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To cite this version:
Norbert Schnell, Victor Saiz, Karim Barkati, Samuel Goldszmidt. Of Time Engines and Masters An API for Scheduling and Synchronizing the Generation and Playback of Event Sequences and Media Streams for the Web Audio API. WAC, Jan 2015, Paris, France. <hal-01256952>

HAL Id: hal-01256952
https://hal.archives-ouvertes.fr/hal-01256952
Submitted on 18 Jan 2016

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Of Time Engines and Masters
An API for Scheduling and Synchronizing the Generation and Playback of Event Sequences and Media Streams for the Web Audio API

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ABSTRACT
In this article we present an API and a set of Javascript modules for the synchronized scheduling and aligned playback of predetermined sequences of events such as notes, audio segments, and parameter changes as well as media streams (e.g. audio buffers) based on the Web Audio API logical time. The API has been designed to facilitate the development on both ends, the implementation of modules which generate event sequences or media streams as well as the integration of such modules into complex audio applications that require flexible scheduling, playback and synchronization.

Categories and Subject Descriptors
H.5.3 [Group and Organization Interfaces]: Web-based interaction; H.5.5 [Information Interfaces and Presentation]: Sound and Music Computing – Systems

Keywords
HTML 5; Web Audio API; Audio Processing; Scheduling; Synchronization

1. INTRODUCTION
Flexible and precise scheduling and sequencing of audio events and synthesis parameter changes is an important feature of any real-time audio synthesis authoring environment \[4\] \[9\] \[2\]. The Web Audio API \[4\] provides a logical time synchronized to the audio input/output system (i.e. currentTime of an AudioContext) and the possibility to schedule events and parameter changes with perfect accuracy (see also \[8\]). Nonetheless, real-time web audio processing applications that generate events which are required to impact audio synthesis with precise timing (e.g. to generate rhythm- or phase-synchronous signals) generally have to cope with the short-term synchronization between Javascript timers (i.e. setTimeout) and the Web Audio API logical time \[10\]. Multiple libraries propose APIs that formalize flexible scheduling and sequencing of audio events for musical applications based on the Web Audio API \[3\] \[5\].

The API that we present in this article, contributes a unified and interoperable formalization for the synchronized scheduling and aligned playback of predetermined sequences of events such as notes, audio segments, and parameter changes as well as media streams (e.g. audio buffers) based on the Web Audio API logical time. The API has been designed to facilitate the development on both ends, the implementation of modules, “time engines”, which generate events algorithmically or interpret prerecorded sequences or media streams as well as the integration of such modules into complex audio applications that require flexible scheduling, playback and synchronization.

2. TIME, POSITION, AND SPEED
As a very first step to properly formalize the different temporalities of a system-wide reference time and the playback time of predetermined event sequences or media streams, we propose to refer to the former as time and to the latter as position. This allows for intuitively defining the ratio between them as speed. While time is steadily increasing, the evolution of position can be interrupted (e.g. by stopping or pausing the playback), discontinuous (e.g. by rewinding or seeking) and reversed (e.g. by playing backwards). Nevertheless, times and positions are given in seconds.\[7\] Since they always refer to the logical time of the current Web Audio API context – directly or scaled through speed –, time and position can be regarded as perfectly precise when used in conjunction with Web Audio API calls such as the OscillatorNode’s or the AudioBufferSourceNode’s start method and the audio parameter automation methods (e.g. setVal-ueAtTime). They can apply to events on any temporal scale including, for example, elementary waveforms synthesized through granular synthesis, the beats of a drum pattern or the macrostructure of a sound installation over several days, weeks or months.

\[1\]The time-position-speed nomenclature we propose as a clear and intuitive alternative to denominations like current time, playback time and playback rate at least have the advantage of shortening the function and attribute names of the proposed API.
3. TIME ENGINES AND MASTERS

In the API we propose, a component that generates sequences of events or media streams extends the TimeEngine class. We have identified three cases that have been formalized as three different interfaces provided by the TimeEngine:

- **scheduled** – the module generates events that are precisely scheduled in time (e.g., the grains generated by a granular synthesis engine)
- **transported** – the module generates events that are precisely associated to particular positions (e.g., the percussive elements of a recorded beat pattern annotated by onset positions)
- **speed-controlled** – the module provides its own synchronization to the current Web Audio context time as well as a way to control its playback rate (e.g., a Web Audio API AudioBufferSourceNode)

A TimeEngine can be added to a master module that uses one of these interfaces to drive the engine in synchronization with other engines. In apparent symmetry to the three interfaces provided by the TimeEngine class, we implemented three masters, the scheduler, the Transport class, and the PlayControl class. When adding an engine to a master, the master provides it with getters for the attributes currentTime and currentPosition. The engines can use these getters in their implementation to synchronize their processing to the master.

