the true color also depends on fur thickness and organization.

### 1.4.3 - Gray fur strands do not exist: color saturation is instead achieved by alternating black and white bands (“agouti fur”)

As can be seen from the graph above, true gray coloration is not possible with any combination of eumelanin or pheomelanin. Instead, mammals such as gray wolves make use of *agouti* color patterns, where an individual strand will have a near-white and near-black bands, corresponding to low and high concentrations of melanin, which from a distance will give a gray appearance. This type of fur is displayed in figure 1.6.



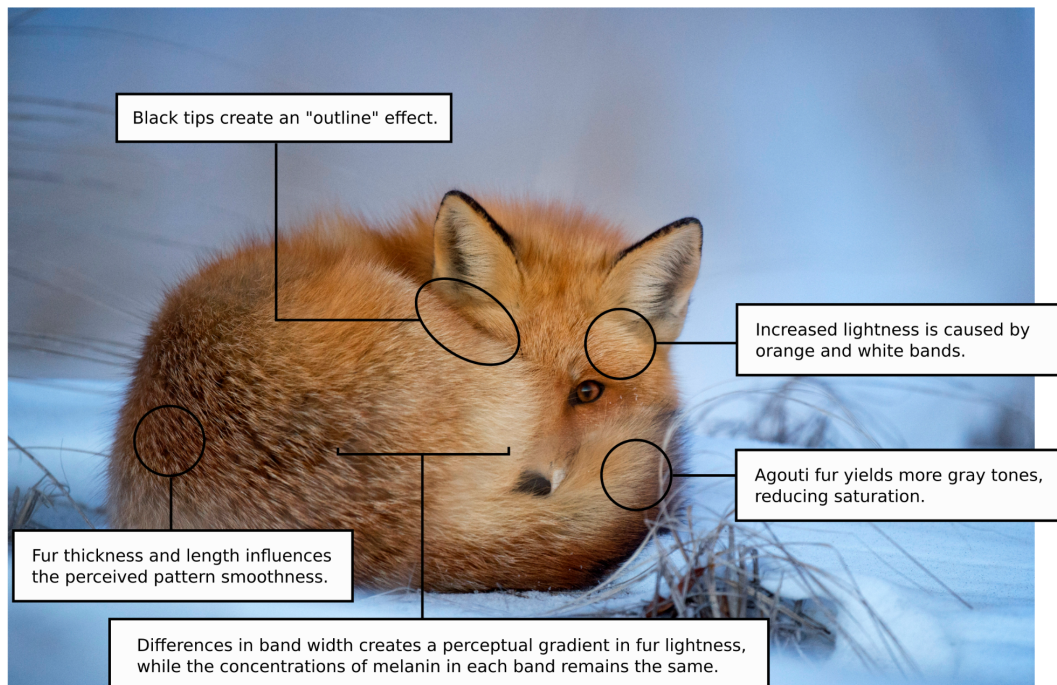
*Figure 1.6: Banded patterns of domestic cat fur. From top to bottom: guard hair, awn hair, and down hair. Note how the guard hairs are banded. This results in the overall appearance of gray fur, when taken in an ensemble in a coat. Picture by user JonRichfield on wikimedia, licensed under CC-BY-SA 3.0.*

The bands themselves are hardly random: usually, each strand in a local area of fur has identical patterning. Instead, the random arrangement of fur strands themselves give rise to the speckled pattern. Individual strands often have four bands: two light-colored and two black bands, though it is unclear how much diversity in the amount of bands exists due to lack of sufficient data.

### 1.4.4 - Agouti fur greatly contributes to the realism of many fur types

This “**agouti**” fur, consisting of banded strands, is common in colorful scenarios as well. Red fox hair strands, for example, contain large streaks of pheomelanin near the center, and the tips of the hairs are colored black from a high total melanin concentration. This has the overall effect of creating a dark outline mostly visible around a fox’s tail.

Other hair strands in the red fox can be banded with orange and white colors, orange and black colors, or even intermediates. This together gives rise to a highly complex fur coat, which requires careful analysis to properly emulate. Different effects in fox fur are shown in figure 1.7 below.



