ChatGPT

Procedural Generation Rules for Barchan Dune Fields

Hierarchical Multiscale Structure of Barchan Dunes

Barchan dune systems exhibit a distinct hierarchy from the field scale down to individual dune features. At the largest scale, barchan dunes often organize into **dune fields or corridors** that stretch for tens of kilometers under persistent winds [1]. Within a field, dunes tend to be distributed fairly uniformly in space, with each region often dominated by a characteristic dune size [1] [2]. Dunes are typically **isolated crescent shapes** separated by interdune areas of exposed ground (e.g. desert pavement or bedrock) – a result of the limited sand supply that prevents a continuous sand cover [3]. In some cases dunes cluster in narrow belts (e.g. between topographic obstacles), forming **corridors** of barchans oriented along the wind direction [4].

At the intermediate scale, each **individual barchan dune** is a **crescentic mound** of sand. It has a gently sloping **windward (stoss) side** and a steep **lee side** (slip face) on the concave downwind side [3] [5]. Two **horns** (tips of the crescent) extend downwind from the main dune body [5]. The horns are usually lower in height than the dune's central crest and taper out toward the desert floor. An accumulation of sand at the dune's brink leads to the development of the slip face: when the brink's slope exceeds the **angle of repose** (~32–34° for dry sand), avalanches occur and a steep slipface is maintained [6] [7]. The upwind stoss slope is much gentler (often on the order of 10–15°) as sand is pushed up by wind [8]. The horns themselves often have very low relief and trail out almost to the level of the interdune surface.

At the smallest scale, **surface textures** and sub-features appear on barchan dunes. The stoss side is typically covered in **wind ripples** (small transverse ridges of sand) that are superimposed on the dune surface. These ripples often run roughly perpendicular to the wind direction and indicate active sand transport across the dune's surface. On the slipface, the sand surface is smoother, interrupted occasionally by avalanche scars or slide lines from recent grain falls. Interdune areas in barchan fields are commonly flat or gently undulating surfaces of harder ground. They may feature coarser lag deposits (gravel or crust left behind as wind removes finer sand) and sometimes minor sand sheets or ripples in areas where sand is temporarily deposited. In some desert settings, interdunes can even host playa lakes or crusts if moisture accumulates, but in a classic barchan field the interdune is usually a wind-scoured, arid surface. This multiscale structure – **dune field → individual dune → slipface/horns → ripples** – gives barchan systems a rich texture that a procedural model must capture.

Physical Drivers and Controls on Barchan Formation

Barchan dunes form under a specific suite of environmental conditions. **Wind regime** is the primary driver: barchans develop under strong, nearly unidirectional winds that blow consistently from one prevailing direction [3]. The persistent wind causes sand to accumulate into crescent shapes whose horns point downwind, indicating the consistent transport direction [9] [10]. If the wind direction varies widely or has multiple prevailing directions, barchan dunes cannot maintain their characteristic shape – instead, dunes might become longitudinal (seif) or star dunes under multi-directional winds. In fact, a slight secondary wind can induce asymmetry by elongating one horn, or can stretch barchans into more linear forms [10]. Thus, a **narrow unimodal wind regime** is a critical control for barchan morphology.

Another key factor is **sand supply**. Barchans occur in areas of **limited sand availability** – there is enough sand to form dunes, but not enough to cover the ground fully [3] [11]. Under these conditions, dunes remain isolated and surrounded by largely sand-free surfaces. If sand supply increases, individual barchans can link and merge into transverse dune ridges (barchanoid ridges), eventually forming continuous dune sheets [12]. Thus, sand scarcity is what keeps dunes as separate crescents. The substrate often plays a role as well: barchans are typically found on **firm, non-erodible ground** (hardpan, desert floor, or rock) that provides a stable base over which sand can blow without the ground itself yielding more sand [11]. A flat or gently sloping terrain is ideal; significant slopes or rough terrain disrupt the wind flow and sand transport, preventing classic barchan shapes.

Surface roughness and vegetation are important controls insofar as they remove or add momentum from the wind and can anchor sand. Barchan fields are usually **un-vegetated**, since plants would stabilize dunes and lead to different forms (e.g. parabolic dunes when vegetation anchors the horns). Similarly, a very rough surface or obstacles can create wind shadows where sand drops out. In procedural terms, one might treat the ground as a mostly smooth plane with minimal roughness so that dunes move freely. If needed, obstacles could be introduced to force local dune clustering or deviations (for example, dunes accumulating in the windward side of a hill or crater as seen in the Aorounga crater example [4]).