The different interfaces provided by the engines and the getters provided by the masters allow for implementing engines that behave differently when added to different masters and for implementing masters that drive the same engines in different ways, while relying on a clear and simple API on both sides.

3.1 Scheduler and Scheduled

The scheduler object is provided as a global singleton that allows for driving engines which implement the scheduled interface.

Scheduled engines generate a sequence of events by implementing the method `advanceTime` which is called for the first time when the engine is added to the scheduler – or with an optional delay. The method `advanceTime` is called with the corresponding Web Audio context time of the event to be generated and returns the time of the next event (see figure 1). When returning Infinity, the engine’s `advanceTime` method is not called again until it is rescheduled. The scheduler provides the scheduled engines with a function `resetNextTime` that allows for changing their next scheduling time.

We have implemented two versions of the global scheduler singleton. The more complex version maintains a priority queue of the currently scheduled engines. This variant allows for implementing complex systems where the precise order of events is crucial. A simplified version (i.e., the simple-scheduler) is based on the principle laid out in [10] where the next scheduling time of all scheduled engines is tested in a regularly – and recursively – called `setTimeout` callback.

Both variants of the scheduler provide the same attributes to parameterize the scheduling behavior:

- **period** – period (simple scheduler) or minimum period (scheduler) of the recursive `setTimeout` calls
- **lookahead** – lookahead time by which all calls to the engines `advanceTime` method are anticipated in respect to the current Web Audio context time

3.2 Transport and Transported

The Transport class implements the core of a generic player that controls multiple engines. While the engines take over the generation or interpretation of event sequences and media streams, the transport master provides their synchronization and alignment to a common playing position that evolves as a function of the transport’s external control. The user can determine how the engine’s event or media positions are aligned to the transport position through a set of parameters including start, offset and end positions. While the `transported` interface is the preferred interface of the transport, it also accepts engines that implement the other two interfaces.

Both `transported` interfaces provide the same attributes to parameterize the scheduling behavior:

- **advancePosition** – period (simple scheduler) or minimum period (scheduler) of the recursive `setTimeout` calls
- **transporter** – lookahead time by which all calls to the engines `advanceTime` method are anticipated in respect to the current Web Audio context time

![Figure 1: Two engines generating events at different pace. The scheduler successively calls the engines’ `advanceTime` method just before their scheduled time and reschedules each engine at the returned time using a priority queue.](image1.png)

![Figure 2: The same engines as in figure 1 controlled by a transport. The transport’s `scheduled` event translates the engines’ positions in scheduling times depending on the transport’s playing controls.](image2.png)

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2In the TimeEngine base class, the getter of `currentTime` returns the current Web Audio context time and that of `currentPosition` returns 0.
3In addition, the scheduler allows for scheduling simple – one-shot – callbacks with arbitrary delay times.
4When adding an engine to the transport, the transport checks first whether the engine implements the `transported` interface followed by the `speed-controlled` and the `scheduled` ones.
With regard to transported engines, the transport can be seen as a translator that translates the engines’ positions into scheduling times. The translation process is illustrated in the figures 2 and 3. Similar to the scheduled interface, the transported interface essentially consists of a method `advancePosition` that generates an event and returns the position of the next event regarding the current playing direction (i.e., whether the speed is positive or negative). To translate the event positions into scheduling times the transport adds an internal scheduled engine – its scheduled cell – to the global scheduler. This cell is always scheduled – and rescheduled – at the time that corresponds to the position of the next transported engine (see figure 2). Similarly to the scheduler, a transport keeps a priority queue of the next positions of its transported engines. When playing in one direction, these positions do not depend on the transport speed, so that only the first position of the priority queue has to be rescheduled when the transport’s speed changes. This allows for efficient scheduling of any number of transported engines.