*Figure 1.7: Various effects caused by agouti fur that contributes to a red fox's appearance.*

Hair and fur are colored by pigments, much like the skin. The density of melanocytes (cells that produce melanin), along with the ratio of eumelanin (black/brown pigment) to pheomelanin (red pigment) that they produce, varies across species to impart diverse colors. The patterns of these melanocytes within follicles and across the body determine the coloration of the fur coat.

One seemingly universal coloration pattern is the agouti pattern. This occurs when one strand of fur is pigmented one way during a period of growth, then pigmented another way during some more growth, and so on - any number of times - to create a banded appearance on the strand. The coloration and number of bands varies between species, but always greatly contributes to the liveliness of the coat.

#### **1.4.5 - Piebald fur occurs where unpigmented patches exist on a pigmented background - mature melanocytes are not present in affected follicles**

In **piebald**-patterned individuals, mature melanocytes are not present in follicles in some areas, creating patches or swathes of white, unpigmented fur. Interestingly, all domesticated animal species have been observed to have at least one individual with piebald coloration. Beagles are a good example of a commonly-piebald dog breed. Piebaldism also occasionally affects humans as an autosomal dominant trait ([Agarwal & Ojha, 2012](#)).

## 1.5 - Strand geometry significantly affects color pattern and saturation of fur

### Abstract

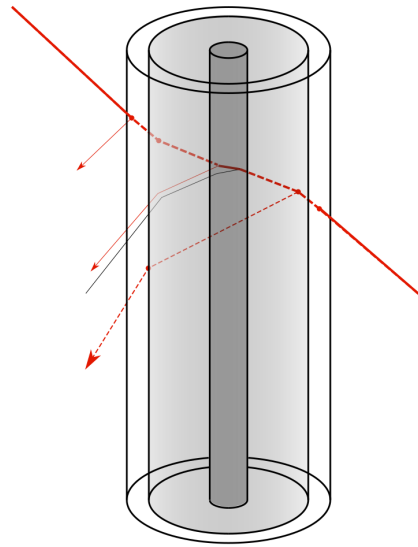
Although arguably the most important difference between human hair and luxurious fur coats is the amount of hairs present, simply increasing the amount of hairs is not enough to reconstruct fur in its entirety. There are subtle geometric differences between human and non-human hairs that lead to a dramatic difference in the look and feel of a fur coat made of human hairs versus a fur coat made of, for example, fox hairs. To understand how we can overcome these differences, we must understand the way light interacts with a single hair, and how this affects the overall look of a fur coat.

### 1.5.1 - Increasing hair density is not enough: unmodified human hair strands cannot replicate all visual properties of a fur coat

Although human hair and the hairs of other species share many features, only changing the amount, color, and size of human hairs is not enough to fully reconstruct a non-human animal's fur coat. The structure of the individual hair strand differs between species, leading to changes in visual characteristics of fur depending on various microscopic features of hair strands. Even a perfectly colorless fur coat will have a distinctive darkening of regions simply by the way it interacts with light. This is because the geometric properties of hair dictate how light scatters within a furry coat, and using human hairs to build a fur coat will lead to qualitatively different results than using fox hairs.

In this section, we will discuss how the visual appearance of hair is dictated by the interaction of light with the hair strand. The properties of strands affecting the look of fur can be subdivided into two categories: *geometry*, such as the roughness of the medulla or the internal structure of a hair, and *light absorption*, which includes pigmentation.

Since hairs are partially transparent cylinders, light rays reflect from the surface or bounce around inside the hair strand before being transmitted back out at a nontrivial angle. This gives rise to the characteristic 'hair highlights' of various colors in human hair, and is the reason why human hair looks distinctly different from cloth fibers. Pigments will absorb some of the wavelengths of rays that enter the hair, leading to vivid coloration in secondary highlights in hairs depending on melanin concentration.



