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FlueBricks: 互動式笛類樂器系統的模組化工具包

FlueBricks: A Modular Toolkit for Interactive Flute-like Instrument Systems

陳柏昱
Bo-Yu Chen

指導教授: 鄭龍磻 博士
Advisor: Lung-Pan Cheng Ph.D.

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四年恍如隔世，已經記不得剛讀碩士的自己是什麼樣子，或許再過多幾年我也會忘記現在這即將畢業的樣子，因此想將這些最值得感謝的文字放在這篇碩士論文裡，謝謝他/她們陪我走了一段。

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摘要

本論文提出 FlueBricks：一套用於製作與客製化笛類樂器的聲學建構模組套件。FlueBricks 將氣動聲學特性融入 3D 列印模組中，使使用者能透過組裝建構出具備不同聲學行為的笛類樂器。FlueBricks 由三種類型的模組構成：(1) 發聲用的生成器模組、(2) 決定管長與共振的共振器模組，以及 (3) 用於連接與氣流導引的連接器模組。透過這些模組，使用者可以操作發聲方式、管身長度與音孔位置，進而改變樂器的音色、音高與外型尺寸。FlueBricks 支援使用者親手製作、調整與測試樂器聲學行為，讓傳統上被視為靜態成品的笛類樂器，轉化為可互動的聲學系統。FlueBricks 將樂器聲學原型設計的機會帶給非專業樂器製作者的使用者，使得設計者—演奏者—樂器的循環不再只是專業樂器製作者的專利，也成為一般演奏者能參與的實作體驗。為了理解使用者如何與系統互動，我們進行了一項探索性使用者研究，邀請 12 位涵蓋新手至專家的參與者進行自由探索。我們觀察到參與者流暢地在設計者與演奏者角色之間轉換，設計出具個人特色的樂器並探索聲音效果，顯示 FlueBricks 在實作式學習上的潛力。我們進一步分析這些行為，並提出對於設計直覺式工具的啟發，使使用者能在更廣泛的樂器類型中促進創造力與聲學理解。

關鍵字：樂器原型設計、聲學模組套件、笛子

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Abstract

We present FlueBricks, a construction kit that enables users to build and customize flute-like instruments by assembling 3D printed building blocks that emobody aeroacoustic properties. FlueBricks consists of three modular types: (1) generator, (2) resonator, and (3) connector modules that allow users to manipulate tone production, tube length, and tone hole placement, resulting in changes in timbre, pitch, and form factor. This supports a hands-on experience of constructing, adjusting, and testing acoustic behavior, shifting from treating acoustic instruments as static artifacts to engaging with them as interactive systems. FlueBricks thus makes instrumental acoustic prototyping—a designer–player–instrument loop that was once exclusive to expert instrument makers becomes accessible to users who traditionally can only be players. To understand how users engage with our system, we conducted an exploratory study with 12 participants from novices to experts. We observe the process of fluently switching between designer and player roles, crafting unique instruments, and discovering sound effects, suggesting the potential of FlueBricks

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for hands-on learning. We analyze these behaviors and derive implications for designing intuitive tools that boost creativity and acoustic understanding across other instruments.

Keywords: Instrument prototyping, acoustic construction kit, flute

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Chapter 1 Introduction

1.1 Introduction

Tangible prototyping toolkits [13, 15] have long been one of the cores in technical Human–Computer Interaction (HCI), enabling non-experts to engage in hands-on learning experiences [35] and rapidly go through design iterations [32]. Many modalities such as visual, haptic, and even olfactory have been embodied as tangible toolkits [9, 11, 24].

In contrast, the relationship between instrument makers and players has long been bifurcated across history [28, 38]. The main reason is that instrument making requires complex acoustic tuning processes involving specialized craftsmanship [36, 44], excluding non-experts from design iterations.

Figure 1.1: Overview of the FlueBricks design and exploration workflow, illustrating the iterative loop between the roles of designer and player while constructing the instrument. (A–C) Users browse modular components, select a mouthpiece, and explore its timbre. (D) As designers, they assemble a resonator body from modular parts. (E) As players, they test the instrument through listening and performance. (F–H) Based on their evaluation, they reconfigure components to refine acoustic outcomes. This process embodies a tangible, user-driven cycle of instrumental acoustic prototyping.

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With the advancement of recent computer and fabrication technologies, researchers have been inventing and reinventing instruments in digital ways, bypassing the constraints from traditional craftsmanship. Several advanced gesture input [16, 22, 23] and acoustic output [26, 31, 33] techniques have been proposed, ready to be combined into a wide range of new digital instruments. With 3D printing technology, many people also have replicated or adapted existing forms of instruments [3, 34, 51].

Flute-like instruments, historically simple yet culturally pervasive instruments [6, 7, 41], also have not been left behind. Functional flutes [20, 50] and computational design tools [45] provide sophisticated resonance modeling in digital ways.

However, these systems rely on extensive digital simulation or complete refabrication for each design change. Few support direct, hands-on, tangible exploration of physical acoustic properties. The closest related system is Acoustic Voxels [25], which still has simulation-based workflows that separate design from real-time experimentation, limiting accessibility for users who wish to engage more intuitively with airflow, resonance, and instrument design.

We present FlueBricks, a construction kit for building and customizing flute-like instruments through 3D-printed building blocks. Fig. 1.1 shows how users work with FlueBricks. FlueBricks offers several tangible building blocks that embody the aeroacoustic properties of flute-like instruments. Users browse these modular components (Fig. 1.1A) and start by picking a mouthpiece for testing (Fig. 1.1B). By breathing directly into the module, users hear the sound it generated (Fig. 1.1C). With its tangibility, it induces users' curiousity to start connecting with other modules, making them switch roles to instrument designers (Fig. 1.1D). As soon as users put on another module, users immediately

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switch back as players and test the sound again (Fig. 1.1E). This keeps users in the rapid design iteration of a flute-like instrument by constantly recombining tangible modules (Fig. 1.1F&G) and responsively evaluating the sound effect (Fig. 1.1H).

To understand how users with various levels of musical and woodwind expertise engage with *FlueBricks*, we conducted a 12-participant exploratory user study. We observed that the participants successfully built working flute-like instruments, showcasing FlueBricks' s potential for accessible and creative instrument design. We also validated a recurring pattern where users iteratively configured, played, and reconfigured their instruments, leading to novel acoustic discoveries. Expert participants also discovered advacned techniques in FlueBricks including the use of overblowing for multiphonic effects and strategic module placement for refined pitch control.

Contribution

FlueBricks emerges as a distinct conjunction of prototyping, acoustic design, human-instrument dynamics, and flute-making, bridging their gaps with a aeroacoustic-embodied toolkit. Unlike simulation-heavy acoustic toolkits that are made for experts with digital precision, it invites hands-on play with airflow and resonance. In contrast existing 3D printed instruments that adapt pre-set acoustic frames, FlueBricks offers more fine-grained modularity. FlueBricks thus bring flute-making' s legacy—from Boehm' s precision [49] to Printone' s [45] resonator— from complex modeling to intuitive, accessible, block-based design, dissolving the gap between instrument makers and players, and welcoming from novices and experts alike into acoustic exploration.

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Chapter 2 Related Works

We broaderly review literature with background on (1) prototyping and DIY tookits, (2) acoustic design and (3) human-instrument relationship in this section.

2.1 Prototyping & DIY Toolkits

Prototyping and DIY toolkits have long been central to Human-Computer Interaction (HCI), enabling users to iteratively transform abstract ideas into tangible systems [15]. Platforms like Arduino and Phidgets [13] have democratized interactive system design, empowering non-experts to experiment with hardware and fostering learning through construction [32, 35, 40].

A wide range of toolkits have emerged to support interaction prototyping across modalities. In the visual domain, ProtoBricks [9] offers modular blocks for tangible data displays; VoxelHap [11] enables customizable haptic proxies for virtual feedback; and O&O [24] introduces a scent-based toolkit combining modular hardware with cardboard templates. These systems lower technical barriers and encourage hands-on exploration.

Compared to visual, haptic, and olfactory toolkits, in the next section, we find that few modular systems support accessible physical experimentation with acoustic behavior

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despite the expressive potential for sonic feedback and musical interfaces.

2.2 Acoustic Design

Acoustic interaction offers unique affordances: supporting hands-free, eyes-free, and ambient feedback through a modality that is always perceptible. Unlike visual or tactile channels, auditory perception , making sound well-suited for implicit interaction, accessibility, and spatial awareness.

Researchers have developed a range of acoustic techniques for sensing and rendering. Systems such as Acoustruments [23], SqueezaPulse [16], and Ubicoustics [22] detect gestures and object manipulation through passive microphones, enabling low-cost embedded sensing. On the output side, systems like Holographic Whisper [33] and VARI-SOUND [26] use phased arrays and metamaterials to spatialize or steer sound. SoundBender [31] extends this by combining phased arrays and acoustic metamaterials to deliver mid-air haptic feedback through controlled ultrasound propagation.

While these systems demonstrate the power of sonic interaction, few resources support physical, hands-on exploration of acoustic behavior. For instance, Acoustic Voxels [25] introduces a geometry optimization algorithm for designing acoustic filters and resonators with precise frequency responses. However, it relies on simulation-heavy, fabrication-first workflows that decouple design from real-time experimentation. Modular systems that invite users to directly manipulate airflow and resonance remain rare, leaving the vacuum for intuitive, iterative tools for acoustic prototyping.

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2.3 Human–Instrument Relationship

The origins of musical instruments reflect a close connection between making and playing. Early humans clapped, stomped, and used simple objects such as sticks or bones to accompany dance and ritual [28]. Over time, instrument design became more complex, requiring specialized skills in construction and acoustic tuning [38]. This evolution widened the divide between players and makers, with modern acoustic instruments often requiring expert craftsmanship to modify.

On the other hand, digital music tools have reshaped this relationship. Synthesizers, samplers, and software-based instruments offer flexible sound manipulation, enabling users to design, modulate, and perform sound within a single system [43]. This convergence blurs traditional roles and raises questions about what defines an instrument [21]. It has also fueled the development of Digital Musical Instruments (DMIs) that emphasize modularity and live control [48].

Acoustic instruments are catching up the trend. Projects like the Modular Fiddle [34] and LeMo [3] break traditional designs into customizable parts for user-defined configurations. However, they often reuse pre-established forms (e.g., violin body plans) or remain structurally modular without engaging directly with acoustic principles. Others, like the Yaybahar [51], explore novel hybrid intstrument designs but lack reconfigurability. These efforts have shown steps toward democratizing acoustic design. We inherit the spirit of these prior works and continue to evolve into accessible, principle-driven systems that empower users to iteratively explore sound through physical construction.