Grain size and sand characteristics also influence barchan formation. Barchans are typically made of **well-sorted medium sand** (often quartzose) that is easily moved by wind but heavy enough to accumulate. Very fine sand or dust tends to be transported farther (forming loess deposits rather than dunes), whereas very coarse sand or gravel requires stronger winds and often forms different bedforms. In modeling, one can assume a representative grain size (e.g. ~0.2 mm) which yields a certain threshold wind speed for transport. The **threshold friction velocity** for initiating sand movement (per the Bagnold or Sørensen law) and the **sand flux** will determine where dunes can form and how they behave. Moisture is typically minimal in barchan settings (arid deserts), because even slight moisture can cause sand to cohesively clump and resist saltation. Dry conditions ensure sand grains are freely mobile. If a procedural model includes a moisture parameter, it should be set to near zero to generate classical barchans; higher moisture could transition the model toward parabolic dune shapes (with fixed upwind “arms” where wet sand/vegetation anchor the dune).

In summary, to generate realistic barchan dunes, the model should enforce: **one dominant wind direction**, **low sand coverage (sand is present in patches)**, **flat, smooth ground with minimal vegetation**, and **dry, loose, sand-sized grains**. These controls create the environment where crescent dunes naturally emerge.

Time-Evolution Dynamics of Barchan Dunes

Barchan dunes are not static – they are mobile landforms that evolve over time through interactions and movement driven by wind. Any generative framework should include **rules for dune migration and morphologic change** to capture their dynamics.

Dune migration: Barchans **gradually migrate downwind** as sand is transported from their stoss side to their lee side. Wind pushes sand up the gentle windward slope; once sand reaches the crest and exceeds the angle of repose, it avalanches down the slipface, effectively moving the dune forward. This continuous cycle causes a net displacement of the dune in the wind direction [13]. A key characteristic is that **migration speed is inversely related to dune size** – small barchans move faster than large ones [13] [14]. This is because a smaller dune has less sand volume to redistribute, so a given wind flux can move it more quickly. Field measurements confirm that relationship: for example, 2–5 m tall barchans in Mauritania migrated at rates consistent with $c = Q_0/H$, where c is celerity, H is dune height, and Q_0 is an empirical sand flux constant (~50 m^3/m/yr in that field) [15]. In general, **dune celerity** $c \propto 1/H$ (or similarly $c \propto 1/\sqrt[3]{V}$ where V is volume). Real-world migration speeds are on the order of meters to tens of meters per year: e.g. large barchans (~20 m height) might move ~5–10 m/yr, whereas very small ones (~1 m height) can sprint at >50 m/yr given strong winds [16]. In extreme cases like the Namib Desert's strong winds, some small dunes were observed moving ~83 m in a year [17]. For modeling, one can implement migration velocity as $v(H) = \frac{C}{H}$, where C is a constant set by wind strength and sand supply (with randomness or seasonal variation superposed if desired).

Horn extension and shape maintenance: As a barchan moves, its shape tends to remain self-similar, but subtle changes occur. The **horns elongate or shorten** in response to sand distribution and wind flow. Because the dune's edges (horn tips) are lower in height, they experience faster horizontal movement (lower H → higher c) [18]. This causes horns to **stretch out downwind** over time. If sand supply to the horns is plentiful, they can grow longer and thinner. If a horn becomes sand-starved or the wind shifts slightly, it may stall or even get "amputated" (leading to calving, described below). In a steady wind and constant supply, a mature barchan reaches an equilibrium shape where horns extend to a length that the available sand flux can sustain. The **horn length** L_h often scales with dune width; field data suggest larger dunes have disproportionately longer horns (positive allometry) [19] [20], until some process intervenes.

Avalanching and slipface dynamics: On short timescales, the slipface undergoes cycles of sand accumulation and avalanching. When wind brings sand to the brink faster than it can stabilize, a small landslide occurs down the lee. These avalanches typically maintain the slipface at ~33° slope (the static angle of repose) [7]. In a simulation, one might implement a rule: *if local lee slope > 34°, trigger avalanche downwind until slope* $\approx$ *33°*. This rule keeps dune profiles realistic and allows dunes to adjust shape as they migrate.

Dune collisions and merging: Barchan dunes in a field can **interact when they come close together.** A faster-moving smaller dune can catch up to a larger, slower one in front of it. Several outcomes are possible depending on their sizes and alignment: - **Solitary-wave passing:** Often observed is that the smaller dune **overtakes and passes through the big dune**, emerging on the other side with nearly the same size, while the big dune may lose some mass or slow down [21]. This astonishing behavior, likened to solitons, happens when the small dune essentially climbs up the back of the big dune and reappears downwind. - **Merge (Coalescence):** If two dunes of more comparable size collide or a smaller one doesn't pass completely through, they can merge into a single larger dune. The combined dune conserves the sand volume of both (minus any loss to the interdune area). Mergers can temporarily create irregular shapes (e.g. an elongated dune or a transient ridge), which then relax back into a crescentic form. - **Exchange and fragmentation:** During collision, dunes may exchange sand. The upstream dune might lose some volume to the downstream one. In some cases, a piece of the smaller dune can be left behind (a sort of "fragment") that becomes a new, even smaller dune.