*Figure 1.8: light ray path through a hair. The core (darkest part) is the medulla, the next region outwards (medium gray) is the cortex, and the outermost region (clear) is the cuticle.*

Light only reflects or refracts off of surfaces of different index of refraction. Absorption, however, only occurs within volumes. This allows the system to be described by a hair's surfaces and volumes, which will determine the visual characteristics of the hair. As a result, changing the roughness or position of one of the surfaces, or the opacity of a volume, will significantly impact the overall looks of a hair strand or fur coat from afar. Therefore, we will describe the different surfaces, and the differences between humans and other species.

Human hair contains three main volumes, arranged as shells around the core. In the center is the **medulla**, which is surrounded by the **cortex**, which in turn is surrounded by the **cuticle**. The boundaries between these three volumes are physically relevant to the perceived coloration of the hair, since light will bounce off of these surfaces. In non-human fur, this same process gives rise to the hair's visual properties.

## 1.5.2 - Modulating key hair strand properties faithfully restores fur-like coat characteristics

Human hair can be made to look indistinguishable from, say, canine fur, if all relevant properties of hairs are modulated to match those of fur. Listed below is a list of key properties which are expected to have the most visual impact, and have significant differences between human hair and non-human fur.

### Total hair width

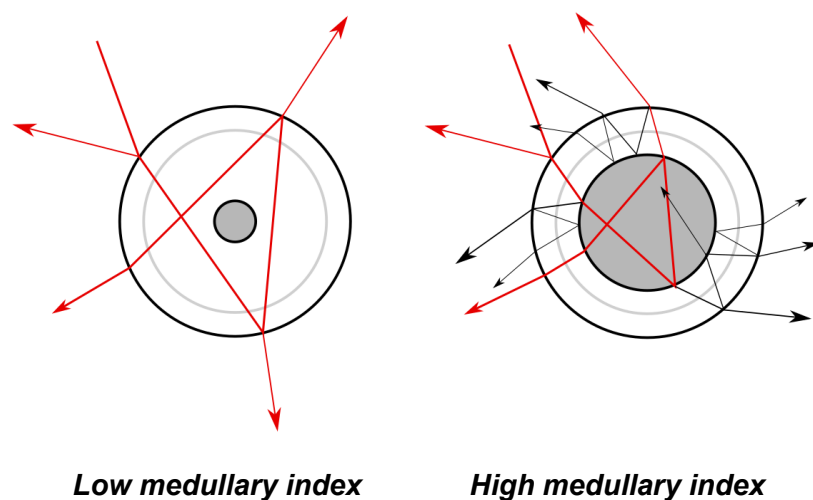
Light rays moving through an absorptive volume will experience more attenuation of the light beam when passing through thicker materials. This effect is known as the **law of Lambert-Beer**. This has the consequence that hairs will look increasingly translucent the thinner they get, even if the concentration of pigment remains the same. This can be seen in fur itself, where the tips of fur look much more transparent than the thicker base.



## The medullary index (MI)

The medullary index is the ratio of the width of the medulla compared to the total width of the hair. This parameter is relevant for identifying species, since human hair tends to have a medullary index of less than  $\frac{1}{3}$ , while many non-human animal species have hairs with a medullary index of more than this value ([Zafarina et al., 2009](#)).

Since the medullary index describes the size of the medulla, this property affects both the amount of light absorption using Lambert-Beer's law. Importantly, it also affects the light reflections within the cortex due to moving the cortex-medulla boundary ([Yan et al., 2015](#)). This latter effect will lead to a qualitative difference in the look of fur, since the positions at which light rays leave the strand will shift in distinctive ways, and as such will be very hard to replicate by changing any other parameters.



*Figure 1.9: A cross-section view of a hair strand with a low and high medullary index, respectively. Light passes into the hair from the top left in both cases. A hair strand with a low medullary index, shown on the left, has sharper but fewer highlights, since the medulla is often not intersected by the light ray. A hair strand with a high medullary index has many more secondary light bounces giving rise to a more diffuse set of highlights. The overall exit angle of the light ray, determining the highlight angle of the hair strand, changes drastically depending on the size of the medulla. In the far-field, the medullary index plays an important role in the apparent overall brightness, saturation, and highlights of fur.*

## Cuticle scale radial and longitudinal roughness

The outside layer of hair strands — the **cuticula** — has a distinctive microstructure in different species ([Teerink, 2004](#)). This microstructure has a large impact on the far-field visual properties of the hair. Assuming that we only care about the far field, the cuticular microstructure is commonly modelled with just two parameters: the radial and longitudinal roughness ([Chiang et al., 2016](#); [Huang et al., 2022](#)). In this case, these ‘roughness’ properties model the surface using microfacet theory, which describes the surface of an object as having a fully random light scattering effect. This is of course just an approximation, but overall appears to work well for simulating hair and fur in the far field.

