**Unified Engines, DrumKit & FX Requirements — v1.5**

**Target**: STM32H7 @ ~600 MHz, 48 kHz, float32, external RAM available  
**Scope**: Real-time synthesis engines (Mutable-inspired), DrumKit engine, per-voice **Channel Strip**, **per-engine insert FX**, **bus/send FX**, **master FX**, modulation, SmartKnob haptics, budgets, presets, metadata, testing, deliverables, and licensing.

**1) Goals**

* Musically solid, **deterministic**, **real-time safe** engines ready for polyphony.
* Consistent macro interface across engines: HARMONICS, TIMBRE, MORPH.
* Per-voice **Channel Strip** (HPF → LPF/SVF → Comp → Drive → Tilt EQ).
* **DrumKit** with multiple synthesized slots, choke groups, and shared sends.
* Lightweight **per-engine inserts**; heavier/latent FX on **buses**; final polish on **master**.
* Tactile **SmartKnob** experience with detents, torque ramps, and “feel the curve” where helpful.

**2) Platform & Audio Contract**

* **Sample rate**: default 48 kHz (engines are rate-agnostic; host passes sampleRate to prepare()).
* **Block size**: power-of-two 32–128 samples (≤256 supported).
* **Format**: 32-bit float in [−1.0, +1.0], ≥6 dB internal headroom.
* **Channels**: mono per voice unless an engine is intrinsically stereo (exposes isStereo()).
* **RT constraints**: no heap allocation after prepare(), no locks/logging/I/O on audio thread.
* **Determinism**: identical events + seed ⇒ bit-identical output.
* **Denormals**: FTZ/DAZ enabled (or DC guards where needed).

**3) Processing Model & Scheduling (Host)**

Per audio block:

1. Pull MIDI/events (lock-free queue).
2. For each active voice: **Engine Core** → **Channel Strip** → **Insert FX (≤2)** → **Sends tap**.
3. Sum parts and buses; process **Bus FX A/B/C**; sum with dry; process **Master Inserts** → **Limiter**.
4. Output via SAI/I²S DMA (double-buffer).

**Control-rate**: host smooths parameters every 1–2 blocks (≈750–1500 Hz). Engines also apply internal 2–10 ms slews for click-free moves.

**4) Common Engine API**

struct RenderContext {

float pitch\_semitones; // MIDI note as semitones

float fine\_cents; // +/-100c

float gate; // 0/1

float aftertouch; // 0..1

float modWheel; // 0..1

uint32\_t randomSeed; // per-voice or per-block seed

// Smoothed, per-block macros (0..1 unless noted)

float HARMONICS, TIMBRE, MORPH, LEVEL;

float EXTRA1, EXTRA2; // engine-specific optional

};

class IEngine {

public:

virtual void prepare(double sampleRate, int maxBlockSize) = 0;

virtual void reset() = 0; // silent within 1 block

virtual void noteOn(float note, float velocity, uint32\_t id) = 0;

virtual void noteOff(uint32\_t id) = 0; // may tail

virtual void setParam(int paramID, float v01) = 0; // normalized

virtual void setMod(int paramID, float value, float depth) = 0; // per-block

virtual void render(const RenderContext&, float\* out, int n) = 0; // mono unless stereo

virtual bool isStereo() const = 0;

virtual ~IEngine() {}

};

**Canonical parameter IDs** appear in **Appendix C**.

**5) Modulation Contract**

* Required destinations: PITCH (in **semitones**), HARMONICS, TIMBRE, MORPH, LEVEL.
* Host pre-sums modulation sources; engine clamps to domain and slews (2–10 ms).
* FM-style engines may bypass pitch slew (documented per engine).

**6) Anti-Alias & Quality**

* Oscillators: **BLEP/PolyBLEP** (or equivalent) for band-limited discontinuities.
* Folders/shapers: **2× oversampling** above drive/brightness threshold; linear-phase FIR decimator ≤16 taps.
* Wavetable: **≥4 mip levels**, cubic interpolation.
* Target at 48 kHz: alias energy ≥20 dB below fundamental at nominal settings (document exceptions).