When adding an engine that only implements the `scheduled` interface, the transport delegates the scheduling of the engine to the global scheduler and generates an adapter. The adapter consists of a minimal `transported` engine adds the engine to the scheduler at its start position and removes it when the transport stops or reaches the engine’s end position. To align its processing to the transport’s position, the engine can obtain a precise position corresponding to the current time through the `currentTime` attribute getter provided by the transport (see figure 4).

```javascript
1 scheduler.add(engine, Infinity, () => {
2     // get currentPosition
3     return (this.transport.currentTime - this.offsetPosition) * this.scalePosition;
4 });
```

Figure 4: The `currentTime` attribute getter provided by the adapter for `scheduled` engines added to a transport. The getter is given as third argument – an ECMAScript 6 arrow function –, when adding the engine to the global scheduler. The `Infinity` given as scheduling delay (second argument) makes that the engine is not called until it is actually started – and rescheduled – by the transport.

The third kind of engines that can be added to the transport are those implementing the `speed-controlled` interface. Similar to the case of `scheduled` engines, the transport automatically generates an adapter that controls the engine through the provided interface. The `speed-controlled` interface is described in the next section. An example that illustrates the functioning of a `speed-controlled` engine added to a transport is given below as the `PlayerEngine` (see 4.4).

The `Transport` class itself extends the `TimeEngine` class and implements two of its interfaces. Through its transported interface, a transport can be added to another transport, which allows for constructing hierarchical structures of transports being slaved to transports and, ultimately, to compose sequences of sequences. The `speed-controlled` interface allows for keeping the transport class to its essential functionalities. Play control methods and attributes can be added to a transport by associating it to a `PlayControl` master.

### 3.3 PlayControl and Speed-Controlled

The `PlayControl` class allows for controlling a single engine that is given as an argument of its constructor. Like transports, instances of the `PlayControl` class accept engines of all three `TimeEngine` interfaces. The basic idea of the `PlayControl` is to transform any engine into a player that provides common media player control methods and attributes such as `start`, `stop`, `seek`, and `speed`.

The preferred interface of `PlayControl` masters is the `speed-controlled` interface – followed by the `transported` interface. This interface aims at controlling engines that, other than `scheduled` and `transported` engines, ensure their synchronization to the current Web Audio context time independently. This is for example the case for transports, which are internally driven by the global scheduler, as well as for audio players based on the Web Audio API `AudioBufferSourceNode`.

**Figure 3:** The transport translates the positions of the transported engines into scheduling times depending on the transport’s variable speed. In the illustrated example corresponding to figure 2, the transport position evolves continuously (no seek) and without reversing the playing direction (`speed ≥ 0`).

However, the transport’s priority queue is reconstructed each time the transport starts playing, seeks to a new position, or reverses its playing direction. Therefore, each `transported` engine provides a method `resetPosition` that returns its next position regarding the master’s current position and playing direction.

5 The `Transport` class requires the version of the scheduler based on a priority queue in order to properly synchronize the transported engines and their control.

6 The transport provides the engines under its control with a function `resetNextPosition` that allows for changing their next transport position.
4. IMPLEMENTED ENGINES

We have developed a set of engines that implement different interfaces provided by the TimeEngine class. Here, they are included to further illustrate both the functioning of the TimeEngine API and its masters as well as the motivations for its development.

4.1 A Metronome

The Metronome class extends TimeEngine and implements both the scheduled and the transported interface. In both cases, the engine periodically generates click sounds using the Web Audio API. A set of attributes allows for setting the period and adjusting the sound of the click. As a scheduled engine, the metronome produces clicks of the given period as soon as it is added to the scheduler. When added to a transport, the metronome is aligned to the transport position and occurs when the transport reaches its positions depending on its external control. Figure 5 shows the implementation of the interface methods of the metronome.

```javascript
// TimeEngine scheduled interface
function advanceTime(time) {
    this.click(time); // generate sound
    return time + this.period;
}

// TimeEngine transported interface
function syncPosition(time, position, speed) {
    var next = (Math.floor(position / this.period) + this.phase) * this.period;
    if (speed > 0 && next < position)
        next += this.period;
    else if (speed < 0 && next > position)
        next -= this.period;
    return next;
}

// TimeEngine transported interface
function advancePosition(time, position, speed) {
    this.click(time); // generate sound
    if (speed < 0)
        return position - this.period;
    return position + this.period;
}
```

Figure 5: Implementation of the scheduled and transported interface methods of the Metronome class.