### 1.5.3 - The roughness of fur strands influences the perceived brightness and colour saturation of the fur strands

A side-effect of the light scattering within hair strands is that the brightness can be modulated not just by absorption, but also by the amount and diffusivity of light reflection. The surface of fur strands plays a big role, according to the microfacet model, in the perceived quality and saturation of hair or fur ([Marschner et al., 2003](#); [Huang et al., 2022](#)). Smooth strands will tend to reflect light in sharp highlights, whereas rougher hair will look more pale and the overall coat more even. Also inner roughness, such as roughness of the medulla, can affect the scattering of light in distinct ways ([Huang et al., 2022](#)). This is important, for example, in modelling the fur of wolves, which appear to lack distinct highlights, and instead assume a strand model with rough surfaces. Human hair, on the other hand, will tend to have a set of shiny reflective highlights, which will become dull when the hair is damaged or if the cuticle scales stand upright. This becomes apparent in greasy hair: greasy hair will tend to look darker in color, not because of pigment in the grease, but because of a reduction in hair strand roughness leading to sharper highlights.

## 1.6 - Heat retention and thermoregulation with the presence of fur

With the addition of a fur coat to humans, there will be a significant increase in the amount of thermal insulation. In addition, fur inhibits evaporative cooling by trapping the sweat. This increase in insulation must be addressed to prevent catastrophic overheating during exercise or when at rest in normal environments.

### Box : Measures of insulation

In the literature, clothing insulation is usually measured in the unit *clo*, which is a non-SI unit. It can be converted into SI units using the definition:  $1 \text{ clo} = 0.155 \text{ K m}^2 \text{ W}^{-1}$  (Kelvin meter squared per watt). This unit is dimensionally equivalent to the R-value often used in house construction, and represents the temperature difference (K) per unit of heat flux ( $\text{W} / \text{m}^2$ ).

Higher *clo* values indicate a reduced ability to conduct heat, and as such warmer clothing. As such, for our purposes, we should aim to lower the *clo* values of fur such that it becomes easier for the human body to cool down.

The thermal insulation of fur can be expressed in terms of the *RSI-value*, which defines the temperature difference (in K) per heat flux (in  $\text{W}/\text{m}^2$ ) required to sustain one unit of heat flux. In practical terms, this means that a material with a high RSI-value is more insulative than one with a low RSI-value.

### 1.6.1 - Insulative values of different types of animal fur

The structural properties of fur differ between species, leading to different insulation values. The amount of heat retention and risk of inducing heat stress by fur therefore depends on the type, thickness and composition of the fur, and this should be taken into account when designing a fur coat. For example, visually pleasing coats may be engineered with less

insulative values by leaving out less-visible parts of the design, such as all or part of the undercoat.

A list of physically measured values for various animal coats is published in [Hammel, 1955](#). Most fur coats have insulative values in the range of 4.0-4.4 clo/inch, with some outliers reaching down to 3.3 clo/inch and up to 4.7 clo/inch. The total insulative value of a coat, however, differs more substantially between species, due to a difference in fur length. This suggests that the main way in which species differ in fur insulation comes from differences in fur length rather than composition, and is useful to know in our design for fur coats for humans. It highlights that using shorter fur will generally lead to less insulation overall. Of course, this can have aesthetic impact, and as such a balance must be struck.

### **1.6.2 - Leaving a small part of the body bare has a large impact on heat survivability**

Human beings have evolved to survive with little to no fur. Our sweat glands provide essential cooling in warm environments. In colder climates, humans wear extra clothing to keep warm. However, when wearing warm clothes on a warm day, overheating can pose a significant health risk, and in the worst cases, can result in heat stroke or death. The practical solution, obviously, is to reduce the amount of clothing worn on a hot day.