**7) CPU & Memory Budgets (per 64-sample block, indicative)**

* **Light** ≤3 k cycles: MacroVA/FM/Noise/Peaks-style drums
* **Medium** ≤4 k: Wavetable/Tides/Waveshaper
* **Heavy** ≤12 k: RingsVoice; MacroChord/Harmonics (high partial counts)
* **Very Heavy** ≤18 k: ElementsVoice
* Per-voice state ≤16 KB (Rings/Elements ≤64 KB).
* Keep hot state (filters, envelopes, modal lines) **on-chip**; large tables in flash; long histories in cacheable external RAM only when necessary.

**8) Per-Voice Channel Strip (all engines & DrumKit slots)**

**Default order (“Clean”)**: Core → HPF → LPF(SVF) → Comp → Drive → TiltEQ  
**Alternate (“Dirty”)**: Core → Drive → HPF → LPF → Comp → TiltEQ

**Parameters & ranges** (normalized unless noted)

* HPF\_CUTOFF 10–1000 Hz (log)
* LPF\_CUTOFF 200 Hz–18 kHz (log)
* LPF\_RES 0–0.90 (gain-comp; self-osc blocked >0.9)
* FLT\_KEYTRACK 0–1 ⇒ 0–100 % tracking
* FLT\_ENV\_AMT −1..+1 (center=0)
* FLT\_ATTACK 0.5–100 ms (log)
* FLT\_DECAY 5–2000 ms (log)
* FLT\_SUSTAIN 0–1
* FLT\_RELEASE 10–3000 ms (log)
* COMP\_AMOUNT 0–1 (one-knob; soft knee; A≈10 ms, R≈120 ms; no lookahead)
* PUNCH 0–1 (transient enhancer macro)
* DRIVE 0–1 (asym soft-clip; level-compensated)
* DRIVE\_TONE 0–1 (odd/even emphasis, pre/post blend)
* BODY −6..+6 dB (low shelf ~120 Hz)
* AIR −6..+6 dB (high shelf ~6–8 kHz)
* STRIP\_MODE {Clean, Dirty}, STRIP\_ENABLE {On, Off}

**Strip CPU target** ≤1.2 k cycles/voice/block.  
**Defaults (pitched)**: HPF 30 Hz, LPF 16 kHz, RES 0.15, KEYTRACK 0.5, FLT EG 5/200/0.2/300 ms, FLT\_ENV\_AMT 0.2, COMP 0.15, PUNCH 0.2, DRIVE 0.1, BODY +0.5 dB, AIR +0.5 dB.  
**Drum defaults** in §10.5.

**9) Engine Catalogue**

Each engine supports the macro triplet (HARMONICS, TIMBRE, MORPH), optional EXTRA1/EXTRA2, the Channel Strip (§8), per-engine inserts (§11), and exposes metadata (§16).

**9.1 MacroVA (Virtual-Analog)**

* **Role**: band-limited classic shapes + unison.
* **Macros**: HARMONICS (shape blend), TIMBRE (PW/curve), MORPH (unison amount).
* **Extras**: UNISON\_COUNT {1,2,3,5}, UNISON\_SPREAD (0–20 c), SUB\_LEVEL (−∞..0 dB), NOISE\_MIX (0–1), SYNC\_DEPTH (0–1; BLEP’d).
* **CPU**: ≤1.5 k (no unison), ≤2.5 k (with unison).
* **Quality**: Normal/High (unison dithering & mild phase randomization).

**9.2 MacroFM (2-Op)**

* **Macros**: HARMONICS (ratio index map {0.5,1,1.5,2,3,4,5,7,9}), TIMBRE (index, exp mapped 0..~8), MORPH (feedback).
* **Extras**: ALGO {C←M, C←M+FB, Cross}, BRIGHT\_TILT (±6 dB), FIXED\_MOD {Off, On}.
* **CPU**: ≤2.0 k; optional 2× OS when index>0.7 and f0>3 kHz.

**9.3 MacroWaveshaper (Fold)**

* **Macros**: HARMONICS (pre-emphasis tilt), TIMBRE (fold depth), MORPH (symmetry).
* **Extras**: FOLD\_MODE {tanh, diode, folder}, POST\_LP (2–12 kHz).
* **CPU**: ≤3.5 k including 2× OS at high drive.