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2.4 Flute Design & Making

The flute is among the oldest known instruments, with early forms—crafted from bone, bamboo, or wood—dating back over 40,000 years [4]. Across civilizations, end-blown, side-blown, and fipple flutes emerged with distinct designs and cultural functions [46]. In the 19th century, designers like Boehm and Rockstro introduced tone-hole placement systems grounded in acoustical principles [49], initiating a shift from empirical craft to theoretical modeling. This work laid the foundation for later researchers to develop mathematical and computational models that explain the mechanisms of flute-like instruments [44]. Meanwhile, organ research on flue pipes contributed key insights into airflow dynamics, turbulence, and jet-edge interactions [36], complementing modern flute acoustics.

Widely adopted for their simplicity, affordability, and accessibility, recorders—a type of fipple flute—have long been central to music education. Introduced in 1930s England during a Renaissance revival, they became staples in schools worldwide by the mid-20th century [41]. Contemporary efforts like Yamaha’s School Project continue this legacy by supplying instruments, materials, and training to foster collaborative and expressive learning [6, 7]. In recent years, alternative materials such as PVC [19] and paper [18] have enabled DIY flutes for educational use. More significantly, 3D printing has expanded the design space, allowing functional plastic and titanium flutes [20, 50]. Computational tools like Printone [45] use acoustic simulations to generate 3D models with precise resonance control, enabling novel tunings and unconventional geometries.

Despite these innovations, most flute making remains limited to experts or simulation-driven systems. For example, Printone prioritizes resonator optimization but offers little

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support for hands-on modular exploration. Most of physical adjustments require complete refabrication, making real-time experimentation difficult, not to mention supporting intuitive engagement with airflow, tone production, and acoustic behavior.

2.5 Summary

FlueBricks bridges gaps across existing toolkits, acoustic design, musical interaction, and flute-making by introducing a modular, aeroacoustic system for hands-on sound exploration. Unlike toolkits focused on visual or haptic modalities [9, 11], or simulation-driven design tools like Acoustic Voxels [25], it enables physical experimentation with airflow and resonance. Compared to structurally modular systems like the Modular Fiddle [34] or design-centric tools like Printone [45], FlueBricks supports intuitive, principle-driven assembly. By making acoustic construction accessible and modular, it invites both novices and experts to engage in playful, iterative instrument design.

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Chapter 3 Flute-like Sound Mechanisms

FlueBricks decompose and embody the acoustic behaviors of flute-like instruments based on their sound mechanisms. Figure 3.1 illustrates the three-phase mechanism of sound production in flute-like instruments, highlighting how airflow, edge interaction, and resonance are tightly coupled to sustain oscillation. The sound occurs as the player breathes an air jet to strike a sharp edge, and the acoustic feedback of the resonator reinforces the vibrations, sustaining the oscillations at the pipe’s natural frequencies [12].

The pipe-shaped resonator amplifies and selectively reinforces specific frequencies because the resulting sound waves reflect between boundaries and form standing waves at resonant frequencies. The pipe’s *effective length*—the portion that acoustically contributes to resonance—is thus shaped by its geometry, depending on whether the ends are open, closed, or partially vented [12]. Figure 3.2 illustrates how these geometries alter the effective length and resonance behavior.

In general, for cylindrical pipes, the resonant frequencies are inversely proportional to their effective length. The open pipes follow $f_n = \frac{nv}{2L}$, while the closed pipes follow $f_n = \frac{(2n-1)v}{4L}$, where f_n is the resonant frequency of the mode n, v is the speed of sound and L is the effective length. These relationships define the standing wave modes that can

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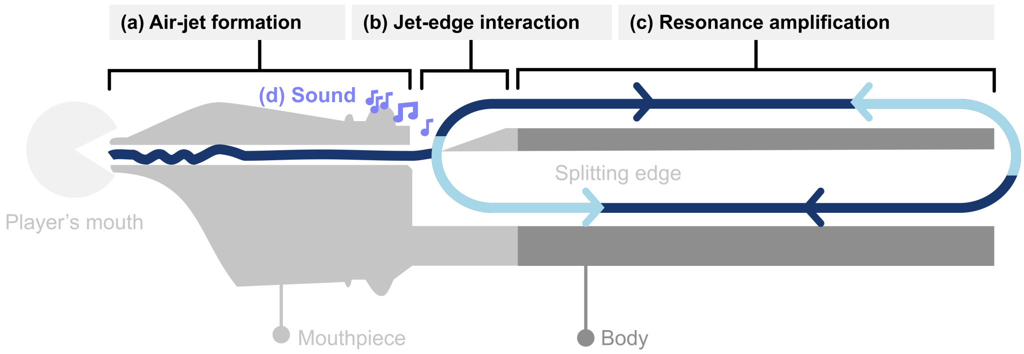

Figure 3.1: **Three coupled phases of flute-like sound production.** (a) *Air-jet formation*: blowing into the mouthpiece creates a focused jet of air. (b) *Jet–edge interaction*: the air jet encounters the labium, a sharp edge, and oscillates between the inside and outside of the pipe, producing an edge tone. (c) *Resonance amplification*: The jet–labium interaction generates pressure oscillations that excite the resonator, which selectively reinforces certain frequencies through resonance to sustain the sound.

form, and explain why longer pipes produce lower pitches, and why closed pipes yield different harmonics than open ones.

Tone holes further complicate the picture by introducing local changes in acoustic impedance. A sufficiently large tone hole behaves like a new open end, effectively shortening the resonator and raising the pitch. If the hole is small or partially open, some wave energy continues passing it, and thus the effective length should be corrected to account for the inertia of the air column in the hole, known as the *open-hole correction* [12]. These structural subtleties enable for precise pitch control without changing the physical tube length; players open or close holes to modify the effective resonator length, thereby adjusting the pitch. A more advanced technique, *glissando* [29], enables continuous pitch variation by gradually altering the resonator length in real time by sliding or deforming the effective length, as seen in a sliding whistle.

Beyond structural manipulation, pitch can also be controlled by overblowing [47]. The edge tone frequency shaped by blowing pressure and jet dynamics can couple with higher-order resonant modes, causing the system to shift resonance to upper harmonics

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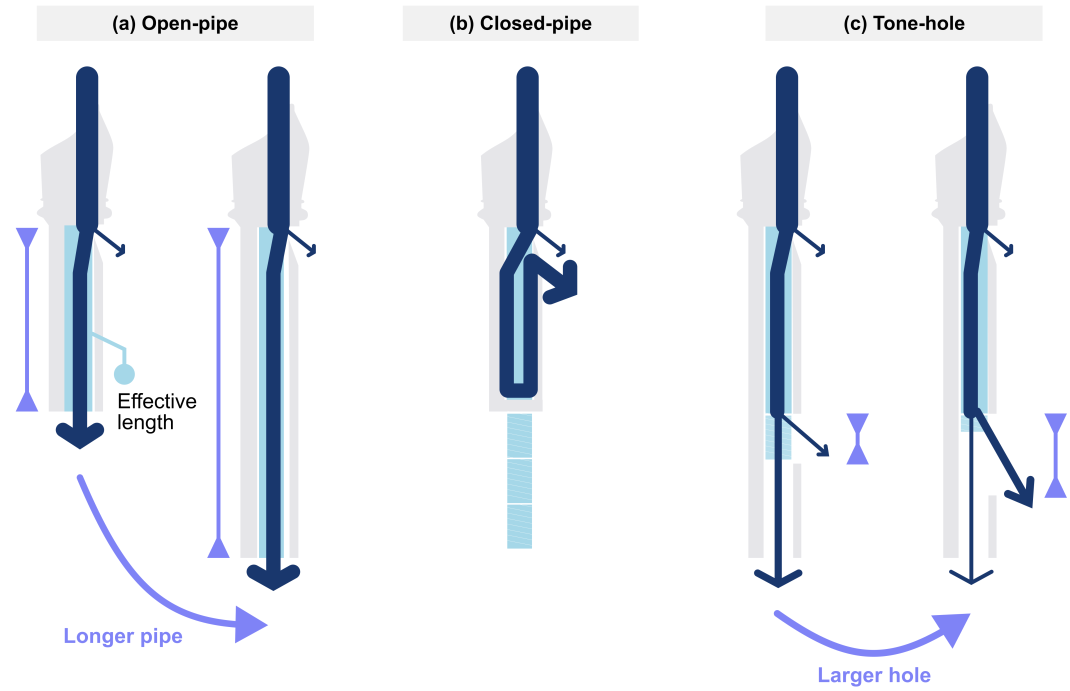

Figure 3.2: How changes in pipe geometry affect pitch. This figure compares three types of resonator configurations. Left: an open pipe creates sound by supporting vibrations along its full length, with both ends open. Middle: a closed pipe supports a different vibration pattern, resulting in a *longer effective length* and a lower pitch compared to an open pipe of the same size. Right: a tone hole acts like a shortcut: if large enough, it defines a new endpoint for vibration, effectively shortening the pipe and raising the pitch. The cyan region shows the *effective length*—the part of the pipe that actually shapes the sound.

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within the same resonator. By carefully controlling air pressure near these mode transition points, players can go a step further with multiphonics [37], simultaneously exciting multiple resonances to produce more than one pitch. These techniques demonstrate how airflow dynamics interact with structural acoustics to expand the expressive range.

This sets the three categories of FlueBricks: connector, generator and resonator. FlueBricks also support all different techniques like multiphonics and glisando.

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Chapter 4 FlueBricks

This section details the FlueBricks system, which supports modular, physically intuitive exploration of acoustic behavior. We first present a walkthrough that demonstrates how users reconfigure components to shape airflow and tone. We then outline the system's core modules—*Generators*, *Resonators*, and *Connectors*—and their design rationales, followed by their fabrication and assembly methods that enable reusability and structural stability.