However, since our aim here is to grow fur on human skin, removing this layer of insulation no longer becomes an option. Furthermore, sweating may reduce efficient cooling under fur, due to a potentially limited ability of the evaporated water to leave the insulated layer. As such, it is essential for us to assess the risk of overheating the human body inside a permanent fur coat, and what limits this imposes on the fur coats we can engineer.

To assess this risk, we will consider a simple model of heat transport, under normal circumstances, without clothing, and with an added fur coat. We aim to find the amount of extra heat that is retained under a fur coat, and to assess strategies to dissipate this extra heat.

This model is not meant to answer more detailed questions, and omits various important aspects such as convection of heat within the human body. It is meant as a *back-of-the-envelope* calculation, as part of our feasibility study about adding permanent fur coats to the human body, and only yields the order of magnitude of extra heat that we can expect to need to dissipate. It is deliberately kept simple for that purpose.

From this model, we can infer the necessity of adding cooling strategies to aid in heat dissipation during exercise and when idling.

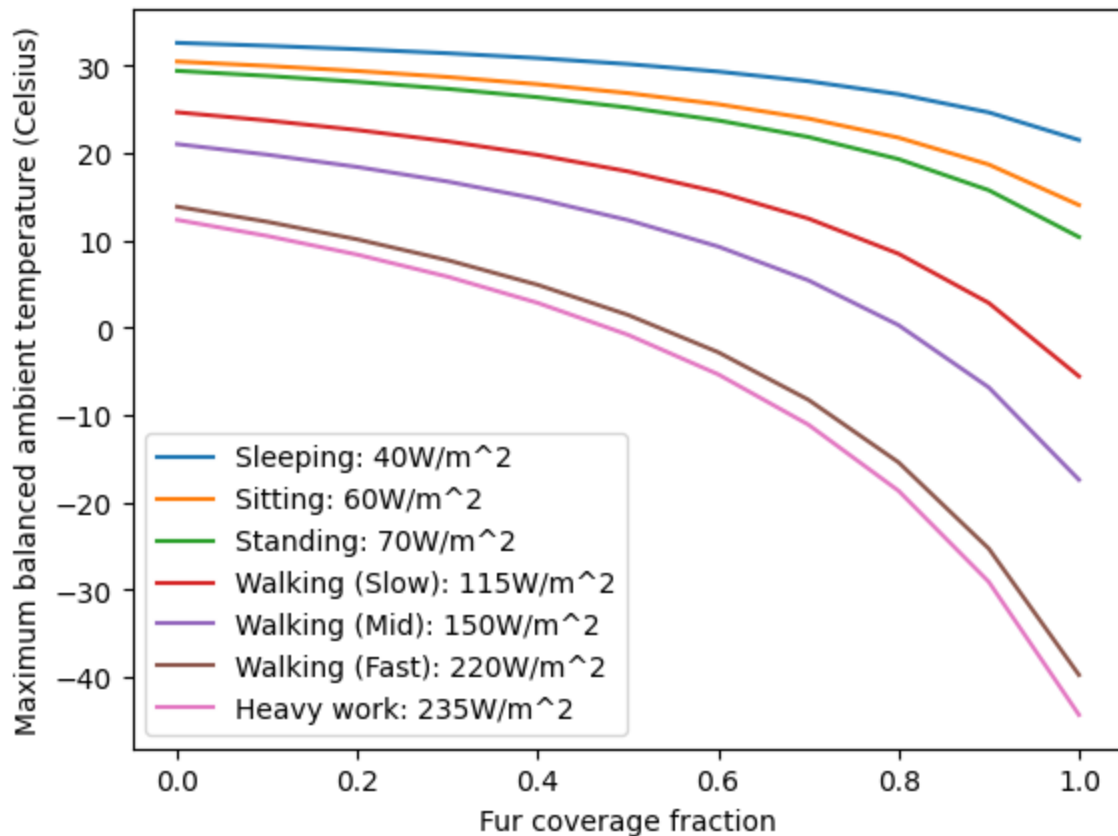


Figure 1.10: Image from [heat transport of spherical furry.ipynb](#) . The left side, at  $x=0.0$ , represents a naked human being. Furred anthropomorphs realistically reside in the region between 0.6 to 0.95, as they will never have 100% fur coverage due to the nose, eyes, mouth, and paw pads being exposed skin.