**9.4 MacroWavetable**

* **Macros**: HARMONICS (frame 0–63), TIMBRE (intra-morph/tilt), MORPH (bank 0–3).
* **Extras**: UNISON\_3V {Off, On} + UNISON\_SPREAD (0–12 c), SUB\_LEVEL, INTERP {cubic, linear}.
* **Tables**: ≥4 banks × 64 frames, 4 mip levels.
* **CPU**: ≤2.5 k.

**9.5 MacroChord**

* **Macros**: HARMONICS (chord type stepped), TIMBRE (spread 0–12 st), MORPH (detune).
* **Extras**: VOICES {3,4,5}, SOURCE {VA, WT-A}, STRUM\_MS (0–40 ms).
* **CPU**: ≤4 k.

**9.6 MacroHarmonics (Additive)**

* **Controls**: PARTIAL\_COUNT (1–16), DECAY\_EXP (0–2; 1/f^x), INHARMONICITY (0–1), EVEN\_ODD\_BIAS (−1..+1), BANDLIMIT\_MODE {auto, strict}.
* **CPU**: ≤4 k @16 partials.

**9.7 Formant/Vocal**

* **Controls**: VOWEL (A-E-I-O-U morph), BANDWIDTH (0–1), BREATH (0–1), FORMANT\_SHIFT (±12 st), GLOTTAL\_SHAPE (0–1).
* **CPU**: ≤3 k.

**9.8 Noise/Particles**

* **Controls**: DENSITY\_HZ (1–200 Hz), GRAIN\_MS (5–60 ms), BP\_CENTER (400–6 kHz), BP\_Q (0.5–2), SPRAY (0–1).
* **CPU**: ≤2 k.

**9.9 TidesOsc (Slope Oscillator)**

* **Controls**: CONTOUR (sine→ramp→pulse), SLOPE (0–1), UNISON (0–1), CHAOS (0–1), LFO\_MODE {Off, On}.
* **CPU**: ≤2.5 k.

**9.10 RingsVoice (Exciter + Modal Resonator)**

* **Controls**: STRUCTURE, BRIGHTNESS, POSITION; EXCITER {mallet,bow,blow}; DAMPING, SPACE\_MIX, STEREO {Off, On}.
* **CPU**: 8–12 k; recommended ≤4 voices.

**9.11 ElementsVoice (Rich Physical Model)**

* **Controls**: GEOMETRY, ENERGY, DAMPING; EXCITER\_BAL (bow/blow/strike); SPACE, NOISE\_COLOR, STEREO.
* **CPU**: 12–18 k; recommended ≤2–4 voices.

**10) DrumKit Engine**

**10.1 API**

class DrumKit {

public:

void prepare(double sr, int maxBlockSize);

void reset();

void render(const RenderContext&, float\* outL, float\* outR, int n);

void noteOn(uint8\_t midiNote, float velocity, uint32\_t id);

void noteOff(uint32\_t id);

void setKitParam(int kitParamID, float v01);

void setSlotParam(int slot, int paramID, float v01);

void setMapping(uint8\_t midiNote, int slot, uint8\_t variation); // 0..3

void setChokeGroup(int slot, int groupId); // 0 = none

void setSeed(uint32\_t);

SlotMeters getSlotMeters(int slot) const; // optional

};

**10.2 Structure & Performance**

* **Slots**: default 12 (configurable 8–16).
* **Per-slot polyphony**: Kick/Snare/Tom/Clap 1–2; Hats/Cymbals 2–4.
* **Choke groups**: ≥4 (OH/CH share).
* **Accent**: global 0..1 + per-hit from velocity curve.
* **Sends**: per slot SEND\_A/B/C (scalar taps).
* **Mixer**: per slot LEVEL (log), PAN (−1..+1), mute/solo.
* **CPU**: ≤120 k cycles/block with ~8 concurrent hits (no bus FX).
* **Channel Strip**: identical to §8 per slot.
* **Per-slot insert**: one slot from §11 (default off).