4.1 Walkthrough

Users start building their instrument by choosing a *basic node* block from three different lengths: Short, Medium, and Long (Fig. 4.1a). Users pick a *basic node (M)* and breathe into it, hearing a low, rounded tone (Fig. 4.1b-1). They also verify that swapping in a *basic node (S)* raises the pitch and produces a brighter quality. Driven by curiosity, they stack a *basic node (S)* onto a *basic node (M)* (Fig. 4.1b-2) and hear slightly lower pitch; doubling the *basic node (M)* deepens it further (Fig. 4.1b-3). When stacking ten *basic node (M)* modules (Fig. 4.1b-4), the instrument produces a deep resonant sound, ocassionally resulting in multiphonic effects. Attaching an *adapt cap* to the base-node shifts to a closed-pipe mode (Fig. 4.1c), lowering the pitch again and imparts a darker

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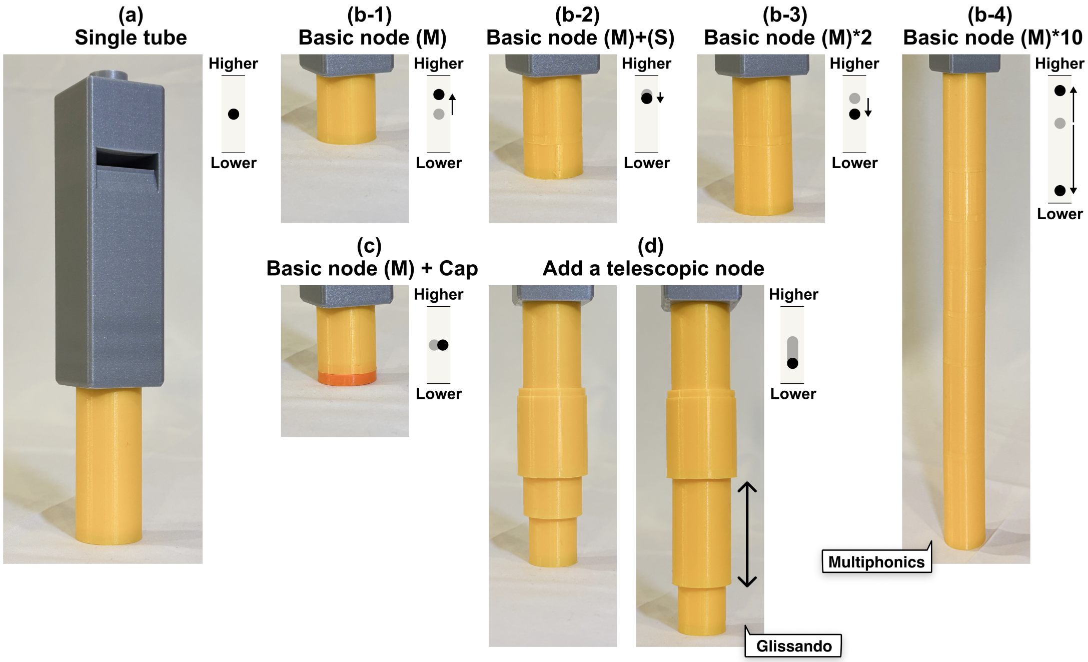

Figure 4.1: Users explore pitch and timbre by assembling different resonator configurations in FlueBricks. Starting from a single tube (a), they experiment with stacking (b-1 to b-4), sealing (c), and telescoping (d) to modify sound. Each action responsively changes acoustic feedback, helping users learn how shape and length influence tone.

tone. By assembling a *telescopic-node*, they discover how sliding it enables smooth pitch bending—mimicking a glissando (Fig. 4.1d). These modules let users tangibly explore how structural changes in the instrument shape pitch and timbre.

Users continue exploring tone shaping by attaching a *branch node*, whose tone hole fully opens and produces a relatively high pitch due to reduced resonator length (Fig. 4.2a), Adding a small *adapt cap* closes the opening and lowers the pitch (Fig. 4.2b-1). Swapping it for a wider *adapt cap* raises the pitch slightly, highlighting how tone-hole size influences tone (Fig. 4.2b-2). Rotating the cap reveals subtle pitch shifts based on hole alignment (Fig. 4.2b-3). For more continuous control, users switch to a *tuning node*, where a vertical slot enables broader tone shaping with fingers (Fig. 4.2c-1). Sliding a *tweak ring* over the slot allows real-time pitch modulation, producing smooth glissando effects (Fig. 4.2c-2). These modules let users to tangibly explore how tone-hole size, placement, and movement

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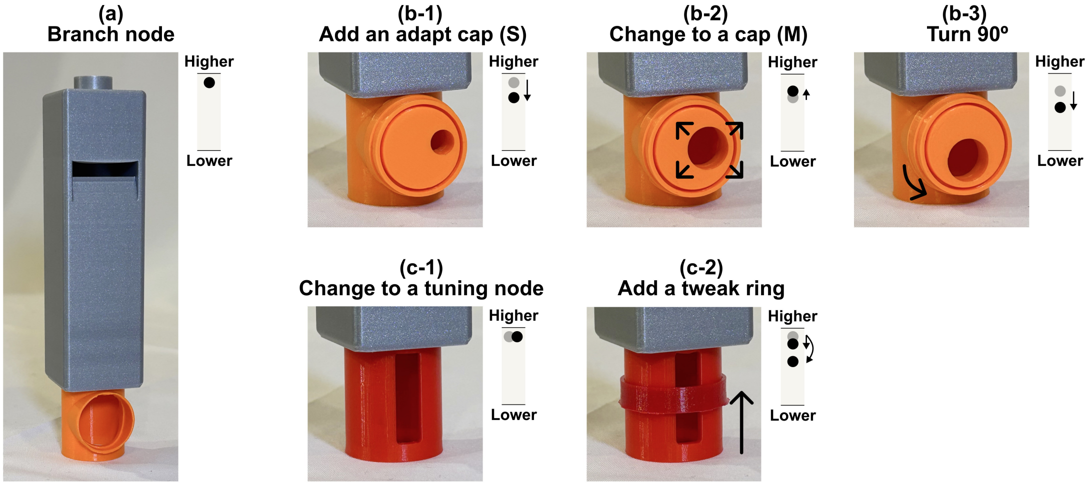

Figure 4.2: Users explore tone shaping with various tone holes and alignment. (a) A fully-opened *branch node* creates a high pitch. (b-1–3) Adding and rotating *adapt caps* adjusts pitch by changing tone-hole size and direction. (c-1) A *tuning node* with a vertical slot enables broader tone shaping with fingers. (c-2) A sliding *tweak ring* supports real-time modulation for glissando effects.

shape tone of the instrument.

Next, users explore how structural adjustments by combining the *basic node* and the *branch node* shape pitch contrast and articulation behavior. They shift the tone hole vertically while keeping the total tube length fixed, discovering that a higher tone hole reduces the pitch gap between the covered and the uncovered states (Fig. 4.3a). They keep the height constant but extend the side branch horizontally (Fig. 4.3b). As the branch grows, the lower note drops progressively ([E4] → [Eb4] → [Db4] → [Bb3]), while the upper note descends gradually ([G4] → [Gb4] → [F4]) before suddenly jumping an octave to [F5], producing a distinct multiphonic effect (Fig. 4.3b-4). These combinations further tangibly prompt users to treat spatial layout as a tool for musical expressivity.

Users can also combine FlueBricks with a familiar soprano recorder (Fig. 4.4a) to personalize their instrument. Here they test modular compatibility by inserting a green *bridge connector* between the mouthpiece and body (Fig. 4.4b). After confirming a secure fit, they remove the recorder’ s built-in mouthpiece and swap in an *all-in-one (L)*

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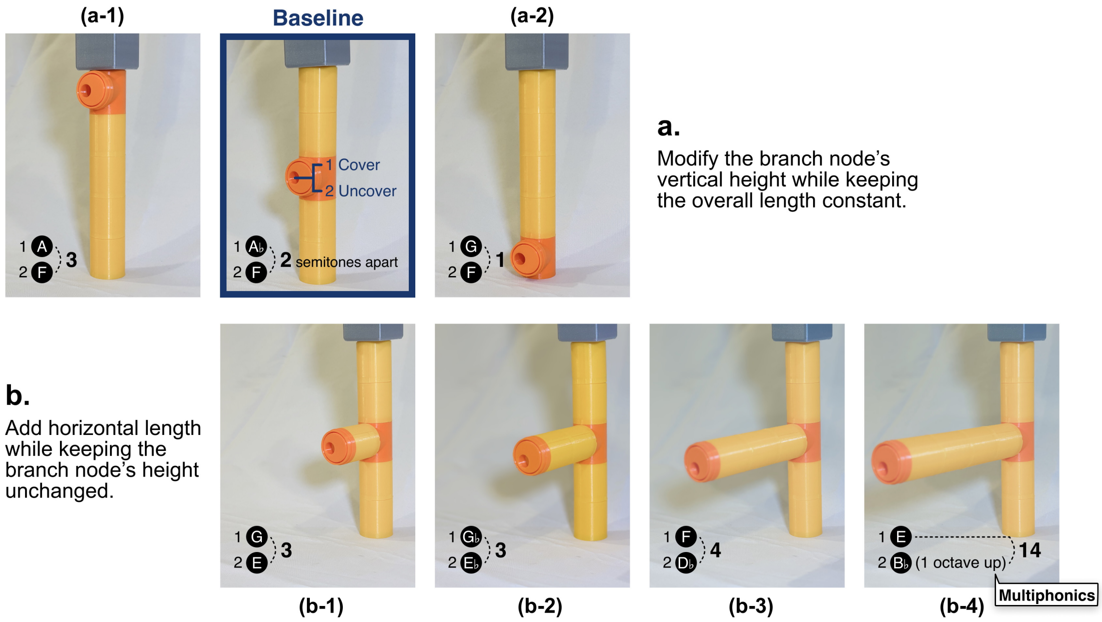

Figure 4.3: Users explore pitch contrast with *branch node* and *basic node*. (a) Raising the tone hole with fixed tube length narrows the gap between covered and uncovered tones. (b) Extending the horizontal branch lowers the covered tone and increases the pitch difference—eventually producing multiphonics at extremes.

generator (Fig. 4.4c). By breathing in, they immediately notice a timbral shift from focused clarity to a more breathy tone. They then attach an angled *air regulator* (Fig. 4.4d), which redirects the airstream to modify resistance while improving ergonomics. Finally, they add another *bridge connector* with a narrower inner diameter, acting like a muffler to reduce pressure and enable finer control over breath dynamics (Fig. 4.4e). This progressive reconfiguration transforms the recorder into a personalized airflow-controlled flute.

Users can even transform a traditional recorder into a multi-voice instrument—a **dual-chamber drone flute** (Fig. 4.5). After inserting a *bridge connector* to interface the mouthpiece with FlueBricks modules (Fig. 4.5a&b), they attach an *air distribution hub* to split airflow (Fig. 4.5c). They first test the setup with a single *basic node* (Fig. 4.5d), noticing how diverted air creates a second stable tone. They also combine with more *basic nodes* and *branch nodes*, eventually creating two simultaneous voices: a drone and a melodic line. This configuration demonstrates how FlueBricks supports multi-voice in-

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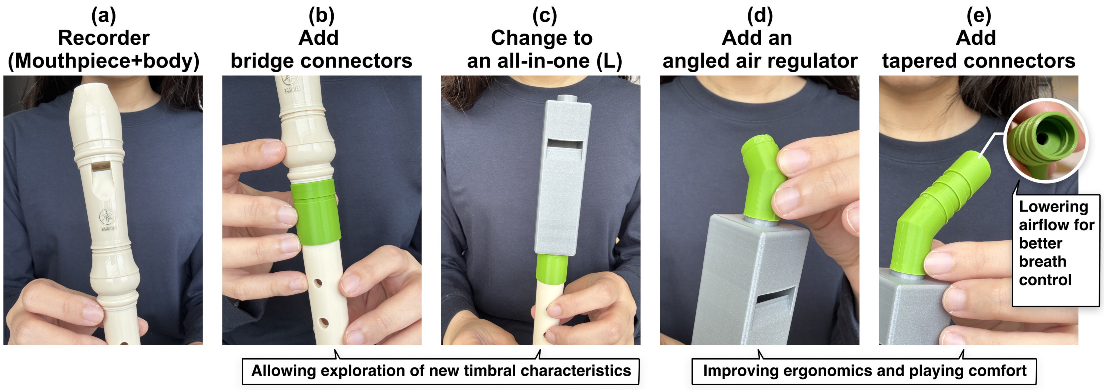

Figure 4.4: Users progressively personalize a recorder using FlueBricks modules. (a–b) A *bridge connector* ensures airtight compatibility. (c) Swapping in an *all-in-one (L)* generator alters the tone. (d–e) An angled *air regulator* and a *tapered connector* improve ergonomics and airflow shaping without changing the resonator body.