The graph above shows the ambient temperature at which the human body maintains its internal body heat without overheating, in absence of sweat, and with varying degrees of fur coverage. In principle, ambient temperatures that exist above the plotted graph will lead to overheating, and can only be withstood for a limited amount of time. As such, the higher the graph curve, the more ambient temperatures the anthro can survive. As can be seen, even leaving a small amount of skin exposed leads to a drastic increase in the ability to survive warmer ambient temperatures. This fact can be used in our engineering strategies.

Please note that this graph considers a uniform coat of thick fur, even in places where thin fur is expected, such as the face. More realistically, there will be less total insulation of the body, and as such, this graph represents a worst-case scenario.

### 1.6.3 - Mitigation strategy: furred animals expel heat through exposed vascularized surfaces

To cool down, many furred animals utilize specialized, highly vascularized and sparsely furred regions on the skin to quickly transport heat away from the body. Such regions often occur inside the ear shells, such as in the fennec fox.

The human body also increases the blood flow towards the skin when it tries to cool down. This provides a relatively easy method to cool the body. However, for this strategy to be effective, blood circulation must be taken into account, to ensure that the heat can properly be transported from the warmer areas of the body to the site where heat is expelled, which should be part of future research.

#### **1.6.4 - Mitigation strategy: sweating still occurs and is effective in certain fur types**

Although generally, sweat glands are not present in densely furred regions, some furred animals do sweat through their fur, such as horses ([Evans & Smith, 1956](#)). This indicates that sweating is indeed a viable strategy in at least some fur types. Even so, more research is needed to assess the effectiveness of this type of cooling, as well as its applicability in fur types with a dense undercoat, such as those in wolves or foxes. Although unlikely, in the worst case scenario, moisture may cause air to be trapped more efficiently, and by extension increase the insulative value of the fur type. This would lead to a positive, rather than negative, regulation of heat, and as such would lead to catastrophic heating.

At least one model has been proposed to assess the effectiveness of using water to cool down the fur of cows ([Gebremedhin & Wu, 2001](#)), which concludes that for cows, such a strategy is indeed effective.

#### **1.6.5 - Apocrine sweat glands may have different cooling properties than eccrine sweat glands**

**Apocrine** sweat glands are sweat glands closely associated with the hair follicle itself. The sweat is deposited directly inside the hair follicle tract and drawn up the hair strand, presumably through capillary action. **Eccrine** sweat glands, however, are those sweat glands that are between hair follicles, and lack the association. As such, the sweat that is produced by these different types of sweat glands, even if they are identical in chemical composition, will cover a different surface. This may affect the cooling rates induced by each of these glands.

Although evaporative cooling of water only depends on the amount of water evaporated, the geometric organization of the wetted surface can have a significant impact on total cooling rates. For example, water does not vapourize as efficiently in environments that have higher humidity, and when the air is saturated, will not vapourize at all. By being carried up the hair strand, apocrine sweat may more quickly transport the heat away from the body and towards air that is not yet saturated by water vapour, increasing the effective cooling rate. This requires further research to confirm.

Humans have both eccrine sweat glands (mostly across the body) and apocrine sweat glands (e.g. in armpits). Horses, who are known to sweat through their fur, also have apocrine sweat glands, and primarily use those for sweating ([Porter, 2001](#)). This indicates that there may be an evolutionary advantage to using apocrine sweat glands over eccrine sweat glands when cooling fur, although this is also only a hypothesis.