**10.3 DrumModel Interface (reused stand-alone)**

class IDrumModel {

public:

virtual void prepare(double sr, int maxBlock) = 0;

virtual void reset() = 0;

virtual void trigger(float velocity, float accent, uint8\_t variation) = 0;

virtual void noteOff() {} // optional

virtual void process(float\* out, int n) = 0; // mono

virtual void setParam(int id, float v01) = 0;

virtual ~IDrumModel() {}

};

**Variations**: up to **4** per slot; switching is click-free (≤5 ms crossfade if required).

**10.4 Required DrumModels (v1)**

1. **KickAnalog** — TUNE, DECAY, ATTACK, BEND, TONE, DRIVE.
2. **KickFM** — RATIO, INDEX, DECAY, CLICK, TONE, DRIVE.
3. **SnareAnalog** — TUNE, DECAY, SNAPPY, TONE, BODY.
4. **Clap** — BURSTS, SPREAD, DECAY, TONE, DRIVE.
5. **HatClosed/HatOpen** — DECAY, TONE, METAL, DRIVE (shared choke).
6. **Tom** — TUNE, DECAY, DAMP, TONE, DRIVE.
7. **Cymbal/Ride** — PING, DECAY, TONE, SHIMMER.

**10.5 Defaults (per-slot)**

* **Kicks**: HPF 20 Hz, LPF 8–10 kHz, COMP 0.35, DRIVE 0.2, BODY +2 dB, AIR −1 dB.
* **Hats**: HPF 200 Hz, LPF 11–12 kHz, COMP 0.2, DRIVE 0.25, AIR +2 dB.

**10.6 Mapping (26-key)**

Provide presets: **GM-ish**, **Drum Wall (26)**, **Split** (left drums/right pitched).  
Custom mapping is editable and saved with the kit. (See Appendix B for GM-ish default.)

**11) Per-Engine Insert FX (per voice)**

**Design rules**: zero added latency; light CPU; **≤2 insert slots** per engine voice; default off (presets may enable one); tails decay to −60 dBFS ≤2 s after noteOff().

**Types & parameters**

1. **Chorus / Ensemble (2–4 voices)**  
   FX\_CHORUS\_RATE 0.1–6 Hz (log), FX\_CHORUS\_DEPTH 0–1, FX\_CHORUS\_VOICES {2,3,4}, FX\_CHORUS\_MIX 0–1.  
   CPU: **Light** (≤1.2 k). RAM: short delays on-chip.
2. **Flanger (optional through-zero)**  
   FX\_FLANGE\_RATE 0.03–2 Hz, DEPTH 0–1, FEEDBACK −1..+1, MANUAL 0–1, MIX 0–1.  
   CPU: **Light–Med** (≤1.8 k).
3. **Phaser (4/6/8 stages)**  
   STAGES {4,6,8}, RATE 0.05–3 Hz, DEPTH 0–1, FEEDBACK −1..+1, MIX 0–1.  
   CPU: **Light** (≤1.2 k).
4. **Tremolo / Auto-Pan**  
   RATE 0.1–15 Hz, SHAPE {sine,tri,sq}, DEPTH 0–1, STEREO {Off,On}, MIX 0–1.  
   CPU: **Tiny** (≤0.5 k).
5. **Bit/Rate Crusher**  
   BITS 6–16, SRATE\_DIV ×1–×16, FILTER 2–12 kHz, MIX 0–1.  
   CPU: **Tiny**.
6. **Mini Delay (slapback ≤120 ms)**  
   TIME 10–120 ms, FEEDBACK 0–0.7, TONE (LP tilt), MIX 0–1.  
   CPU: **Light**; on-chip RAM.

**Suggested defaults**

* MacroVA: Chorus subtle.
* FM: Phaser 6-stage slow.
* Wavetable: Chorus → Flanger (light).
* Waveshaper: Phaser subtle.
* Chord/Harmonics: Ensemble 3–4 voices.
* Formant: Mini Delay 60 ms, dark.
* Tides: Chorus subtle.
* Rings/Elements: typically none (use sends).

**12) Sends & Bus Architecture**

* **Sends**:
  + **Send A** → **Reverb bus**
  + **Send B** → **Texture bus** (granular/looper)
  + **Send C** → **Spatial/Delay bus**  
    Tap **post-inserts** (after Channel Strip and per-voice inserts). Range 0..1.  
    Defaults: A/B as in v1.3; **C defaults to 0**.
* **Each bus** has: Bus Input Sum → Bus Inserts (≤2) → Bus Output.