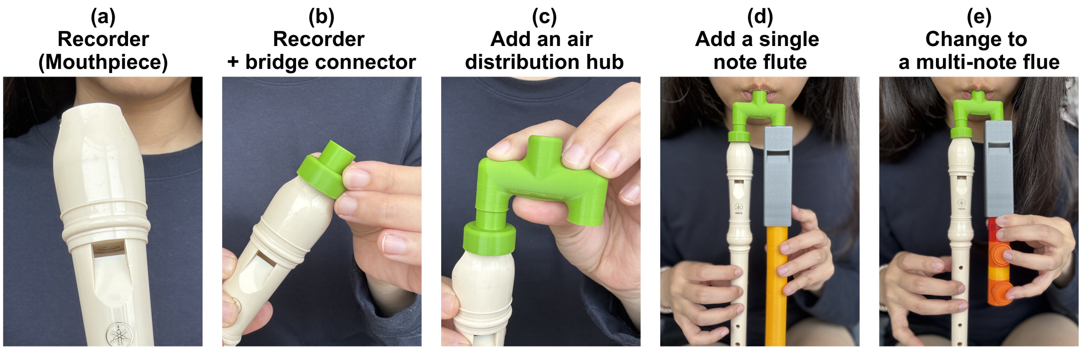

Figure 4.5: Users convert a recorder into a **dual-chamber drone flute**. (a–b) A *bridge connector* interfaces with FlueBricks. (c) An *air distribution hub* splits airflow. (d–e) Adding one or two resonators allows simultaneous drone and melody lines using breath-controlled harmony.

strument design, blending harmony and articulation with a single breath.

For advanced exploration, users dive into the modular generator system (Fig. 4.6). They assemble a standalone generator using eight interchangeable components, each modifying airflow and tone in targeted, controllable ways (see component labels in Fig. 4.7). Adjusting the *air deflector* angle (90°, 78°, 35°) reshapes airflow into the sound chamber, shifting the tone from focused high frequencies (90°), to rounded mid-frequency sounds (78°), to overtone-rich textures (35°). They then swap *air facade* variants—*sharp*, *flat*, and *arc*—to fine-tune timbre brightness and ease of onset: *flat* speaks clearest, while *sharp*

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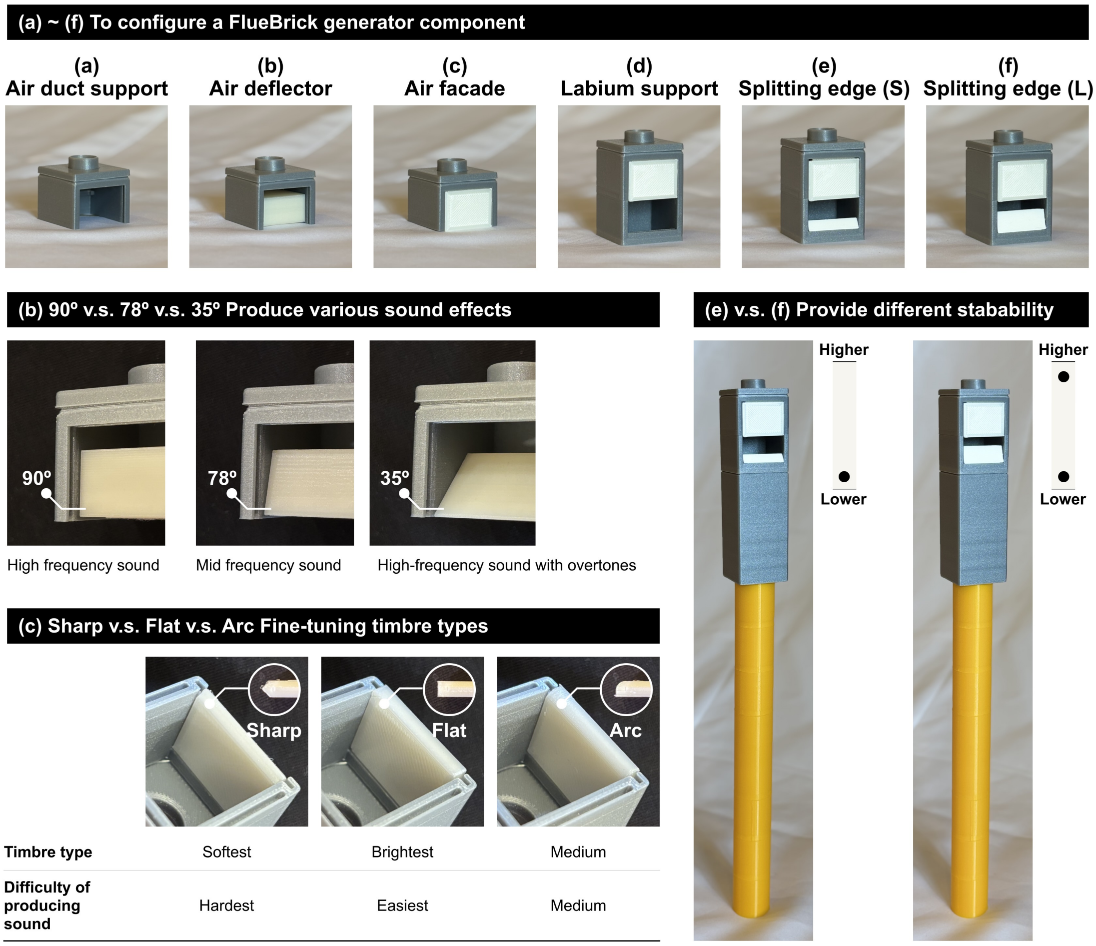

Figure 4.6: Advanced users explore how generator subcomponents shape tone and stability. (a–f) The generator is assembled from eight modular parts. (b) Varying *air deflector* angles alters airflow and frequency profile. (c) Changing the *air facade* affects timbre and onset behavior. (e–f) A shorter *splitting edge* raises the overblowing threshold, improving pitch stability in lower ranges.

yields a soft, airy tone that is hardest to control. Finally, they compare two *splitting edge* heights and find that a shorter edge increases the overblowing threshold, resulting in more stable pitch control especially in lower registers. This highlights the depth of FlueBricks incorporating acoustic properties, alllowing advanced users to construct fully personalized sound generators that have customized tone, response, and pitch stability through modular airflow design.

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4.2 Overview

Overall, FlueBricks consist of three component categories: *Generator*, *Resonator*, and *Connector*, as shown in Fig.4.7. This structure aligns with the modular taxonomy proposed in LeMo[3], except the radiator component, because in flute-like instruments the sound radiates primarily through the resonator body, tone holes and the mouthpiece window, making a discrete radiator element difficult to define. FlueBricks thus focus on components that modulate airflow, resonance, and articulation through physical configurations.

Generator

The *Generator* initiates airflow-induced vibrations and functions as the mouthpiece in woodwind instruments. To replace the monolithic design of conventional mouthpieces, we draw from fipple flute architectures—including the recorder, organ flue pipe [10], and Native American flute [8]—to create a modular structure based on two core acoustic elements: the fipple and labium [2]. To resolve inconsistent terminology across traditions, we adopt a function-based naming scheme: historical terms are referenced where relevant, but each part is labeled according to its acoustic role for clarity and modular consistency.

FlueBricks provides two sets for the Generator: a fully modularized advanced set and a standard set of pre-assembled *all-in-one* variants, labeled *all-in-one (m)* and *all-in-one (l)*. The standard set preserves the same internal geometries as the advanced set while maintaining affordances for intuitive use and rapid testing. The modularized set consists of eight components: *air intake*, *air duct support*, *air deflector*, *air facade*, *window regulator*,

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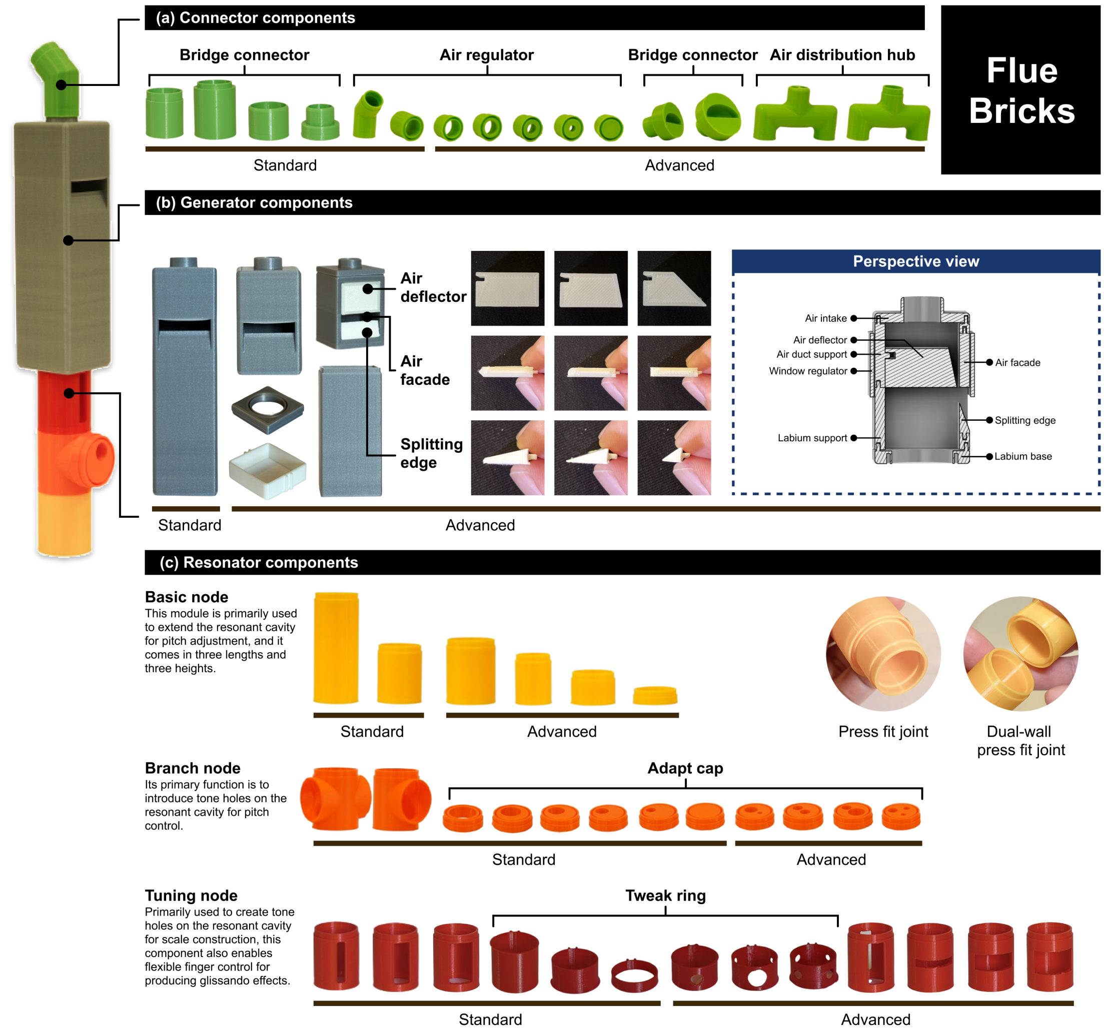