These interactions act as a **size-regulation mechanism** for the dune field. Collisions tend to even out sizes by sand exchange, but also introduce fluctuations. For modeling collisions, rules can be set such as: *if a faster dune approaches a slower dune within a certain distance, then trigger an interaction*. Possible interaction rules: - If volume_ratio is large (tiny dune hits big dune): small one simply overtakes (passes through) with minor volume transfer. - If volume_ratio is ~1 (similar size dunes collide): combine volumes and form one dune (merger) or an intermediate scenario where one dune absorbs the other. - If volume_ratio is intermediate: small dune climbs on big dune, big dune loses a portion of sand which forms a new small dune ejected forward (simulating a partial pass-through with a "calf" ejected).

Calving (horns shedding new dunes): Barchan dunes have a remarkable ability to **spawn new dunes from their horns**. When a barchan grows large (beyond some width W_c), its elongated horns can become unstable and **"calve" off small dunes** at their tips [22] [23] . Essentially, the horn accumulates a packet of sand that becomes an independent mobile dune, which breaks away and migrates faster out of the horn. This process is frequently observed and is a major source of smaller dunes in a field [24] . Calving helps limit dune size: as soon as a dune gets too large, it sheds mass as baby dunes, reducing its volume [25] [26] . In a procedural model, a rule for calving could be: *If dune width > W_c (a threshold, perhaps ~some multiple of saturation length or empirical value), then generate a new small dune at the tip of a horn and subtract that volume from the parent.* The new dune's volume might be a fixed fraction of the parent's (e.g. 5–10% of parent volume) [27] , and it inherits the position at the horn and an initial speed (often faster than the parent). Calving usually happens at one horn (sometimes triggered asymmetrically by wind gusts or collisions enhancing one horn's growth [28]). The result is a **swarm of small dunes** downwind of large ones, which is commonly seen in real fields (small dunes trailing in the "wake" of big dunes).

Over time, these dynamics lead to a sort of **steady state** in active barchan fields: dunes migrate, occasionally collide or calve, and sizes get recycled. There is evidence from both nature and modeling that such fields reach a dynamic equilibrium with a roughly stable size distribution and spacing [29] [30] . For example, small dunes continually appear (from calving) and disappear (by merging into larger dunes or leaving the field), while larger dunes oscillate around a quasi-stable size by shedding calves when they grow too big. This balance prevents unlimited growth and maintains the characteristic "size gap" between typical barchans and the very largest dunes or proto-transverse ridges.

In sum, a physically accurate model should incorporate: - **Migration** proportional to $1/$ size. - **Slipface avalanching** to enforce the angle of repose. - **Horn advancement** (faster motion of low areas) to extend horns. - **Collisions** with rules for passing, merging, or sand exchange. - **Calving** of new dunes from horns once dunes exceed a size threshold. - **Volume conservation** (sand is neither created nor destroyed, just moved or partitioned among dunes and the ground). Any sand that leaves a dune (by calving or being shaved off in a collision) should either be gained by another dune or left as a thin sheet in the interdune area.

These time-evolution rules allow a generative simulation to not only create a static image of a dune field, but also to *evolve* it, ensuring the snapshot is consistent with realistic dune history.

Static Generation Rules for a Barchan Dune Field Snapshot

When constructing a single snapshot of a barchan dune field (without explicitly simulating the full dynamics), we need rules to place and shape dunes so that the scene is **geologically plausible** at that frozen moment. The goal is to capture the **spatial patterns** and **morphological variations** one would expect in a real barchan field.

Field layout and dune spacing: Orient the entire field with a given wind direction D_w . All dunes should face the same way: their horns point downwind (i.e. oriented along D_w). Choose a region size and dune **density** consistent with the sand supply. A more sand-rich field will have dunes covering a larger fraction of the ground (densely packed, perhaps even touching horns occasionally), whereas a sand-poor field will have widely separated dunes in clusters or "corridors" with vast bare areas between patches [31] [32]. As a baseline, **space dunes roughly 1–3 dune-widths apart** from one another. This prevents dunes from overlapping unnaturally, while not spacing them so far that they appear unrelated. Empirical analyses suggest that within a given field, interdune spacing tends to be surprisingly uniform and uncorrelated with dune size (owing to the field's self-organized dynamics) [2]. For a static model, an approximate rule is: *compute an average spacing L_s based on an assumed dune density*, and then place dunes such that the centroid-to-centroid distance is around L_s (with some random variation). If generating procedurally on a grid, one could use a Poisson disk sampling approach to ensure a minimum spacing between dune centers.