### **1.6.6 - Blocking radiation from sunlight can avoid buildup of heat**

Fur, in some cases, can act to prevent heating. Sunlight causes intense heating of surfaces, and fur can act as a boundary that keeps this heating away from the skin surface. For preventing absorption of heat in the body with this method, hair must either:

1. Reflect a substantial amount of sunlight, rendering it lighter in colour without being transparent; or
2. Act as a buffer by absorbing sunlight without transmitting it to the lower layers.

The effects of this can be modelled and depend highly on the environment, as well as the type of fur used. This will be part of our future modelling work to ensure adequate heat management properties of nonhuman integument on the biologically human body.

## **1.7 - Mechanical properties of strands affect the look and feel of fur**

### **1.7.1 - Hair strand strength is influenced by strand thickness and may nontrivially affect geometric properties**

Hair strands are remarkably strong, in part due to their elastic properties. It takes a substantial amount of force to snap a hair strand, and when bundled enough, hair can easily sustain the weight of a car.

The strength of any homogeneous elastic material increases proportional to its cross-sectional surface area. It comes to reason, then, that the mechanical strength of the hair strand is roughly proportional to the strand's thickness squared. Although the exact relationship may depend on additional factors, and its nonlinearity may be empirical, it remains important to take thickness into account when predicting mechanical properties, such as the hair strand's persistence length ('floppiness'), curliness, or the like. For example, counterintuitively, the tensile strength of hair has been found to negatively correlate with the thickness of the individual strands ([Yang et al., 2020](#)). As such, we must not assume that the general geometry of a hair strand remains qualitatively similar when we scale up the width of a hair strand.

As well, the different layers of hairs (the medulla, cortex, and cuticle) necessarily have different mechanical properties. Generally, a thick medulla is associated with straight and brittle hair, whereas a more prominent hair cortex is associated with greater flexibility and tensile strength ([Singh B, Veterinary Anat 5ed, p344](#)).

### **1.7.2 - Strength is also related to the degree of crosslinking within and between keratinized cells**

Even so, hair strands of varying stiffness exist in nature, some of which may not differ in width. Another mode of modulation of hair strength comes from the degree of crosslinking within and between keratinized cells, which modulates the hardness (Young's modulus) and tensile strength of a hair strand directly.

Interestingly, hairs in humans that have turned white from age appear to be stiffer and more fragile ([Duvel et al., 2019](#)). We are not aware of any studies that have investigated the molecular or cellular cause of this difference in tensile properties. However, it is relatively unlikely that the lack of pigment cells directly affects strength, and so the loss of pigmentation is probably correlated with additional variables associated with age and follicle status. Despite this likelihood, we will evaluate the effect of pigmentation on artificially grown hair for purposes of transplantation to ensure that any strategy to whiten hair, when required, does not significantly affect the strength of the resulting coat.

## **1.8 - Natural behaviours for maintenance and care of fur in animals**

Grooming behaviours such as licking and combing aid in cleaning, and sometimes heat dissipation. While many animals groom themselves, such as canines' and felines' licking, there are other animals that groom each other instead throughout adulthood. This is particularly apparent in primates, such as lemurs and monkeys, who comb and pick each other as part of their social behavior, removing parasites. Animals with fur have evolved to perform these activities regularly, while humans have not; flexibility for reaching places with the tongue and the ability to shake out the coat are not genetically coded into our skillset.

### **Mat formation, removal and prevention**

Mats can form naturally in certain coat types — specifically when the fur is longer and curly, such as in poodle mixes and sheep or even long-coat cats, though they can form in other coat types when unkempt.

Mats are overgrown knots in fur that typically start as smaller tangles towards the ends of the fur, but grow in size as more fur gets tangled in, and grow closer to the skin as they accumulate. Mats cause great discomfort for the individual, especially while being removed; they can occasionally be clipped out, but usually require shaving when close to the skin.

To prevent mats, regular brushing is required. On some animals, mats form specifically in certain places, especially those that experience friction or have fur going different directions: behind the ears and near the legs for some dogs, on the hips and back towards the hindquarters for some cats, etc. Where these mats may form on 'humans' with fur is unknown. It is likely, however, that it would occur more often in spots that experience a lot of rubbing, such as between the thighs, the sides of the neck, the armpits, and the lower back and butt, due to the way that we sit.

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