**13) Bus FX**

**13.1 Bus A — Reverb (primary)**

**Algorithm**: stereo FDN/plate with optional early reflections.  
**Params**: BUS\_REV\_PREDELAY 0–40 ms, BUS\_REV\_RT60 0.6–6.0 s, BUS\_REV\_SIZE {S,M,L}, BUS\_REV\_HFDAMP 0–1, BUS\_REV\_LOCUT 20–200 Hz, BUS\_REV\_MOD 0–1, BUS\_REV\_MIX 0–1.  
**CPU**: **Med** (≤120 k). **RAM**: ~0.5–1.0 MB (aim on-chip). **Latency**: 0.

**13.2 Bus B — Texture (granular/looper)**

**Algorithm**: stereo granular with freeze.  
**Params**: BUS\_GRAN\_DENSITY 0–1, BUS\_GRAN\_SIZE 30–120 ms, BUS\_GRAN\_PITCH ±12 st, BUS\_GRAN\_SPRAY 0–30 ms, BUS\_GRAN\_FB 0–1, BUS\_GRAN\_DIFF 0–1, BUS\_GRAN\_FREEZE {Off,On}, BUS\_GRAN\_MIX 0–1.  
**CPU**: **Med–Heavy** (150–250 k). **RAM**: 10–30 s stereo buffer in **external** RAM (≈11.5–34.5 MB). **Latency**: 10–40 ms (document).

**13.3 Bus C — Spatial Delay / Chorus**

Pick one per scene:

* **Stereo Delay (tempo-sync / ping-pong)**  
  BUS\_DLY\_TIME\_L/R (ms) or BUS\_DLY\_SYNC (1/64…2 bars), BUS\_DLY\_FB 0–1, BUS\_DLY\_TONE (tilt), BUS\_DLY\_XFEED 0–1, BUS\_DLY\_MIX 0–1.  
  **CPU**: **Light–Med** (≤80 k). **RAM**: seconds of stereo delay in external RAM.
* **Wide Chorus (bus level)**  
  RATE, DEPTH, VOICES (4–8), MIX. **CPU**: **Med** (≤80 k).

**13.4 Bus utilities (optional Insert 2)**

**Tilt EQ** (±6 dB) / **Shelves** (±6 dB @120 Hz, @6–8 kHz) / **Saturator** (0–1). CPU: **Tiny–Light**.

**14) Master Bus**

**Fixed order**: (Bus A + Bus B + Bus C + Dry) → Master Inserts (≤3) → Limiter → Output

**14.1 Master Inserts**

1. **Glue Compressor**  
   MASTER\_COMP\_THRESH −30..0 dB, MASTER\_COMP\_RATIO 1.3–2.5:1, MASTER\_COMP\_ATTACK 10–30 ms, MASTER\_COMP\_RELEASE 80–200 ms, MASTER\_COMP\_MIX 0–1. (No lookahead.)
2. **Tone (Shelves/EQ)**  
   MASTER\_TONE\_LOW ±4 dB @120 Hz, MASTER\_TONE\_HIGH ±4 dB @8 kHz.
3. **Stereo Tool**  
   MASTER\_ST\_WIDTH 0–1.5, MASTER\_ST\_TILT ±3 dB.

**14.2 Master Limiter**

**Brickwall** with ≤1 ms lookahead.  
MASTER\_LIM\_CEILING −0.3 dBFS, MASTER\_LIM\_RELEASE 50–200 ms.  
**CPU**: **Light**. **Latency**: ≤1 ms (global).

**15) SmartKnob Interaction & Haptics**

**15.1 Policies**

* **Perceptual-Uniform (default)**: constant torque; mapping handles log feel (freq/time/level).
* **Curve-Expressive**: torque ∝ normalized |dx/dp| (slope in physical units) to “feel” hot zones (FM index, fold/drive, resonance, comp amount, inharmonicity).
* **Guard-Rail**: ramp torque in last 5–10 % (or earlier for resonance/feedback).
* **Landmark-Centric**: detents at named values (center, octaves, ratios, vowels, frames).
* **Center Notch**: strong detent at 0 for bipolar params.
* **Acceleration**: fast=coarse, slow=fine. **Press-to-fine** halves step & torque.
* **End-stop**: torque rises last 3–5 % of arc.

