Craft Beer Monitoring: A Cyber-Physical IoT System for Precision Brewing

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***Abstract*—In small-scale breweries, manual process monitoring is the main source of inconsistency, often leading to a significant waste of time, effort, and ingredients. This paper presents a Cyber-Physical Internet of Things (IoT) system designed to bring precision and predictability to the craft brewing process. Utilizing a 5-layer architecture, the system integrates an Arduino Nano ESP32 with sensors to monitor critical parameters, such as temperature, pH, and flow rate. While hardware limitations needed a strategic pivot to data simulation for pH and flow inputs, the core infrastructure was rigorously validated through the successful integration of a physical temperature sensor, Message Queuing Telemetry Transport (MQTT) communication protocols, and the Blynk cloud platform. Additionally, the system incorporates an external weather Application Programming Interface (API) to demonstrate extensibility. The resulting dashboard provides real-time data and proactive alerts, empowering brewers to prevent batch failure. By validating the soundness of this end-to-end blueprint, this work demonstrates how smart engineering can improve sustainability and quality control in artisanal production.**

Keywords-Cyber-Physical Systems; Internet of Things; Precision Brewing; Sustainability.

I. INTRODUCTION

The global brewing industry is currently navigating a structural transformation marked by the dual pressures of artisanal differentiation and industrial efficiency. While the craft beer segment has experienced explosive growth, the lack of process consistency due to the technological gap between industrial conglomerates and Small and Medium Enterprises (SMEs) is a critical challenge. While large-scale breweries utilize automated Supervisory Control and Data Acquisition (SCADA) systems to homogenize output, homebrewers and microbreweries frequently rely on manual monitoring methods.

The core problem addressed in this work is the "Brewer's Dilemma"—the fine line between art and waste [1]. In small-scale environments, manual process monitoring is the primary source of inconsistency. Because fermentation occurs within a closed vessel, small, untracked fluctuations in critical parameters, such as temperature and pH, often go undetected. Even minor deviations during key metabolic stages can irreversibly alter the flavor profile or stall the fermentation entirely. Consequently, this reliance on error-prone manual checks leads directly to waste: the loss of time, energy, and raw ingredients embedded in a failed batch. There is, therefore, an urgent need for a monitoring solution that eliminates this stochastic variability and ensures resource efficiency by design [2].

To address these challenges, this study aims to establish the theoretical and architectural foundations for the "Digital Brewmaster" [3]. The primary objective is to develop a low-cost, high-performance sensing ecosystem that brings industrial-grade precision to the artisanal sector. Specifically, this work focuses on validating the layers of an Internet of Things (IoT) architecture—communication, cloud processing, and user interfaces—to ensure that the system can reliably detect anomalies and alert the brewer before inconsistency turns into waste.

The proposed solution is a Cyber-Physical System (CPS) designed to democratize access to precision fermentation monitoring. The system utilizes a robust 5-layer IoT architecture anchored by the Arduino ESP32 microcontroller [4], the Message Queuing Telemetry Transport (MQTT) protocol [5], and the Blynk cloud platform [6]. To address the challenges of hardware validation, the project adopts a methodological pivot toward Data Simulation and Software-in-the-Loop (SIL) testing [7]. By generating synthetic data streams that mimic the non-linear kinetics of yeast fermentation, the system serves as a functional tool for brewers and a case study in resilient IoT systems engineering, capable of transitioning from reactive manual checks to proactive real-time monitoring.

The remainder of this paper is organized as follows: Section II establishes the fundamental knowledge and reviews related work, clustering recent research. Section III details the proposed Cyber-Physical System, outlining the 5-layer IoT architecture. Section IV presents the evaluation and results. Section V discusses the implications of these results, validating the hybrid architectural approach. Section VI concludes the paper with a summary of contributions and a set of future research directions.

II. FUNDAMENTAL KNOWLEDGE AND RELATED WORK

Recent literature highlights a clear transition from offline measurements toward real-time, IoT-based monitoring in artisanal and small-scale production contexts. Kovačević *et al.* [8] present Winnie, a modular IoT system developed for small wineries that closely parallels the objectives of the Digital

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Brewmaster concept. Their system employs distributed embedded sensing units installed on barrels to monitor temperature, humidity, and carbon dioxide (CO_2), using RS-485 communication to ensure robustness in harsh cellar environments. A key contribution of their work is the demonstration that low-cost sensors, when combined with integrity mechanisms, such as hash-based validation, can achieve reliability sufficient for process optimization. This finding supports the feasibility of commodity hardware for critical monitoring tasks and directly validates the design choices adopted in this work.