4.2 The GranularEngine

The GranularEngine is an example of a TimeEngine that only implements the scheduled interface but nevertheless can be aligned to the position of a transport. The engine performs granular synthesis on a given AudioBuffer. A set of attributes determines the engine’s synthesis parameters such as the grain period, duration, and resampling (i.e. pitch transposition) as well as the position of the grains in a given AudioBuffer. When added to the scheduler, an engine generates grains with the given period at the given position — that usually is randomly varied for each grain within given boundaries.

```javascript
get currentPosition() {
    return this.position;
}
```

Figure 6: The default currentPosition attribute getter of the GranularEngine class.

Internally, the engine uses the currentPosition attribute to generate a grain, that by default is defined as the value of the position attribute (see figure 6). When added to a transport, the getter of currentPosition is redefined by the transport to return the current transport position transformed through the alignment parameters defined for the engine (see figure 4 in 3.2).

This way, the engine becomes a granular player that is automatically aligned to other engines controlled by the same transport. To create a simple granular player, the user can create a GranularEngine instance with PlayerControl instance (see figure 7).

```javascript
var engine = new GranularEngine();
var player = new PlayControl(engine);
engine.period = 15;
engine.duration = 120;
player.start();
```

Figure 7: Example code composing a granular player from a GranularEngine and a PlayerControl.

4.3 The SegmentEngine

The SegmentEngine synthesizes sound segments that are defined by an array of onset positions and durations referring to an AudioBuffer. The engine’s implementation and parameters largely resemble those of the GranularEngine class described in 4.2. Like the metronome (see 4.1), the SegmentEngine implements both the scheduled and transported interfaces. In the scheduler, the engine produces sound segments selected through the segmentsIndex attribute at regular time intervals while allowing for controlling their period, duration, and resampling by a set of attributes. When added to a transport, the segment onset positions are aligned to the transport position, which allows for playing the segments with different tempi – also backwards – and for rearranging their order by appropriately controlling the transport speed and position.
4.4 The PlayerEngine

The PlayerEngine completes the set of TimeEngine classes that implement different interfaces to playback recorded audio aligned and synchronized through a transport by a simple audio player. The engine implements the speed-controlled interface and derives the control of an AudioBufferSourceNode from the syncSpeed method calls (see figure 8).

```javascript
// TimeEngine speed-controlled interface
syncSpeed(time, position, speed, seek) {
    var lastSpeed = this.speed;

    if (speed !== lastSpeed || seek) {
        if (seek || lastSpeed * speed < 0) {
            this.start(time, position, speed);
        } else if (lastSpeed === 0 || seek) {
            this.start(time, position, speed);
        } else if (this.bufferSource) {
            this.bufferSource.playbackRate = speed;
            this.bufferSource.setPitchValueAtTime(speed, time);
        }
    } else if (speed === 0) {
        this.halt(time);
    }
    this.speed = speed;
}
```

Figure 8: Implementation of the speed-controlled interface in the PlayerEngine class. The internal methods start and halt create, start and stop an AudioBufferSourceNode using the given parameters.

Associated to a PlayControl the PlayerEngine provides a simple audio player. When added to a transport, multiple instances of the class can be composed to multi-track audio player synchronized to engines of the other interfaces.

5. CONCLUSION

We have presented an API and a set of Javascript modules for the scheduling and synchronization of modules that generate or playback sequences of events or media streams using the Web Audio API. The article summarized the underlying concepts as well as the implementation of the provided TimeEngine base class and masters: the scheduler singleton, the Transport class and the PlayControl class. Finally, we have briefly described a set of example modules extending the TimeEngine class to further illustrate the presented concepts.

Since early on, the TimeEngine API and the presented master and audio processing modules have been used in the development of prototype applications for the WAVE and CoSiMa projects. These developments have guided the design and allowed for validating many of its aspects.

The developed software modules are available on GitHub, under BSD-3-Clause license, as separate repositories associated to the Ircam-RnD organization. The repositories include documentation and working examples. The documentation of the TimeEngine API can be found in the time-engine repository.

6. ACKNOWLEDGEMENTS

The developments described in this article have been conducted in the context of the WAVE and CoSiMa research projects, partially funded by the french National Research Agency (ANR, projects ANR-12-CORD-0027 and ANR-13-CORD-0010). We would like to thank our colleagues and project partners Sébastien (Robi) Robaszkiewicz, Benjamin Matuszewski, and Emmanuel Fréard for their precious contributions to this work.

7. REFERENCES