**Torque model (implementation hint)**

T(θ, ω) = T0

+ T\_detents(θ)

+ k\_curve \* normalize(|d x / d p|)

+ k\_guard \* guard(p)

+ k\_end \* endstop(p)

+ k\_vel \* |ω|

Detents = sum of Gaussians (width 6°/12°/20°). Clip normalize() at 95th percentile.

**15.2 Recommended feel (summary)**

* **LEVEL**: Perceptual-Uniform; detents at −∞/−18/−12/−6/−3/0 dB; 270°.
* **PAN**: center notch + ±25/50/75/100 %; 180°.
* **SENDS**: 0/.1/.2/.3/.5; 270°.
* **HPF/LPF**: Perceptual-Uniform (log); LPF tiny guard near max; 270°.
* **RES**: Curve-Expressive + Guard-Rail from 0.75; detents 0/.2/.4/.6/.75/.85; heavy >.9.
* **ADSR**: Perceptual-Uniform (log landmarks: 1/3/5/10/20/50/100/300/600/1000/2000 ms); 270°.
* **COMP\_AMOUNT**: Curve-Expressive (ramp .3→.7), detents 0/.15/.3/.5/.75/1; 180°.
* **DRIVE**: Curve-Expressive + guard top 15 %; 270°.
* **BODY/AIR (±6 dB)**: center notch, detents −6/−3/−1/0/+1/+3/+6; 180°.
* **MacroVA**: shape landmarks (Tri/Saw/Square); unison count hard steps; spread soft.
* **FM**: ratio hard steps (360°); index Curve-Expressive; algo hard.
* **Wavetable**: frame 360° with light detents every 4 frames; bank hard steps.
* **Chord**: chord type hard (360°); spread soft; detune soft.
* **Harmonics**: partial count hard 1–16; inharmonicity Curve-Expressive (ramp >.6).
* **Formant**: vowels hard A/E/I/O/U (soft in-betweens); formant shift semitone detents (press-to-fine=cents).
* **Tides**: contour hard (sine/ramp/pulse) + soft mids.
* **Rings/Elements**: macros uniform with landmarks 0/.25/.5/.75/1; exciter hard; space/noise soft.
* **DrumKit**: kick tune landmarks (28/34/41/55/73/82/110 Hz), decay logs; hat/snare mix soft; **choke event** emits one sharp click.
* **Per-engine inserts & buses**: see §11 & §13 haptics (Curve-Expressive for feedback; landmark sync steps for delay time; freeze toggle click).

*(A machine-readable HapticsMap with arc/policy/detents per parameter is part of deliverables.)*

**16) Metadata for UI/Automation**

Each engine (and DrumKit/FX modules) exposes:

* EngineID / FxID, DisplayName, ShortName, IsStereo (where applicable), CPUClass {Light|Med|Heavy|VHeavy}.
* Parameter descriptors: {id, name, unit, default, min, max, taper, isDiscrete, steps, group}.
* Suggested modulation destinations (bitmask).
* **Haptics hints**: policy {Uniform|Curve|Guard|Landmarks|CenterNotch}, **arc** (180°/270°/360°), detent list (values in engineering units).

**17) Presets & Scenes**

* ≥4 **presets per engine** (macros/extras, Channel Strip, per-engine inserts).
* ≥4 **kits** for DrumKit (models, per-slot params, mapping, chokes, variations, strip, slot inserts, sends).
* **Global scenes** (3): *Dry & Tight*, *Plate & Ping-Pong*, *Lush Texture* (bus FX settings).
* Presets/scenes are versioned (JSON or compact binary). Presets store Quality mode.

**18) Testing & Acceptance**

**Per engine**

* **Reset silence**: RMS < −90 dBFS within 1 block.
* **Lifecycle**: noteOn → sustain → noteOff tails to −60 dBFS within documented time; no NaN/Inf; DC < −60 dBFS.
* **Determinism**: golden event stream + seed ⇒ bit-identical renders.
* **Bounds**: params at 0/1 stable; output never hard-clips > +1.0f (soft-clip OK).
* **Spectral**: alias energy target per §6 (FFT sweep C2→C8).
* **CPU**: DWT cycle counts within §7 budgets at representative polyphony (Light/Med ≥8 voices; Heavy ≥4).