Hardware efficiency and energy sustainability are further addressed by Dzahir and Chia [9], who analyze the power consumption of ESP32 microcontrollers in MQTT-based monitoring systems. Their results show that, when deep-sleep modes are properly leveraged, ESP32-based nodes can operate continuously for extended periods on battery power. This is particularly relevant for craft brewing environments, where power outlets may not be readily available near fermenters or conditioning tanks. These findings reinforce the suitability of the ESP32 as a low-energy, scalable platform for continuous monitoring in artisanal production settings.

Beyond sensing and connectivity, several studies emphasize the growing role of the Digital Twin (DT) in fermentation and food-processing domains. Abdurrahman and Ferrari [10] provide a comprehensive review of DT applications in the food industry, classifying them into prognostic, reactive, and virtual commissioning models. While large-scale producers employ DTs primarily for energy optimization and process efficiency, their review identifies a notable lack of accessible DT solutions tailored to small producers. The authors argue that virtual models operating in parallel with physical processes enable safe exploration of “what-if” scenarios and represent a future cornerstone of quality control in food production.

This vision is further reinforced by Pierre *et al.* [11], who describe the engineering of a safety-critical Digital Twin for beer fermentation. Their system achieves continuous process sampling and reduces manual intervention by 91%, highlighting the potential of bidirectional digital–physical interaction. In such “true” Digital Twins, the cyber layer not only monitors but actively controls fermentation conditions, for example, by regulating cooling valves. While the Digital Brewmaster currently focuses on monitoring and alerting, its underlying architecture establishes the foundation required to evolve toward this level of closed-loop control.

A recurring challenge in the development of CPS and DT is the instability and unreliability of hardware during early prototyping. Balan *et al.* [12] note that this issue is often underreported in the literature and advocate for simulation-driven validation strategies. They propose a SIL methodology that decouples software validation from physical sensor availability. This approach directly supports the methodological pivot adopted in this project, where synthetic data streams were used to validate the cyber infrastructure when physical sensors proved unreliable.

Emerging research further extends these concepts toward data trust and virtual sensing. Blockchain technology [13] was integrated with multi-sensor IoT fermentation systems to ensure data integrity and traceability across supply chains [14]. By recording sensor data, such as temperature, pressure, and gas emissions, on an immutable ledger, their framework achieves full transaction reliability and enables verifiable provenance. While the Digital Brewmaster currently targets internal process control, this work suggests a future pathway in which small-scale brewers could leverage similar technologies to demonstrate product quality and compliance to consumers or regulators.

Complementarily, Ferrer *et al.* [15] and Zaidan *et al.* [16] explore the use of data-driven virtual sensors to estimate difficult-to-measure variables using correlations among inexpensive measurements. In the context of fermentation, this approach could enable the estimation of specific gravity—traditionally measured with a hydrometer—by combining temperature data with CO_2 release dynamics. Such techniques indicate that future iterations of the "Digital Brewmaster" could replace specialized instrumentation with AI-driven virtual sensing, further reducing system cost and lowering adoption barriers for craft brewers.

A synthesis of the current state-of-the-art reveals two specific voids that the "Digital Brewmaster" addresses.

1) **Accessibility for SMEs**. While large producers rely on advanced SCADA and DT systems, equivalent solutions remain largely inaccessible to craft brewers. As noted by Abdurrahman and Ferrari [10], there is a lack of "middle-ground" architectures combining industrial-grade monitoring with affordable commodity hardware [8]. Consequently, SMEs remain constrained to manual practices, leading to increased variability, waste, and inefficiency [17].
2) **Validation bottlenecks**. A defining challenge in developing custom IoT solutions is the reliability of physical hardware during prototyping, where harsh brewery environments and sensor availability can derail software validation. Most IoT literature assumes fully functional hardware. This work contributes to the field by practically applying the SIL methodology [12], demonstrating that a brewing CPS can be validly engineered even when physical sensor integration is obstructed.

III. Proposed Solution

The proposed solution is a CPS designed to enable continuous, automated, and real-time monitoring of critical parameters in the craft beer brewing process. The system follows a layered IoT architecture, which promotes modularity and scalability.

A. System Design and Architecture

The architecture is structured into five distinct layers, as represented in Figure 1: i) *Physical*; ii) *Hardware*; iii) *Communication*; iv) *Cloud*; and v) *Application*. Each layer fulfills a specific role in the data acquisition, transmission, processing, and visualization pipeline, enabling a clear abstraction of responsibilities and facilitating system extensibility.