Dune size distribution: Assign each dune a size (e.g. width or volume). Natural barchan fields often exhibit a **right-skewed size distribution** – many more small dunes than large ones – roughly resembling a log-normal distribution [33]. However, there is usually a **characteristic size** that is most common, controlled by wind and sand supply conditions [1] [33]. For example, one field might predominantly have 50 m wide dunes with some smaller ones (~20 m) and a few larger (~100 m). Another field (with more sand) might center around 150 m wide barchans. To implement this, pick a mean or modal width W_{mode} and a standard deviation such that $W_{\min}$ and $W_{\max}$ are within realistic bounds (e.g. smallest barchans ~5–10 m wide, largest isolated barchans ~300–400 m wide at most). Sample each dune's width from that distribution. **Height and length** can then be derived from width using morphological scaling relationships (see **Formulas** section). Ensure that heights are all below the stable limit for dunes (which is usually governed by the saturation length of sand transport – on Earth typically dunes max out around 20–30 m high for barchans).

Orientation and shape variance: While all dunes have their slipfaces roughly perpendicular to the wind, introduce slight orientation noise (a few degrees variation) or gentle curvature in dune crestlines for natural effect. In real fields, local wind deviations or interactions cause some horns to slightly twist or some dunes to be a bit askew. One horn may be longer than the other on some dunes – introduce some **asymmetry** by extending one horn an extra percentage of the mean horn length (e.g. +20%) and shortening the opposite horn (−20%) for a subset of dunes. This can be randomly assigned or correlated with neighbor interactions (e.g. if a smaller dune is immediately downwind off-center, it might have nudged one horn of the larger upstream dune to grow longer). Also, if dunes are near obstacles or field edges, their shape might skew (the horn nearer an obstacle could be shorter due to sand shadowing). A procedural trick is to allow a random "asymmetry factor" per dune that skews its shape left or right.

Interdune surface and small-scale features: Between dunes, the ground can be generated as mostly flat, possibly with a lighter color or different texture to distinguish it as sand-poor. Adding noise to simulate crusty soil or scattered pebbles can increase realism. Also consider adding **smaller sand patches or mini-dunes** in the interdune areas: for instance, tiny barchanettes or dome dunes can exist in the wakes of big dunes (remnants of calving or unformed accumulations). Including a few sand sheets or ephemeral ripples in low-lying interdune zones (especially downwind of large dunes where some sand might spill over) gives the scene authenticity.

Clustering and patterns: If simulating a **corridor**, you might concentrate dunes in a band. For example, dunes could be aligned in rows. Observations show barchans sometimes align in a staggered array: one row of dunes with another row offset downwind, creating a quasi-hexagonal packing when viewed from above (each dune flanked by neighbors off to its rear-left and rear-right). This arises from the aerodynamic wake of dunes funneling sand to certain zones [32] [34]. To mimic this, one can position dunes in semi-regular patterns: e.g., create a line of dunes, then a second line downwind offset such that dunes of line 2 sit in the gaps of line 1, and so on. Then apply random jitter to all positions to break perfect order. Also, allow for a **gradient of sizes** if applicable: sometimes upwind in a field you get smaller dunes (recently formed or regenerated) and they gradually grow larger downwind before perhaps shrinking again if they starve. This downwind size grading can be implemented by correlating dune size with position (e.g. increase mean size with distance into field, then maybe decrease near the very end if sand is depleted).

Windward vs leeward of field: If the synthetic domain has an upwind boundary (like an upwind edge where sand is coming from a source), you might want to leave the far upwind area mostly sand-free or with only embryonic dunes (since barchans often initiate where a sand influx starts). The main field would lie a bit farther downwind after sand has had a chance to accumulate into dunes. At the far downwind end of the field, if sand truly runs out or dunes exit the field (perhaps migrating into a vegetated area or a topographic trap), you might thin out the dunes again. These nuances depend on the scenario being modeled.

In summary, the static generation procedure is: 1. **Define wind direction** and field extent. 2. **Determine dune count and size distribution** based on sand supply (total sand volume in field) and desired dune density. 3. **Place dune centers** using a spacing rule (e.g. no centers closer than a certain distance; possibly use random sequential addition or Poisson-disc sampling). 4. **Assign each dune a width, height, length** (with height ≈ constant * width, etc.) and initial perfect crescent shape (symmetric horns). 5. **Orient dunes** perpendicular to wind and align horns downwind. 6. **Apply asymmetry or variation**: tweak horn lengths or dune orientation slightly per dune. 7. **Ensure no overlaps**: if dunes overlap or one's slipface intersects another's volume, adjust positions or remove one to mimic natural avoidance (dunes in reality can collide, but at any given snapshot, you usually don't see them literally overlaying; they'd be merging rather than ghosting through each other). 8. **Add small dunes or sand patches**: sprinkle a few very small dunes in between (especially downwind of big ones) to represent calves or recently formed dunes. 9. **Add surface textures**: ripple patterns on stoss slopes (could be simulated via a smaller-scale procedural noise or repeating pattern aligned perpendicular to wind), smoother slipfaces (perhaps uniformly sloped with little noise), and a different texture/colour for interdune ground.