**Insert FX**

* No added latency; tails ≤2 s post-release; voice steal crossfade ≤5 ms.

**DrumKit**

* **Choke**: OH choked by CH within 15 ms, click-free.
* **Variation switch**: ≤5 ms crossfade.
* **Humanize**: zero-mean timing variance; seeded reproducibility.
* **Throughput**: ≤120 k cycles/block at 8 concurrent hits.

**Bus & Master**

* **Reverb** latency 0; **Granular** latency 10–40 ms documented; **Limiter** ≤1 ms.
* **Clip safety**: post-limiter ceiling −0.3 dBFS.
* **CPU** fits §19 roll-ups.

**Haptics**

* All parameters carry haptics hints; detents matched; torque ramps bounded; end-stops ramp in last 3–5 % of arc.

**Golden audio**

* 3–5 short WAVs per engine & representative FX scenes (sustain, sweep, extremes) with CRCs.

**19) Performance Roll-Ups**

* **Per-voice inserts**: ~1–2 k cycles/blk each; two inserts ≤3 k added worst-case.
* **Bus A Reverb**: ≤120 k; RAM ~0.5–1.0 MB (prefer on-chip).
* **Bus B Granular**: 150–250 k; RAM 11–35 MB (external).
* **Bus C Delay/Chorus**: ≤80 k; RAM in external.
* **Master (incl. limiter)**: ≤50 k.

**Profiles**

* **Voice-Centric**: 24 voices, light inserts, Reverb Normal, Delay off, Texture light → ≈55–65 % total.
* **Texture-Centric**: 8–10 voices, richer inserts, Reverb High, Texture Medium, Delay on → ≈70–80 %.  
  Global Quality switch downshifts **bus FX first** (granular density, reverb taps) before reducing voices.

**20) Deliverables**

1. **C++ sources**
   * Engines (one class each), DrumModels (one class each), DrumKit, Channel Strip, Insert FX modules, Bus FX modules, Master modules, shared DSP utils (BLEP, SVF, envelopes, interpolation, RNG).
2. **Headers**
   * Engine/FX interfaces, parameter IDs/enums, metadata accessors.
3. **Test harness**
   * Offline renderer to emit golden WAVs; spectral/bounds tests; DWT cycle stats; scene renders.
4. **Preset pack**
   * Engine presets, DrumKit kits, Global scenes (JSON/compact binary), versioned.
5. **Docs** (2–4 pages)
   * Engine/FX list, params, defaults, CPU/mem table, known limits.
6. **Haptics map**
   * Machine-readable JSON of arc/policy/detents per parameter.
7. **Kit mapping**
   * Default 26-key tables (3 presets) + mapping schema.

**21) Licensing & Attribution**

* MIT-compatible only (no GPL).
* Include Mutable attribution/LICENSE in source and “About”.

**22) Acceptance Checklist**

* Compiles clean (-O2, C++17); no RT warnings.
* Unit, spectral, CPU, and haptics tests pass.
* Metadata & haptics hints present for **every** parameter.
* Presets/scenes load; golden renders CRC-match.
* DrumKit choke/variation/humanize verified.
* Bus/Granular latency documented; limiter ceiling enforced.
* LICENSE/attribution included.

**Appendix A — Default Ranges & Tapers (reference)**

* **HPF** 10–1000 Hz (log); **LPF** 200 Hz–18 kHz (log); **RES** 0–0.90 (linear, gain-comp).
* **ADSR** A: 0.5–100 ms, D: 5–2000 ms, S: 0–1, R: 10–3000 ms (log times).
* **COMP** 0..1; **DRIVE** 0..1; **BODY/AIR** ±6 dB.
* **Unison spread** VA 0–20 c; WT 0–12 c.
* **Additive partials** 1–16; **Wavetable frames** 0–63; **Banks** 0–3.

**Appendix B — Default 26-Key Drum Mapping (GM-ish)**

C: Kick1, C#: Rim, D: Snare1, D#: Clap, E: Snare2, F: Tom1, F#: ClosedHat, G: Tom2, G#: OpenHat, A: Tom3, A#: Crash, B: Ride.  
Remaining keys map to slot **variations** (Kick2–4, Snare3–4, alt hats, etc.). Fully editable.