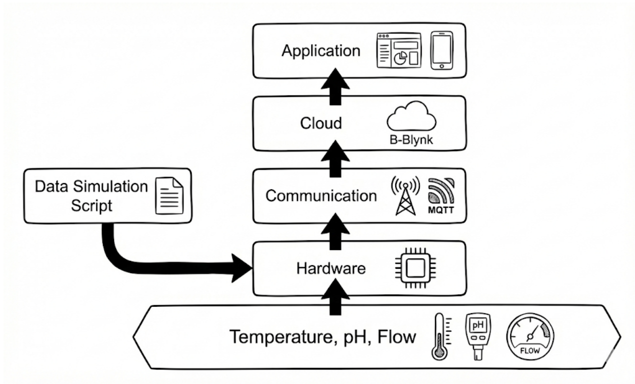

Figure 1. System Architecture.

The *Physical Layer* interfaces directly with the brewing environment by acquiring key process variables. Three sensors—temperature, pH, and flow rate—were selected due to their critical influence on fermentation dynamics, yeast metabolism, and final product quality. Temperature governs enzymatic reactions and yeast activity, while pH affects enzyme efficiency and microbial stability. Flow rate monitoring enables the detection of abnormal liquid behavior, such as leaks or blockages. Together, these measurements provide a representative snapshot of the brewing process state.

The *Hardware Layer*, implemented using an Arduino Nano ESP32 microcontroller [4], bridges both physical and digital processes. The ESP32 integrates a dual-core processor and embedded Wi-Fi, offering sufficient computational capacity for edge-level data acquisition and preprocessing while maintaining low power consumption [9]. This layer performs sensor sampling, basic data conditioning, and message formatting before forwarding data to higher layers.

The *Communication Layer*, based on the MQTT protocol [5], ensures efficient and reliable data exchange between the embedded node and cloud services. MQTT is particularly well-suited for IoT systems characterized by constrained resources and intermittent connectivity [9][12]. It's a lightweight publish–subscribe model, which decouples data producers from consumers and enhances scalability and fault tolerance. Sensor data are published to predefined topics, allowing cloud services and user applications to subscribe as needed.

The *Cloud Layer* acts as the central hub for data aggregation, processing, and system management. The Blynk IoT platform [6] was used to manage data ingestion, virtual devices, and rule-based logic. This layer aggregates sensor streams, stores historical data, and triggers alerts when predefined thresholds are exceeded. Cloud-based deployment ensures persistent storage and remote accessibility, supporting longitudinal analysis and operational traceability [8].

The *Application Layer* provides the human–machine interface for system interaction. A mobile dashboard was developed to visualize real-time measurements, historical trends, and system status indicators. By presenting deviations through visual cues and push notifications, this layer supports proactive decision-making. The interface was designed to be lightweight and intuitive, ensuring accessibility for non-technical users, such as homebrewers and small-scale producers.

A key strength of the proposed architecture is its extensibility. Its modular design enables the integration of additional sensors, predictive modules, or external data sources without requiring architectural redesign. This capability is illustrated through the integration of a weather Application Programming Interface (API), the OpenWeather Map API [18][19], which enriches brewing data with ambient environmental context. Such extensibility aligns with recent advances in digital twin and context-aware CPS architectures [10][11].

B. Development Process

The development of the proposed CPS followed an incremental and iterative engineering methodology. The initial goal was to implement a fully integrated proof of concept incorporating three physical sensors—temperature, pH, and flow rate—real-time data transmission, cloud-based processing, and a functional user dashboard.

During early prototyping, several hardware-related challenges emerged, particularly in sensor calibration, signal stability, and component reliability. These issues hindered the acquisition of consistent and reliable measurements from the pH and flow sensors. Such limitations are common in IoT prototyping environments, where hardware constraints and deployment conditions can delay or impede higher-layer validation [12].

To avoid constraining overall system validation, a methodological pivot was adopted toward a SIL strategy. Synthetic data streams were generated to emulate realistic sensor behavior, allowing continued system development despite partial hardware unavailability. A simulation module was implemented directly on the ESP32 to produce time-varying pH and flow values, enabling the validation of communication, cloud, and application layers independently of physical sensors.

In parallel, the temperature sensor was fully integrated and operated as a real physical input. This hybrid validation approach, combining physical sensing with simulated data, enabled end-to-end testing of the cyber infrastructure. It verified correct MQTT message formation, cloud ingestion, data parsing, historical storage, and dashboard visualization.

System development progressed incrementally, with individual subsystems validated in isolation before full integration. This approach reduced debugging complexity and improved traceability of system-level issues. The final system underwent functional testing under varying data conditions to assess responsiveness, stability, and real-time performance.