Using these static rules will result in a snapshot that "looks right" – dunes of plausible sizes and shapes, spaced in a way that is neither too regular nor too random, all consistent with having been shaped by the same wind and limited sand.

Key Formulas and Scaling Relationships

Including quantitative relationships ensures the model remains grounded in real physics and geomorphology. Here are some key formulas and typical values relevant to barchan dunes:

- **Dune migration velocity:** A simple migration law is $**c = \frac{Q_0}{H}**$, where c is the dune's downwind speed, H is its height, and Q_0 is an effective sand flux (volume per unit width per time) available to move the dune [15]. This captures the inverse dependence on size – e.g. for one field

$Q_0 \approx 50\ \mathrm{m^3/m/yr}$, a 5 m tall dune would move at ~10 m/yr while a 1 m tall dune moves at ~50 m/yr [15] . In a model, Q_0 can be tuned to represent wind strength (higher Q_0 for stronger winds drives faster movement).

- **Flux continuity and volume conservation:** As a dune migrates, it should maintain volume if no sand is gained or lost. Volume V can be approximated for a barchan as a function of width W (distance between horns) and height H . Empirically, **dune volume scales with the cube of a linear dimension**, since shapes are roughly similar [35] . For example, $V \approx \alpha W^3$ for some proportionality α (or likewise $V \sim H^3$, since H ~ constant fraction of W). Calibration from real dunes might give α such that a 100 m wide, 10 m high dune contains on the order of 10^4–$10^5\ \mathrm{m^3}$ of sand. Volume conservation means if a dune calves or two dunes merge, the sum of volumes before equals sum after (aside from a small loss that might be distributed as low-amplitude sand sheets). This can be implemented by transferring volume between dunes in collision rules or by explicitly keeping track of a global sand budget.

- **Height–Width–Length relationship:** Barchans maintain a consistent shape aspect ratio in steady conditions. A common approximation is **height is about 1/10 to 1/20 of width**. Field examples: dunes 10–100 m wide and 1–10 m high are typical [36] . More precisely, one could use $H = k * W$ (with $k \approx 0.067$ as one literature value giving ~6.7% of width [37]). The **length (along wind from upwind foot to slipface brink)** is often about the same order as width (perhaps a bit less since barchans are wider than long). If needed, formulas like $L_{\text{dune}} \approx 0.8W$ could be used, or derived from the shape assumption (some studies define length from crest to horns tips, etc., but for simplicity using body length ~ width is fine). The **horn lengths** can be parameterized as a fraction of width as well: for a symmetric barchan, each horn might extend roughly 1–3 times the dune height beyond the slipface. In absolute terms, small dunes often have short horns, while large dunes develop relatively longer horns. A rule of thumb from observations is that **horn length** L_h grows faster than dune width (positive allometry) [19] . You might set $L_h \approx \beta W$ with β increasing slightly with W or just pick a representative value (e.g. $\beta\ 0.5$ for average cases, meaning each horn ~50% of the dune width in length).

- **Slipface slope:** The lee slope should be maintained at the **angle of repose** θ_r of dry sand, roughly **33°** (tan $\theta_r \approx 0.65$). This isn't a variable but a constant: if modeling the cross-section, enforce that the slipface segment has slope = $tan(33^\circ)$. In a heightmap representation, one could ensure no cell on the slipface exceeds this critical slope by cascading any surplus material downward (simulating avalanches) until the slope is ~0.65. The stoss slope, by contrast, will be whatever emerges from the equilibrium between wind transport and sand supply (usually ~5–15°). Some models use an exponential profile for the stoss based on the concept of **saturation length** of sand transport [38] [39] , but for a snapshot an acceptable simplification is to shape the stoss as a smooth convex-up curve from ground to crest, peaking at ~10–15° near the crest.

- **Saturation length & minimum dune size:** There is a concept of **minimum barchan size** governed by the wind's saturation length ℓ_s – the distance required for moving sand to reach equilibrium flux [38] . On Earth, ℓ_s is on the order of tens of meters, which coincides with the smallest observed dunes (~a few meters high, ~15–20 m across) [40] [5] . In practical terms, one can enforce a minimum width (e.g. ~10 m) in the model, since anything smaller might not be stable as a dune (it would be just a sand sheet or proto-dune quickly caught by wind).