Figure 4.7: **Overview of the FlueBricks Modular Component System.** This figure presents a complete flute constructed entirely from FlueBricks modules, categorized into **Connector**, **Generator**, and **Resonator** components. Modules are designed with varying levels of complexity—ranging from *standard* to *advanced*—to support a gradual progression from basic structural assembly to rich acoustic experimentation. Subcomponents of the Connector and Resonator modules are annotated directly on the physical flute, while a zoomed-in sketch illustrates the internal structure of the Generator, highlighting its modularity and replaceability.

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splitting edge, *labium support*, and *labium base* (Fig. 4.7).

air intake. The *air intake* serves as the entry point for player breath input, regulating the amount of air entering the flute and initiating the airflow required for sound production. Functionally, it corresponds to the "foot" or "foot hole" in organ flue pipes, which is adjusted during voicing to control airflow volume [42].

air duct support. The *air duct support* provides the structural base for aligning and stabilizing all upstream airflow components. While it has no direct historical analogue, it plays a crucial role in ensuring consistent airflow and enabling modular assembly in the FlueBricks system.

air deflector. The *air deflector* redirects the incoming airflow toward the *splitting edge*, shaping the angle and stability of the airstream. Inspired by the *languid* in organ flue pipes and the *plug* in Native American flutes—voicing elements known to affect harmonic content and tonal balance [8, 27]—it forms a slow air chamber that buffers airflow before oscillation. Interchangeable slope angles in FlueBricks allow users to explore how internal redirection influences sound onset and tonal stability.

air facade. The *air facade* forms the outer boundary of the windway, preserving airflow speed and direction as it reaches the *splitting edge*. Functionally analogous to the lower lip in organ flue pipes—a common voicing site shaped to fine-tune tone [30]—this component in FlueBricks is offered in interchangeable forms that allow users to explore how outlet shaping affects tonal color, stability, and ease of speaking.

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window regulator. The *window regulator* adjusts the height and shape of the air window, influencing pitch, brightness, and articulation [17, 30]. Inspired by the “cut-up” in organ flue pipes and adjustable blocks in Native American flutes [8], it is made from soft TPU to support manual sliding, letting users shape tonal clarity and dynamic control in real time.

splitting edge. The *splitting edge* divides the airstream to trigger oscillation, with its geometry—sharpness, bevel, and alignment—shaping clarity, articulation, and harmonic content. Analogous to the ‘upper lip” in organ flue pipes [27, 30], it governs sound onset via edge-tone mechanisms. In FlueBricks, users can swap edge variants to explore how shape affects response and tonal stability.

labium support. The *labium support* stabilizes the *splitting edge* for consistent alignment with the windway and defines part of the cavity beneath the labium, subtly affecting pitch and resonance. While it has no direct historical analogue, it enables modularity by decoupling edge shaping from the base and supporting interchangeable labium configurations.

labium base. The *labium base* forms the bottom of the generator and connects to the resonator. Similar to the recorder’s ‘head joint” [14], it anchors the *labium support* and defines the generator’s chamber length—affecting its base pitch before further tuning via the resonator.

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Resonator

The *Resonator* modifies, selects, and amplifies the sound generated by the *Generator*, and plays a central role in pitch control—particularly in woodwinds [3]. While woodwind resonator designs vary across instruments [1], they share core acoustic principles, detailed in the *Flute-Like Sound Mechanism* section. Drawing from tone-hole–based instruments such as the flute, recorder, and organ flue pipe, FlueBricks adapts these architectures into modular, reconfigurable components. The system' s resonator includes five elements: *basic node*, *branch node*, *tuning node*, *adapt cap*, and *tweak ring* (Fig. 4.7).

basic node The *basic node* is the foundational unit of the FlueBricks resonator system, available in multiple diameter and length combinations—such as **M-short** (medium diameter, short length) or **S-medium** (small diameter, medium length)—that define segments of internal air volume. This modular naming enables users to intuitively compare and assemble parts with different acoustic characteristics, supporting both coarse and fine-grained control over resonance through geometric variation (see Fig. 4.1).

branch node The *branch node* introduces a lateral tone hole that acts as an acoustic termination, enabling pitch modulation through side-hole placement—much like traditional woodwind instruments. By default, it features a large circular opening and supports attachments like *adapt caps* for further control.

adapt cap The *adapt cap* attaches to a *branch node* to reduce the effective tone-hole size. Available in multiple diameters, these caps can be **rotated** to reposition their offset hole, enabling subtle pitch adjustments. Advanced variants may include multiple holes

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for more complex acoustic effects which show in Fig 4.7.

tuning node The *tuning node* replaces circular holes with vertical slots, inspired by the tuning slots found in organ flue pipes, traditionally used for fine pitch adjustment during voicing [39]. Slot dimensions and orientations vary which show in Fig 4.7., supporting both fixed and expressive (e.g., glissando) tuning behaviors. It pairs with the *tweak ring* for live control.

tweak ring The *tweak ring* wraps around a tuning node to dynamically cover or reveal parts of the slot. Users can slide or rotate the ring to modulate tone-hole exposure, enabling fine pitch control. Variants may include built-in holes to adjust tone through alignment with the underlying slot which show in Fig 4.7.

Connector

Unlike the *Generator* and *Resonator*, which produce sound, the *Connector* serves as the infrastructural backbone—supporting airflow routing, branching structures, and multi-voice configurations. Inspired by drone flutes and bagpipes [5], it enables users to construct multi-chambered instruments. The connector family includes three main components: *air distribution hub*, *air regulator*, and *bridge connector*.

air distribution hub The *air distribution hub* is the central airflow routing node in FlueBricks, enabling multi-chambered configurations by distributing air from a single source across multiple outputs. Inspired by drone flutes and bagpipes [5], it supports parallel airflow paths for dual-pitch instruments, layered articulations, or sustained drones. When

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paired with the *air regulator*, users can fine-tune airflow balance across outputs for dynamic control.

air regulator The *air regulator* shapes the geometry and orientation of the *air intake* to control airflow and improve player comfort. By adjusting the opening size and angle, it modulates internal pressure and loudness. When paired with the *air distribution hub*, it enables precise airflow balancing for dynamic expression across multi-voice setups.

bridge connector The *bridge connector* links FlueBricks modules or adapts them to standardized instruments such as soprano and alto recorders. It ensures airtight connectivity across diverse geometries, supporting hybrid constructions like dual-chamber flutes or extended resonator bodies.

4.3 Module Fabrication and Assembly

All FlueBricks modules were fabricated using fused filament fabrication (FFF) on Ultimaker S3 and S5 printers with a 0.1mm layer height for surface smoothness and dimensional precision. Rigid parts were printed in PLA, while flexible components—such as the *window regulator* and *tweak ring*—used TPU to support deformation and sliding (Fig.4.7).

Most modules use a dual-wall press-fit joint, where a male inner wall locks into a female outer wall to ensure structural stability without fasteners. Others—such as soft-material parts and telescoping *basic nodes*—rely on single-wall friction to enable flexible, reconfigurable positioning through simple press-fit interaction (Fig. 4.7).

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To enhance usability and remixability, we apply color coding to signal modular pairings (e.g., *tuning node* and *tweak ring*, *branch node* and *adapt cap*), visually reinforcing component relationships (Fig. 4.7).

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Chapter 5 Exploratory User Study

To investigate how users with various levels of musical and woodwind expertise engage with *FlueBricks*, we conducted an exploratory user study. Our goal was to examine the designer-player-instrument loop. We observed how participants interact with a deconstructed flute-like instrument toolkit with only minimal guidance to uncover emergent strategies, interpretations, and challenges that arise through self-guided exploration. We were particularly interested in how users interpret modular components without prior instruction (RQ1), how their musical and woodwind backgrounds shape exploration and design (RQ2), how they transition between designing and performing (RQ3), and what learning behaviors and discovery patterns emerge in an unguided setting (RQ4).

5.1 Participants

We recruited 12 participants, 7 males and 5 females, aged 20 to 51 (M=31.9, SD=7.5), evenly distributed across four distinct user profiles to ensure a range of musical and woodwind expertise:

- **Novice** = no formal musical training or woodwind experience.
- **Amateur** = informal musical training with some experience playing woodwind in-

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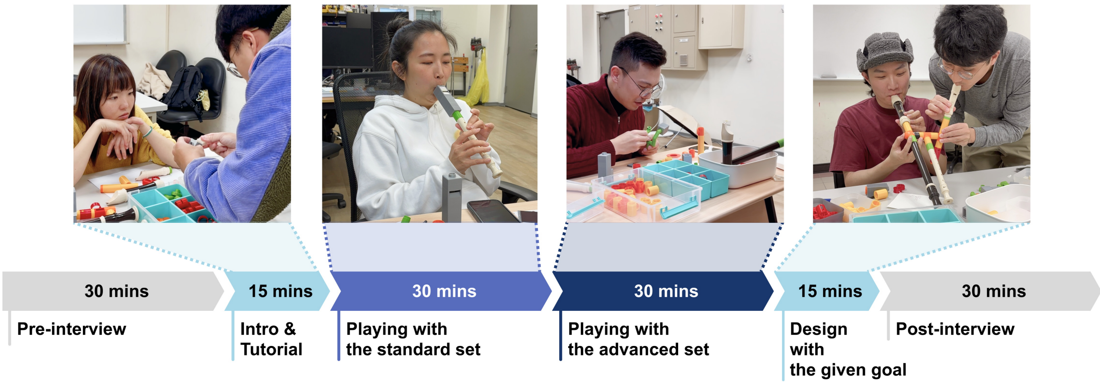

Figure 5.1: Overview of the user study procedure. The study consisted of six phases, alternating between interviews, open-ended exploration, and goal-directed design. While time blocks were planned, the schedule was flexibly adjusted based on each participant’s engagement level and curiosity.

struments.