**Appendix C — Parameter ID Canon**

PITCH, FINE, LEVEL,

HARMONICS, TIMBRE, MORPH, EXTRA1, EXTRA2,

HPF\_CUTOFF, LPF\_CUTOFF, LPF\_RES, FLT\_KEYTRACK,

FLT\_ENV\_AMT, FLT\_ATTACK, FLT\_DECAY, FLT\_SUSTAIN, FLT\_RELEASE,

COMP\_AMOUNT, PUNCH, DRIVE, DRIVE\_TONE, BODY, AIR,

STRIP\_ENABLE, STRIP\_MODE,

SEND\_A, SEND\_B, SEND\_C,

PAN,

// Engine-specific examples

UNISON\_COUNT, UNISON\_SPREAD, SUB\_LEVEL, NOISE\_MIX, SYNC\_DEPTH,

ALGO, BRIGHT\_TILT, FIXED\_MOD,

FOLD\_MODE, POST\_LP,

VOICES, SOURCE, STRUM\_MS,

PARTIAL\_COUNT, DECAY\_EXP, INHARMONICITY, EVEN\_ODD\_BIAS, BANDLIMIT\_MODE,

VOWEL, BANDWIDTH, BREATH, FORMANT\_SHIFT, GLOTTAL\_SHAPE,

CONTOUR, SLOPE, UNISON, CHAOS, LFO\_MODE,

STRUCTURE, BRIGHTNESS, POSITION, EXCITER, DAMPING, SPACE\_MIX, STEREO,

GEOMETRY, ENERGY, EXCITER\_BAL, SPACE, NOISE\_COLOR,

// Per-voice Insert FX

FX\_CHORUS\_RATE, FX\_CHORUS\_DEPTH, FX\_CHORUS\_VOICES, FX\_CHORUS\_MIX,

FX\_FLANGE\_RATE, FX\_FLANGE\_DEPTH, FX\_FLANGE\_FEEDBACK, FX\_FLANGE\_MANUAL, FX\_FLANGE\_MIX,

FX\_PHASER\_STAGES, FX\_PHASER\_RATE, FX\_PHASER\_DEPTH, FX\_PHASER\_FEEDBACK, FX\_PHASER\_MIX,

FX\_TREM\_RATE, FX\_TREM\_DEPTH, FX\_TREM\_SHAPE, FX\_TREM\_STEREO, FX\_TREM\_MIX,

FX\_CRUSH\_BITS, FX\_CRUSH\_SRDIV, FX\_CRUSH\_FILTER, FX\_CRUSH\_MIX,

FX\_MINIDLY\_TIME, FX\_MINIDLY\_FB, FX\_MINIDLY\_TONE, FX\_MINIDLY\_MIX,

// Bus FX

BUS\_REV\_PREDELAY, BUS\_REV\_RT60, BUS\_REV\_SIZE, BUS\_REV\_HFDAMP, BUS\_REV\_LOCUT, BUS\_REV\_MOD, BUS\_REV\_MIX,

BUS\_GRAN\_DENSITY, BUS\_GRAN\_SIZE, BUS\_GRAN\_PITCH, BUS\_GRAN\_SPRAY, BUS\_GRAN\_FB, BUS\_GRAN\_DIFF, BUS\_GRAN\_FREEZE, BUS\_GRAN\_MIX,

BUS\_DLY\_TIME\_L, BUS\_DLY\_TIME\_R, BUS\_DLY\_SYNC, BUS\_DLY\_FB, BUS\_DLY\_TONE, BUS\_DLY\_XFEED, BUS\_DLY\_MIX,

BUS\_EQ\_LOW, BUS\_EQ\_HIGH, BUS\_SAT\_AMT,

// Master

MASTER\_COMP\_THRESH, MASTER\_COMP\_RATIO, MASTER\_COMP\_ATTACK, MASTER\_COMP\_RELEASE, MASTER\_COMP\_MIX,

MASTER\_TONE\_LOW, MASTER\_TONE\_HIGH, MASTER\_ST\_WIDTH, MASTER\_ST\_TILT,

MASTER\_LIM\_CEILING, MASTER\_LIM\_RELEASE