- **Horn curve and planform shape:** The planform of a barchan (as seen from above) can be approximated with simple geometric curves. Some models use parabolic or circular segments for the horns. For instance, the dune's crestline could be modeled as part of a circle or cosine curve, and horns might follow exponential decay curves. While not a single "formula", a possible representation is:

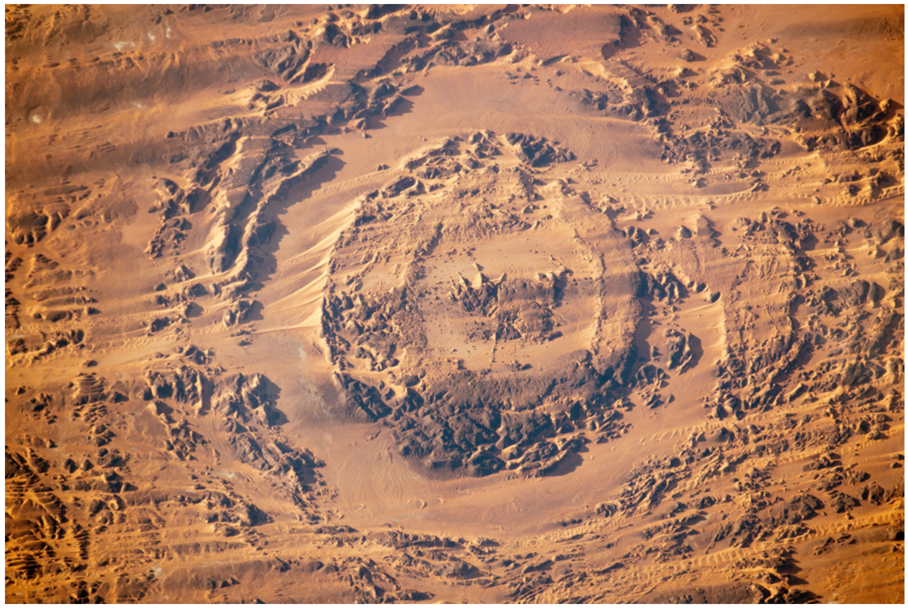
- Define dune center at (0,0). Let dune width = W, height = H.
- The outline could follow $y(x) = a\cos(\frac{\pi x}{W})$ for $-W/2 \le x \le W/2$ to represent the crescent (with $y = 0$ at horns and $y = a$ at the crest).
- Horns themselves can be tapered so that their height drops from H at the attachment to ~0 at the tips over some length L_h . For example, height along horn could linearly decrease: $h_{\text{horn}}(s) = H(1 - s/L_h)$ for $0 \le s \le L_h$ along the horn centerline.

These are implementation details; the key is to maintain that horns are slender and approach the ground at their tips, and the brink-line (boundary between stoss and slipface) is roughly an arc connecting the horn tips through the crest.

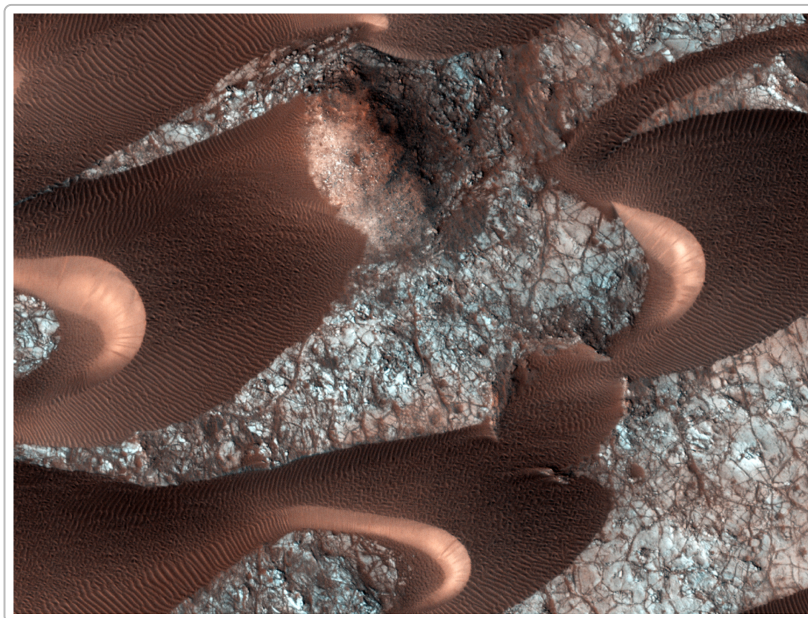
- **Wind transport formulas:** If needed for more fidelity, include Bagnold's transport equation or a similar formula: $q = C(\tau - \tau_c)$ for shear stress above threshold, which leads to the flux on stoss. However, for image generation, it might be overkill to solve wind flow. Instead, ensure qualitatively that more sand accumulates on the lee and less on the horns (horns are often thinner because some sand is shed off their sides).