- **Pro Woodwind** = formally trained in woodwind instruments.
- **Pro Musician** = formally trained music composer and producer.

Each group consisted of three participants. This stratified sampling allowed us to compare the influences on the interaction with FlueBricks between different types of participants. Participants were compensated with 750 TWD for completing the 2-hour session.

5.2 Procedure

The entire procedure is illustrated in Figure 5.1. Each user study session followed a semi-structured process consisting of six phases. While the total planned duration was two hours, we kept flexibility in mind to accommodate participants’ individual needs for exploration.

The session began with a 30-minute pre-interview, where we asked participants about

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their musical background, familiarity with woodwind instruments, and prior experience with creative building.

Next, we provided a 15-minute introduction and tutorial. In this phase, participants were shown how to physically assemble the components in the standard set. However, we deliberately refrained from explaining the function of each part or demonstrating any complete instruments. This allowed participants to form their own mental models and interpretations during the exploration phase.

It was followed by a 30-minute session of unguided exploration with the standard set. Participants were encouraged to assemble, modify, and play with the components freely, using a think-aloud protocol to share their reasoning, hypotheses, and discoveries in real time.

In the subsequent 30-minute session, we introduced the full FlueBricks toolkit with the advanced set, including all component categories: generator modules, an air distribution hub, and more advanced resonator components such as the adapt cap with triple tone holes. However, no instructions or explanations were provided. Participants were free to continue experimenting based on their own intuition and curiosity.

The fifth phase was a 15-minute design task where all participants created a classroom flute for elementary students. While the topic was fixed for consistency, participants could interpret 'classroom,' 'flute,' and 'elementary students' freely, allowing us to observe how personal interpretation shaped design outcomes.

Finally, a 30-minute post-interview concluded each session, where participants reflected on their FlueBricks experience—discussing impressions, takeaways, emotional journey, strategies, challenges, preferences, and improvement suggestions. They pro-

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posed future functionalities for the system. With consent, sessions were video recorded, and reflections were transcribed for thematic analysis of user interpretation, learning behaviors, and perceptions of system creativity.

5.3 Metrics and Coding Scheme

We developed a structured coding scheme to assess participant engagement with the *FlueBricks* system, covering both **module-level acoustic use** and **participant-level perceptual and emotional responses**. Codes were derived from think-aloud data, behavioral observation, and post-session interviews.

Module Use Categories Each participant–module interaction was classified according to its highest level of sound-related engagement:

- **Non-Acoustic**: Structural or aesthetic use, with no acoustic intent.
- **Exploratory**: Sound-focused testing or verbal speculation, even if not included in the final design.
- **Intentional**: Deliberate acoustic use, indicated by integration into an instrument or verbal explanation.

This categorization is visualized in a stacked bar chart (Figure 5.2), where each row represents a participant’s usage of a given module.

Perceptual Attention and Affective Summary We also coded four perceptual dimensions—*Pitch Variation*, *Timbre Variation*, *Onset Sensitivity*, and *Sense of Control*—using

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a 3-point scale based on how frequently each was referenced: **(1)** low (0–2 times), **(2)** moderate (3–4), **(3)** high (5+). Each participant received an **affective label**—*Positive*, *Neutral*, or *Negative*—based on the dominant emotional tone in their post-session interview, guided by a simplified arousal–valence framework. These scores are summarized in a heatmap (Figure 5.3) showing individual variation in perceptual focus and overall emotional response.

5.4 Results

To understand how participants engaged with and interpreted the FlueBricks system, we analyzed usage behaviors, perception patterns, and reflective interpretations through a combination of observational data and post-interview transcripts. Each subsection highlights a major theme supported by visual evidence and participant quotes.

5.4.1 Module Usage Patterns

Participants engaged extensively with the modular system, though the depth and nature of interaction varied across module categories (Figure 5.2).

Generators were universally recognized as sound-producing components. All participants interacted with at least one generator module, though the ways they approached and applied them varied considerably. Traditional generators (recorder-style mouthpieces) were intentionally used by 5 out of 12 participants—all with wind instrument backgrounds—who emphasized their reliability and familiarity. As P2 explained, *"I' m more familiar with it—it feels more reliable."*. The *all-in-one* generator was explored by 11 participants, but only 3 integrated it into final designs. Most used it primarily for experimenting with

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onset sensitivity and timbral variation, without a clearly defined acoustic objective. The *modular* generator saw the most evenly distributed usage: all 12 participants tried it, 5 explored internal variations, and 2 used it intentionally in their designs. Its modularity encouraged iterative play, though unstable airflow often posed challenges. Several participants began with the *modular* generator but switched to the *all-in-one* or traditional variant for more predictable tone production. Many noted difficulty comparing acoustic differences, as each reassembly reset the listening context. As P4 remarked, *"Every time I change it, I forget how the last one sounded."* Some suggested providing another *modular* generator for side-by-side comparison. Others found the assembly effort discouraging, especially when acoustic differences were minimal. Several noted that without a clear sense of improvement, it became harder to justify continued adjustments.

Resonators were the most widely adopted module category, appearing in nearly all final designs. The *basic node* was intentionally used by all 12 participants, typically serving as the primary resonating body. *Branch nodes* and *adapt caps* were each intentionally used by 11 out of 12 participants, often combined to form tone-hole-like structures for pitch modulation. These modules offered strong physical affordances; as P8 noted, *"This looks like it gives us a tone hole."* Many participants used multiple branch nodes simultaneously, exploring non-linear paths for tone control. This playful use of spatial configuration not only reflects a departure from traditional recorder-style designs, but also enabled novel acoustic experiments. The *tuning node* was intentionally used by 8 out of 12 participants, with 2 others exploring it without integrating it into their final designs. While some appreciated its length-adjusting role, others found it difficult to operate—often because they overlooked the *tweak ring*, which was designed to stabilize it during play. As P8 noted, *"Ah! I have to use both hands to cover everything—then it kind of feels not*

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worth it." Only 3 participants (P1, P4, and P12) used the *tuning node* and *tweak ring* in combination with clear acoustic intent. This group spanned different levels of musical background, suggesting that hands-on experimentation was especially important when a module's physical affordance was ambiguous or lacked cues inherited from flute-like instruments. The *tweak ring* was explored by 8 out of 12 participants but intentionally used by only 3. Lacking obvious form-function cues, it was frequently misinterpreted as a connector, stabilizer, or decorative piece. As P6 joked, *"Is this just for decoration?"* Its intended role—enabling smooth length adjustment when paired with the *tuning node*—was not immediately apparent. Three participants (P5, P7, and P11) independently reinterpreted the tweak ring as a sliding element for pitch control. They inserted it into slit-style tone holes and experimented with real-time motion to modulate pitch, later discovering that this use aligned with the designer's intent to adjust hole size. None of them included this behavior in their final design.

Connectors in this section focus on modules with potential acoustic function. The *bridge connector* is excluded, as it was intended purely for structural linkage. While some participants explored unconventional acoustic uses for it, these reinterpretations are discussed in Section 5.4.4 on emergent behaviors. The *air distribution hub* was explored by 11 and intentionally used by 10 participants—surpassing even the tuning node. Unlike most other modules, the hub has no direct counterpart in traditional recorder design. Yet its radial form prompted playful experimentation with airflow routing and tonal divergence. Some participants used it to produce multiple simultaneous tones by directing air into separate resonators. As P4 observed, *"It's like two flutes playing at once."* In one instance, two participants simultaneously blew into a shared generator routed through the hub, producing a combined sound. Several participants described the hub as visu-

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ally interesting or worth experimenting with, even before understanding its function. A similar response was observed with the bridge connector, which drew early attention due to its asymmetry and was often tested playfully. In many cases, these reinterpretations were carried forward into final designs—often to reinterpret the hub as a resonator. As P2 noted, *"It has nice pitch control,"* after experimenting with enclosing different outlets and redirecting internal air paths. The *air regulator*, by contrast, followed a more restrained usage pattern. Most participants treated it as a breath adapter and stopped experimenting once it stabilized airflow. Only four participants used it with explicit acoustic intent—two as unconventional resonators and one (P5) as a muffler for softening tone. Others overlooked its internal multi-hole structure entirely. As P1 reflected, *"I thought it just made blowing easier—I didn' t realize it changed the sound."*

Overall, modules with strong physical affordances or familiar forms—such as recorder-style generators and tone-hole-like branches were readily adopted. In contrast, less transparent or unconventional components, like the *tweak ring* and *air distribution hub*, prompted wider exploration and reinterpretation. Across categories, hands-on experimentation often preceded full comprehension, highlighting how acoustic discovery in FlueBricks emerged through iterative, material engagement rather than upfront understanding.

5.4.2 Perceptual Sensitivity and Exploratory Experience

Participants exhibited high perceptual engagement across sound-related dimensions, though sensitivity varied by expertise and interaction depth (Figure 5.3). **Pitch variation** was universally perceived, serving as the primary means of acoustic reasoning and control. As P1 noted, "*I managed to make something similar to a soprano recorder—something that can produce a sense of scale or pitch variation.*" They demonstrated this by blowing

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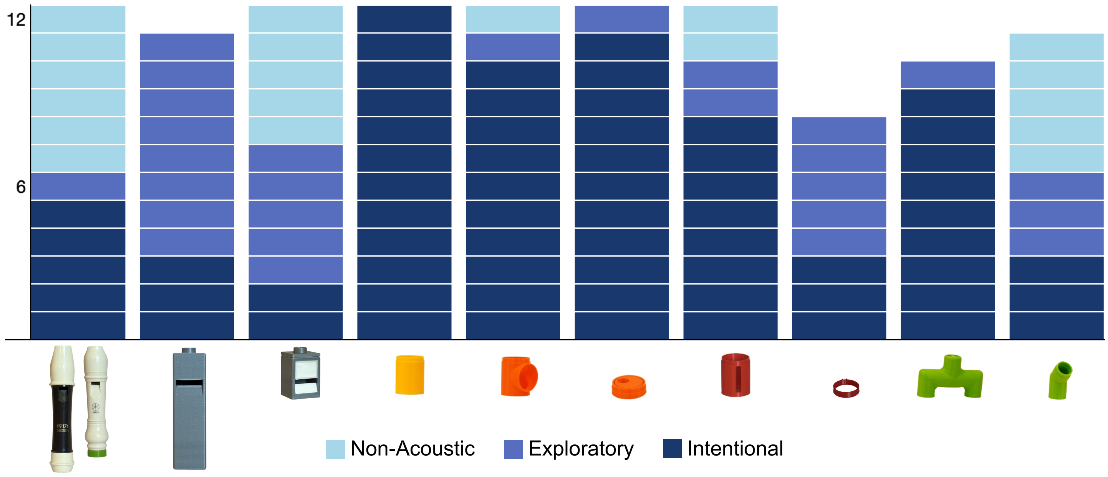

Figure 5.2: **Module-level acoustic use across participants.** Each row represents a participant and each column a module. Colors indicate the highest level of sound-related use: Non-Acoustic (no acoustic intent), Exploratory (acoustic testing), or Intentional (sound-related function).

into their assembled instrument and covering different holes to produce distinct pitches.

Timbre and **onset sensitivity** were less evenly distributed. Timbre variation was often prompted by structural contrasts—such as open vs. closed pipes, or the difference between all-in-one and recorder generators—and by fine-tuning through modular mouthpiece adjustments. Onset sensitivity, while least observed overall, was consistently reported by all three pro woodwind participants (P6, P7, P12). P8, though not a specialist, also exhibited high onset awareness, attributing this to his prior experience with overblowing on bassoon and saxophone.

A strong **sense of control** frequently coincided with positive affect, yet this pattern was not absolute. Most woodwind amateurs and professionals—except P2—demonstrated high control and correspondingly positive or neutral experiences. However, P10 and P11, despite their musical expertise, expressed lower control. P11, in particular, described the experience as frustrating and unpredictable: *"I didn' t know what was working or why… it felt random"*, and was the only participant with a negative summary. Conversely, P10,

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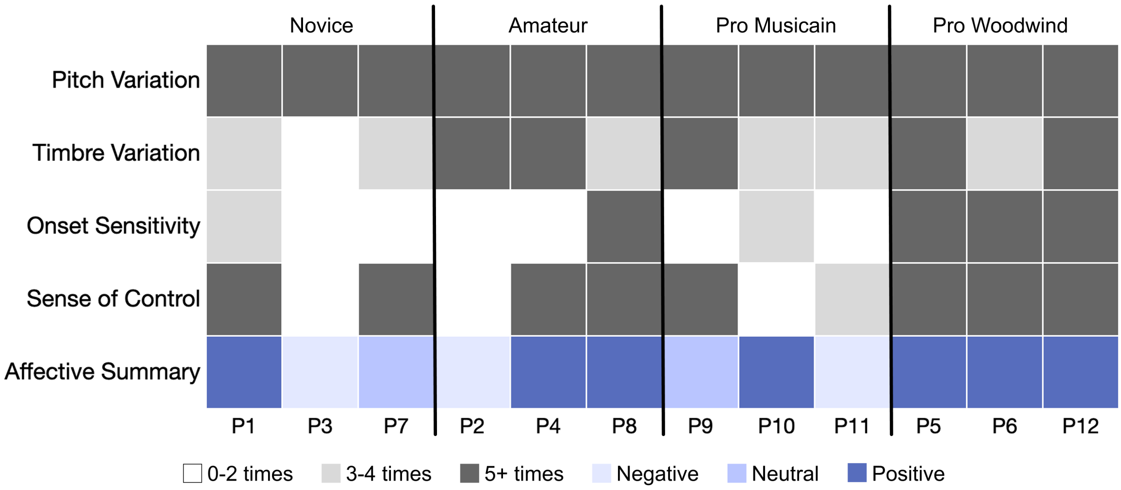

Figure 5.3: **Participant-level perceptual and emotional responses.** Each row shows one participant' s scores across four dimensions: *Pitch Variation*, *Timbre Variation*, *Onset Sensitivity*, and *Sense of Control*, rated by frequency of reference. Affective summaries (Positive, Neutral, Negative), based on post-session interviews, are shown alongside each participant.

while unable to explain several acoustic effects, still enjoyed the ambiguity: *"It didn' t behave like I thought, but that made it fun to explore."*

Overall, pitch was a foundational cue for nearly all participants, while higher-order sensitivities like timbre and onset required either targeted exploration or prior instrumental knowledge. Importantly, a high sense of control appeared to shield participants from negative emotional responses—even when outcomes were unexpected—highlighting the importance of perceived agency in exploratory creative systems.

5.4.3 Designer-Player-Discovery Loop in Action

We observed a recurring interaction pattern across participants, wherein acoustic discoveries emerged through fluid transitions between constructing, playing, and reconfiguring—a process we term the *designer–player–discover* loop. Figure 5.4 illustrates this loop through P12' s session, which exemplifies how iterative manipulation and real-time

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feedback led to novel sound outcomes.

P12 began by testing how far the basic node could be extended using the all-in-one generator before tonal stability was lost. This led to a distinctive *play-while-configuring* behavior, where the participant actively blew into the instrument while adjusting resonator length. As he noted, *"I'm trying to find the longest tube that still works"*.

After reaching a near-failure configuration—where standard blowing no longer produced a tone—P12 adopted an unexpected playing technique: overblowing. This revealed a previously unnoticed acoustic phenomenon, allowing the flute to generate layered textures near the resonance threshold. As he described, *"Wow, it makes a special kind of sound right at the edge—somewhere between two tones"*.

He then explored pitch modulation using the branch node and adapt cap. Initially placing the tone hole near the foot yielded minimal change, but relocating it closer to the mouthpiece produced greater pitch control. *"Putting it here doesn't do much···but up here, I can bend the pitch more clearly,"* he observed. The session culminated in a custom nine-note configuration combining airflow articulation, a bottom-side tone hole, and lateral control, enabling expressive modulation through both breath and finger placement. As he summarized, *"This is my best setting—I can control it with both breath and finger holes"*.

While P12 demonstrated a complete designer–player–discover loop, similar patterns emerged in other sessions. P1 discovered that subtle adjustments to the *splitting edge* angle significantly influenced tone activation, recognizing that edge geometry plays a critical role in sound production. P11, by attaching a *basic node* to a traditional recorder, discovered that multiphonic textures—typically requiring advanced skill—could be easily achieved through modular augmentation and controlled airflow. These examples show

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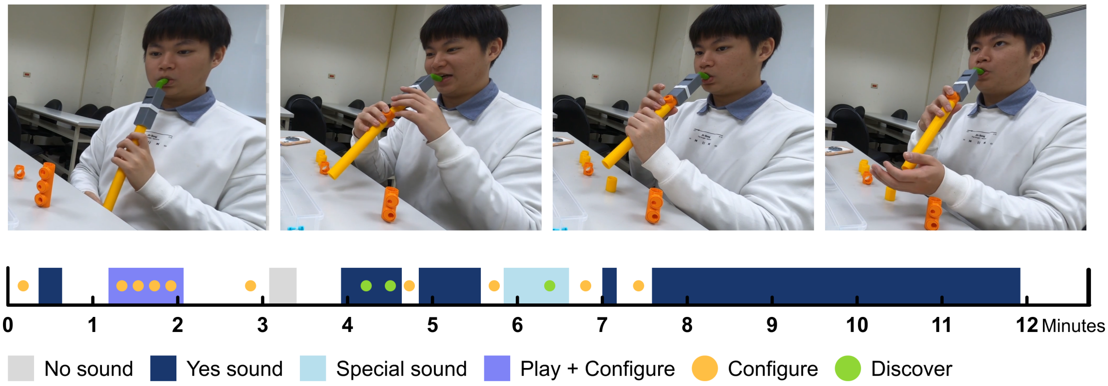

Figure 5.4: P12’ s session illustrates a *designer–player–discover* loop, where iterative configuring, playing, and reconfiguring led to novel sound outcomes. The participant explored resonator length limits, used overblowing to trigger multiphonic effects, and refined pitch control through strategic module placement—culminating in a setup with expressive breath and finger modulation.

how participants, through physical trial-and-error and real-time feedback, progressively evolved their designs in response to sonic outcomes—blurring the boundary between instrument designer and performer.

5.4.4 Reinterpretation and Emergent Acoustic Use

Beyond their expected acoustic roles, several FlueBricks modules were reimagined through tactile exploration and analogical reasoning (Figure 5.5). These reinterpretations often emerged from ambiguous or suggestive physical affordances that invited uses beyond the designer’ s intent. Some reinterpretations were grounded in structural resemblance to known instruments. For example, the *tuning node*, originally designed as a pitch-adjustable *resonator*, was reinterpreted by P6—a professional *dizi* player—as a standalone generator. Citing its similarity to the *dizi*, he remarked, *“Just this piece alone can form the structure of a dizi”*, and used it to prototype a side-blown flute. Others arose from embodied play. The *tweak ring*, intended to pair with the tuning node for length adjustment, was reinterpreted by P5, P7, and P11 as a glissando controller, inserted into tone holes to

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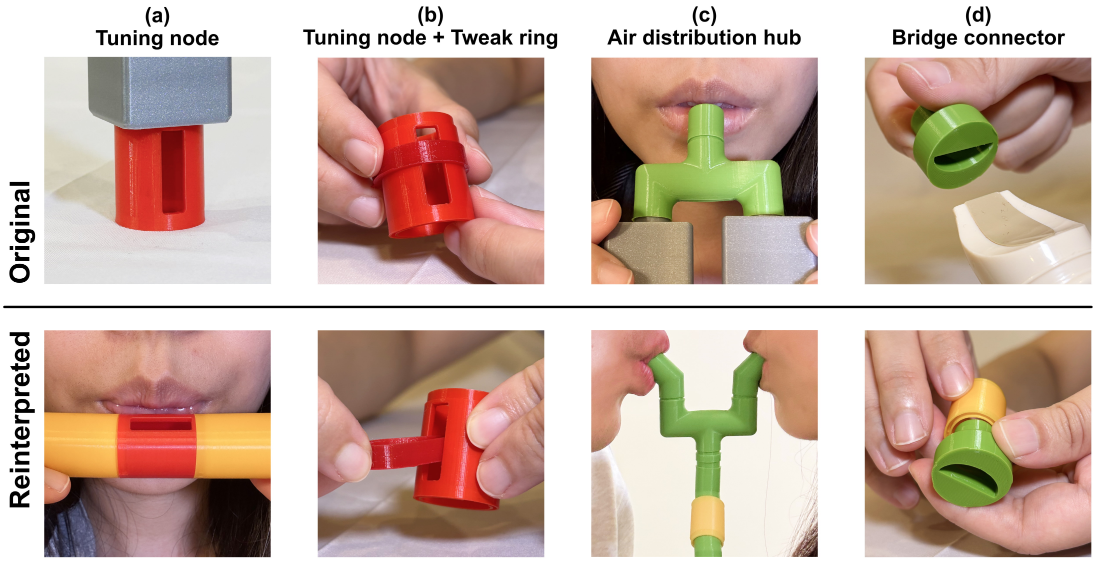

Figure 5.5: User reinterpretations of FlueBricks components. Despite their original functions—(a) tuning node, (b) tweak ring, (c) air hub, and (d) bridge connector—participants repurposed them creatively, revealing unexpected uses and modular flexibility.

modulate pitch in real time. P8 used the *bridge connector*, originally a rigid joiner, as a free-floating pitch slider. Rather than locking it in place, he sealed and unsealed it manually against a basic node, explaining: *"This piece is so responsive—while the others only gave me four notes, this one lets me play all kinds of pitches. When I hold it at just the right distance, it works like a trombone slide."* Similarly, P2 and P9 reimagined the *air distribution hub* and *air regulator* as resonators by redirecting airflow or enclosing openings. Reinterpretation also extended to social interaction: P1 configured the *air distribution hub* for simultaneous dual-player input, transforming it into a collaborative generator. These examples demonstrate a range of user-driven reconfigurations. While most did not appear in final designs, they reflect the breadth of acoustic behaviors discovered through physical assembly and experimentation.