In summary, incorporating these formulas ensures quantitative correctness: - *Use $v = C/H$ for velocity. - Maintain slipface ≈ 33°. - Set $H \approx (5–10)$. - Volume $\propto W^3$* (so if you double width, volume increases 8x, which matches dune mass scaling). - *Horn length ~ some fraction of W,* possibly increasing with W. - *Spacing roughly proportional to dune size (at least on the order of W).* These relationships will guide the proportions of your synthetic dunes to match real-world analogs.

Visual Examples and Spatial Layout Reference



Barchan dunes clustered in a corridor around the Aorounga crater (Chad). Small crescent dunes occupy a narrow band between rocky hills (the crater rims). The horns of each dune point SSE, indicating consistent NNW-to-SSE winds. Larger dunes (with wider, more pronounced crescents) can be seen maintaining spacing as they migrate; measurements over 10 years show they moved a few hundred meters SSE [41]. Smaller dunes are also visible, some trailing just downwind of larger ones, likely formed by calving [24]. This satellite/astronaut image illustrates typical field organization: dunes align with wind and are separated by interdune flats, with a relatively uniform density. [4] [42]



High-resolution view of barchan dunes at Nili Patera on Mars (HiRISE image). Several crescent-shaped dunes are shown from above. Each dune has a gentle upwind slope (covered in fine sand ripples) and a sharp slipface on the downwind side (the brightly illuminated concave slipfaces). The horns extend downwind and are lower in elevation – note how the horn tips almost blend into the surrounding flat surface. Smaller secondary ripples are superimposed on the dune surfaces (visible as fine ridges on the stoss slopes and even on the slipfaces). This image highlights the multiscale structure: large dune bodies with ~crescent planform, and meter-scale ripples on their surfaces. It also shows slight asymmetry – for instance, one dune's right horn is a bit more elongated, possibly due to local wind shifts or interaction with the adjacent dune. [5] [7]

These examples provide guidance for how to arrange and visualize the dunes in a generated scene. In the first image, we see that dunes are not randomly strewn – they form an ordered pattern aligned with wind and constrained by geography (in this case, a crater creates a corridor). Dune fields often have such **semi-ordered patterns**, which a procedural algorithm should aim to reproduce (neither a perfect grid nor complete chaos). In the second image, the fine details of individual dunes (ripples, slipface, horns) inform the texturing and shaping rules needed for realism. The bright/dark contrasts in the dunes come from lighting on the steep slipfaces vs. flatter stoss slopes – in rendering, one must account for the sun angle to cast dunes properly (though that's more relevant to image synthesis than the generative rules themselves, it's worth noting for analog image output).