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5.4.5 Final Design Strategies and Expressive Outcomes

Participants adopted a variety of strategies to construct their final instruments, shaped by the design prompt and their prior exploration. 4 out of 12 participants directly selected a previously assembled prototype—either as-is (P2, P4, P11) or with minimal extension (P9)—sometimes framing it to match the scenario even if the fit was only partial. The remaining 8 participants chose to build new instruments from scratch, with 6 of them explicitly explicitly drew on acoustic patterns encountered earlier. Notably, P7 integrated a prior finding—submerging a resonator in water—to produce "strange and fun" timbres, and P8 reinterpreted the bridge connector as a tunable resonator based on earlier discoveries of its pitch-controlling behavior. In contrast, P6 and P10 focused on imaginative shapes over acoustic refinement, aligning more with their audience goals than technical experimentation.

These strategic choices led to a diverse range of expressive outcomes (Figure 5.6). 4 participants—P2, P8, P9, and P11—leveraged overtone behaviors to mimic animal sounds and explore timbral variation. Another 5—P1, P4, P5, P8, and P12—focused on simplifying pitch control, either through minimal fingerings or telescoping body designs. P10 created a dual-generator flute to support co-performance. P6 and P7 treated FlueBricks as sculptural media, constructing fantastical forms like a gun or castle to appeal to young learners. Only 1 participant, P3, failed to achieve meaningful acoustic control, interpreting the system as a prank toy. Still, 11 out of 12 participants produced musically or pedagogically intentional instruments, affirming FlueBricks' s capacity to support creative, goal-driven instrument construction.

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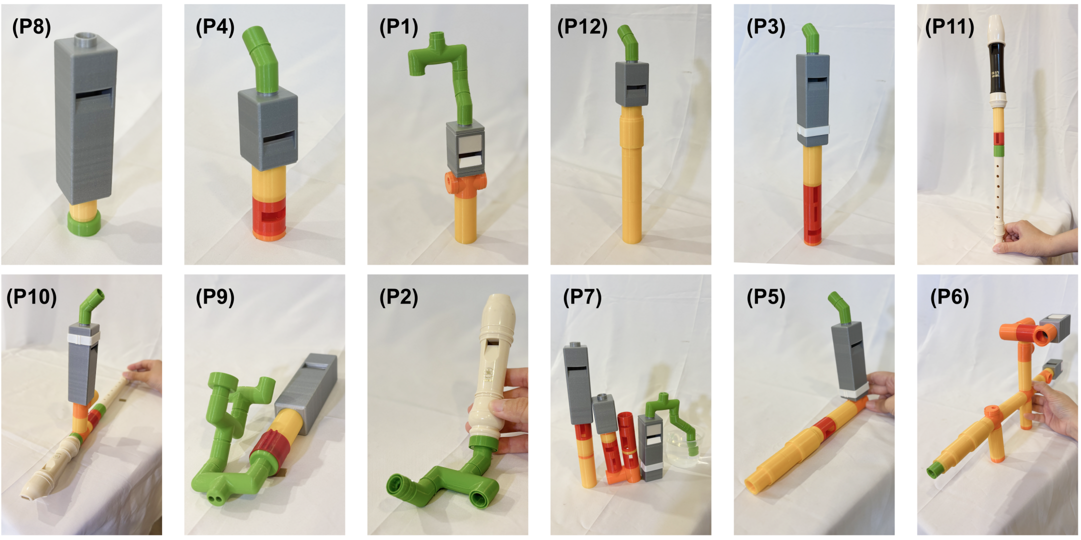

Figure 5.6: Completed instruments from the scenario-based study. All participants, regardless of musical background, successfully built playable flutes using FlueBricks, demonstrating the system’s accessibility and versatility.

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Chapter 6 Discussion

6.1 Emerging Designer–Player–Discovery Loop

By modularizing the traditionally monolithic form of flute-like instruments, FlueBricks reveals a fluid interplay between the roles of designer and player. Across our exploratory study, we observed participants rapidly transitioning between assembling and testing, listening and adjusting—each role informing the other. However, beyond this intended designer–player interaction, we observed the emergence of a third critical component: **discovery**.

Participants often used the designer–player loop as a mechanism to validate or revise their mental models of how flutes work. For instance, P2, P4, and P11 explicitly reflected that the experience helped them *"finally understand how a flute works"* or *"realize things I never thought about before."* This mode of constructive discovery through hands-on iteration suggests that systems like FlueBricks may offer a powerful entry point into acoustical understanding—even for users without technical training.

This reflective mode often drew on participants' prior musical experience. P6, trained in traditional Chinese flutes, applied his knowledge of dizi and suona to interpret how airflow and tone holes functioned in FlueBricks modules which is shown in 5.5. His process

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illustrates how domain expertise can be recontextualized in an unfamiliar modular system. Similarly, P8—who had experience learning multiple wind instruments—remarked that *"this was the first time I saw all my learning really come into play in a real situation."* His recognition underscores how FlueBricks can serve as a testbed for embodied knowledge, enabling experienced players to reapply and even reconfigure what they know.

Several participants with educational backgrounds (P4, P5, P11) immediately envisioned how such a system could be adopted in classroom settings to demystify sound production and empower students to learn through making. Others drew directly from lived or observed knowledge of instrument morphology. P8, for example, designed his instrument with an unperforated lower tube, inspired by his observation that many wind instruments leave a stretch of tubing without tone holes—revealing how the system enables structural analogies across instrument types.

Beyond individual exploration, we also observed the potential of FlueBricks to support collaborative learning. Participants such as P1, P4, P5, and P10 spontaneously engaged in joint assembly, collective listening, and co-playing, forming short-lived yet meaningful ensembles during the study which as a example shown in 5.5. In one case, a group co-designed an unusually long flute body with widely spaced tone holes—so far apart that it physically required multiple people to operate it simultaneously. One participant controlled the generator and airflow, while others covered distant tone holes in coordination, turning a modular design constraint into a shared performance opportunity. This social dynamic transformed the activity from a solitary design task into a cooperative exploration of acoustics, reminiscent of constructionist learning environments where peers co-construct knowledge through shared tinkering.

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This triangulation—between role-shifting, acoustic reasoning, and real-time feedback, both individual and collective—suggests a broader potential for modular, hands-on systems to support both creative instrument design and conceptual learning. We term this emergent pattern the designer–player–discovery loop, where understanding is not front-loaded as instruction, but rather unfolds through physical experimentation, collaborative improvisation, and reflective insight.

6.2 Is It a Toy or an Instrument? Rethinking Instrumentality

While FlueBricks was designed as a modular toolkit for constructing playable flutes, participants' reactions revealed a deeper ambiguity: is this a musical instrument or a toy? This tension was most explicitly articulated by P6, a professional player of dizi and suona. Upon receiving the toolkit, P6 described a "conflicted emotion"—the appearance was "cute" and toy-like, yet the system could produce scales and recognizable tones. Through the process of exploration, P6 found himself confronting the question: what makes something a musical instrument?

Initially, P6 conducted rigorous acoustic experiments inspired by his knowledge of dizi and suona. However, in the final design task, he pivoted toward making a gun-shaped instrument—driven not by acoustic goals but by visual and interactional playfulness. In the post-study interview, he reflected that FlueBricks *"feels more like a toy"* than a proper instrument, noting that *"a traditional flute is already a well-designed end product for musical expression."* Yet he also acknowledged FlueBricks's unique strength: its approachability. *"If you put a violin on a table, few people will touch it. But if you put this out,*

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everyone would want to play with it."

This perception—that FlueBricks exists in a liminal space between toy and instrument—was echoed by P8, who noted that while the toolkit supports scale generation and tonal control, it did not immediately evoke musical performance goals. He appreciated the system as a way to *"understand instruments better,"* but described it as *"closer to a toy for now,"* adding that a real instrument requires a clear musical role—for instance, having a place in an ensemble.

P5 and P11 offered a compositional perspective on this boundary. P5, speaking as a performer, suggested that an instrument gains legitimacy through dedicated compositions: *"Only when someone writes for it, does it become an instrument."* P11, a contemporary composer, similarly noted that to be compelling musically, FlueBricks would need to offer a sound *"beyond the traditional flute"*—something that could inspire compositional exploration.

Together, these reflections position FlueBricks at a rich intersection—not yet a fully-fledged instrument, yet more than a toy. It invites playful appropriation, conceptual reflection, and possibly new directions in participatory music design. Whether viewed as an approachable material for casual tinkering or a provocative platform for imagining new acoustic roles, FlueBricks challenges conventional notions of instrumentality.

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Chapter 7 Limitation and Future Work

Our exploratory user study of FlueBricks, a modular flute-like instrument system, revealed several limitations that inform future directions. Variations in press-fit tolerance often led to air leaks or excessive friction, making it hard for users to distinguish between poor assembly and acoustic outcomes. Component swapping—especially within the generator—was also cumbersome, limiting efficient comparison of subtle sound differences. While the open-ended design supported creative exploration, some users reported feeling lost without guidance, suggesting a need for lightweight scaffolding such as optional tutorials or design prompts. Additionally, although users generated a range of flute-like sounds, the system's acoustic scope remained close to traditional flutes; incorporating hybrid modules (e.g., reed or brass-based) could expand its expressive range. Finally, our findings are based on a limited, exploratory study; further work is needed to validate the system's usability and effectiveness, particularly its potential as an educational toolkit for hands-on learning in acoustics and instrument design.

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Chapter 8 Conclusion

In conclusion, we have introduced FlueBricks, a modular construction kit that allows users—ranging from complete novices to experienced musicians—to build and explore flute-like instruments through hands-on physical experimentation. FlueBricks dissects the flute into three modular categories: *Generator*, *Resonator*, and *Connector*, embodying core acoustic principles in physical components that are both intuitive to assemble and immediately responsive to sound. Our exploratory user study has shown that participants fluently switch between the roles of designer and player, discovering how different configurations affect pitch, timbre, and tonal stability. In particular, novices gained confidence in manipulating airflow and tone holes, while expert woodwind players and composers explored advanced techniques such as multiphonics and glissando in newly invented instruments. These findings have further demonstrated the potential of FlueBricks as a tangible tool for learning and creativity, suggesting broader applications in music education, acoustics research, and interactive instrument design.

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