Pseudocode for Generative Model of Barchan Dune Field

Finally, we outline a possible algorithmic approach (pseudocode) to implement the above rules in a generative model. This combines the static layout with iterative refinement to ensure physical plausibility:

```
# Parameters and initial settings
wind_direction = D_w                       # e.g., in degrees or as a vector
(ux, uy)
domain_size = (X, Y)                       # size of the area to populate with
dunes
N = choose_number_of_dunes(domain_size, sand_supply)  # based on desired density

# Determine dune size distribution (log-normal around a characteristic size)
mean_width = f(sand_supply)                # function of sand supply or user
input
widths = sample_log_normal(mean=mean_width, sd=0.4*mean_width, size=N)
# Enforce min and max limits
for each w in widths:
    if w < W_min: w = W_min
    if w > W_max: w = W_max

# Calculate corresponding heights and lengths for each dune
dunes = []
for each w in widths:
    H = height_factor * w                  # e.g., 0.1 * w
    L_body = length_factor * w             # e.g., 0.8 * w
    volume = volume_factor * w^3           # ensure consistent volume scaling
```

```
    dunes.append(new Dune(width=w, height=H, length=L_body, volume=volume))

# Place dunes in the domain with spacing constraints
placed_dunes = []
spatial_index = init_spatial_index(domain_size)   # for efficient neighbor
queries
attempts = 0
while dunes not empty and attempts < max_attempts:
    dune = pop_random(dunes)
    # sample a random position within domain margins (leave space near edges)
    x = random_uniform(margin, X - margin)
    y = random_uniform(margin, Y - margin)
    # check spacing from existing dunes
    min_dist = infinity
    for neighbor in spatial_index.query_circle((x,y), radius_query):
        dist = distance((x,y), neighbor.position)
        if dist < min_dist: min_dist = dist
    if min_dist >= spacing_factor * dune.width:
        dune.position = (x, y)
        dune.orientation = wind_direction + random_normal(0, orientation_std)  #
slight random offset
        placed_dunes.append(dune)
        spatial_index.insert(dune.position, dune)
    else:
        # if too close, optionally try a few more times or modify dune (e.g.,
smaller)
        dunes.push(dune)   # put it back to try later or handle separately
    attempts += 1

# Assign horn geometry and asymmetry
for dune in placed_dunes:
    # Base symmetric horn length
    base_horn_length = horn_factor * dune.width   # e.g., 0.5 * width
    # Random asymmetry factor (between -0.3 and 0.3 say)
    delta = random_uniform(-asymmetry_max, asymmetry_max)
    horn_length_left  = base_horn_length * (1 + delta)
    horn_length_right = base_horn_length * (1 - delta)
    # Build polygon or mesh for dune shape oriented with slipface downwind:
    dune.generate_shape(wind_direction, horn_length_left, horn_length_right)

# At this point, we have initial dune shapes and positions.
# Next, resolve any overlaps by adjusting positions or merging dunes.
for each dune in placed_dunes:
    neighbors = spatial_index.query_circle(dune.position, radius =
0.8*(dune.width + max_neighbor_width))
    for nb in neighbors:
        if nb is dune: continue
        if dunes_overlap(dune, nb):   # check if their base areas intersect
```

```
            # Resolve overlap based on relative sizes
            if dune.width > 1.5 * nb.width:
                # dune is much larger: possibly absorb nb or push nb aside
(calving scenario)
                dune.volume += nb.volume
                dune.width = (dune.volume)^(1/3) / (volume_factor)^(1/3)   #
recompute width from volume
                dune.height = height_factor * dune.width
                mark nb for removal
            elif nb.width > 1.5 * dune.width:
                # neighbor is much larger: absorb this dune into neighbor
                nb.volume += dune.volume
                nb.width = (nb.volume)^(1/3) / (volume_factor)^(1/3)
                nb.height = height_factor * nb.width
                mark dune for removal
            else:
                # similar size: merge into one new dune at an interpolated
position
                new_vol = dune.volume + nb.volume
                new_w = (new_vol)^(1/3) / (volume_factor)^(1/3)
                new_h = height_factor * new_w
                new_x = (dune.x + nb.x)/2
                new_y = (dune.y + nb.y)/2
                remove dune and nb
                new_dune = Dune(width=new_w, height=new_h, volume=new_vol)
                new_dune.position = (new_x, new_y)
                new_dune.orientation = wind_direction
                placed_dunes.append(new_dune)
                spatial_index.insert(new_dune.position, new_dune)
                break  # re-check overlaps from start since list changed

# Remove all dunes marked for removal from placed_dunes and spatial_index
cleanup(placed_dunes)

# Finalize dune shapes and add surface details
for dune in placed_dunes:
    dune.enforce_slipface_slope(angle=33°)   # adjust profile if needed
    dune.add_surface_ripples(wind_direction, ripple_length=some_value)
    dune.texture = sand_texture_variation()

# Output or render the scene with dunes on the terrain
generate_heightmap_or_mesh(placed_dunes, ground=elevation_field)
```

This pseudocode outlines a possible implementation approach: - It first sets up dunes with random sizes and then tries to place them respecting spacing. - It then orients and shapes each dune (with some asymmetry). - After initial placement, it checks for overlaps and resolves them by mimicking physical outcomes (absorption or merging). - Finally, it fine-tunes each dune's shape (imposing slipface slope, adding ripples, etc.) and prepares for rendering.

In practice, one might iterate the placement and overlap resolution steps multiple times or even integrate a **time-stepping simulation** for a short period to "relax" the configuration into a more natural state (for example, allow dunes to repel each other slightly or undergo one or two collision events in simulation to settle spacing). That would further increase realism but at higher computational cost.

With these rules and algorithms, the generative model will produce a **multiscale physically accurate barchan dune field**: from the overall arrangement down to individual dune geometry. The result should be suitable as a geologic analog for image synthesis, capturing the essential look and structure of real-world barchan systems. Each component – dune shape, positioning, and interactions – follows the known physical principles, ensuring that the synthesized images are not only visually convincing but also scientifically credible.

Sources: The rules and parameters above are grounded in dune morphology and dynamics literature. Barchan dunes form under limited sand and unidirectional winds [11], have characteristic crescent shapes with slipfaces at ~34° [7], and migrate with speeds inversely proportional to their size [15] [14]. They interact through collisions and calving, which regulate their sizes within a field [24] [26]. Typical dimensions span tens of meters in width and a few meters in height [36], maintaining roughly geometric similarity so that volume scales with the cube of linear size [35]. These concepts have been utilized in constructing the procedural framework above. The visual examples provided (ISS astronaut photograph of Aorounga dune corridor [4] and HiRISE image of Martian barchans) further guide the spatial layout and appearance.

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