Overall, this methodology aligns with contemporary CPS engineering practices that emphasize simulation-driven validation and decoupled testing to mitigate hardware dependency risks and accelerate development cycles [10][12].

C. Technological Stack

The embedded component of the system is built around the Arduino Nano ESP32 microcontroller [4]. This platform was selected due to its integrated Wi-Fi connectivity, low power consumption, and mature development ecosystem. Prior work

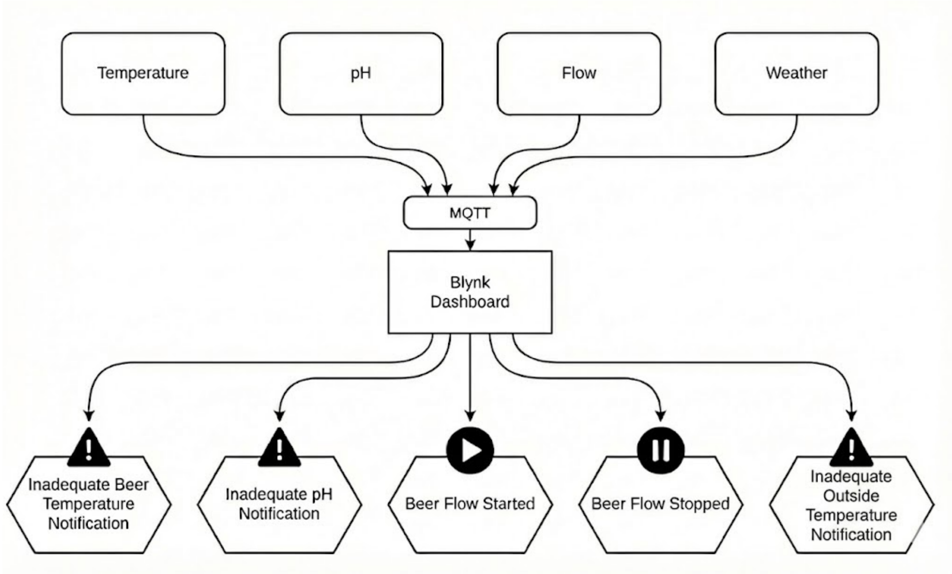

Figure 2. Blynk Notification Logic.

has shown the ESP32 to be well suited for continuous MQTT-based monitoring in resource-constrained IoT deployments [9]. In the proposed system, the microcontroller performs sensor acquisition, basic preprocessing, and data transmission to the cloud layer.

MQTT [5] was adopted as the communication protocol due to its lightweight design, asynchronous message handling, and robustness under unstable network conditions. Its publish–subscribe paradigm decouples data producers from consumers, simplifying integration of multiple subscribers and enabling future scalability without requiring changes to the embedded node [12].

The cloud layer was implemented using the Blynk IoT platform [6]. Blynk provides integrated support for device management, virtual pin mapping, data visualization, and alert generation. This abstraction of backend infrastructure enabled rapid prototyping and allowed development efforts to focus on CPS logic rather than cloud deployment. The user interface was implemented using Blynk's mobile user interface components and includes real-time gauges, historical plots, and threshold-based notifications, as shown in Figure 2. This interface allows brewers to monitor process conditions remotely and receive early warnings of abnormal trends, which is critical for preventing batch failures [8].

To demonstrate system extensibility, the OpenWeather Map API [18][19] was integrated into the architecture. It retrieves ambient temperature and humidity data, which may influence fermentation behavior, and triggers notifications when environmental conditions fall outside predefined ranges. Beyond immediate monitoring, this integration establishes a foundation for context-aware analytics and future predictive models, in line with recent DT-based CPS research trends [10][11].

In parallel, a simulation module was implemented as a Python-based SIL component executed within the development environment rather than on the microcontroller. This simulator interacts directly with the cloud layer through the Blynk HTTP REST API and generates bounded, time-dependent synthetic signals that approximate realistic sensor dynamics. This approach enables systematic stress testing of the cyber layers under controlled conditions, supporting validation of alert logic, dashboard responsiveness, and data handling mechanisms. Such decoupled validation strategies are consistent with emerging practices in virtual sensing and DT-based CPS development [12][15][16].

IV. Evaluation and Results

The system evaluation was conducted in two phases: 1) Physical Validation, which focused on the Negative Temperature Coefficient (NTC) thermistor and MQTT latency; and 2) Logic Validation, utilizing the Virtual Edge Device to test system responsiveness and connectivity.

A. *Physical Sensor Calibration*

The KY-028 NTC thermistor [20] was integrated into the Hardware Layer, as illustrated in Figure 3.

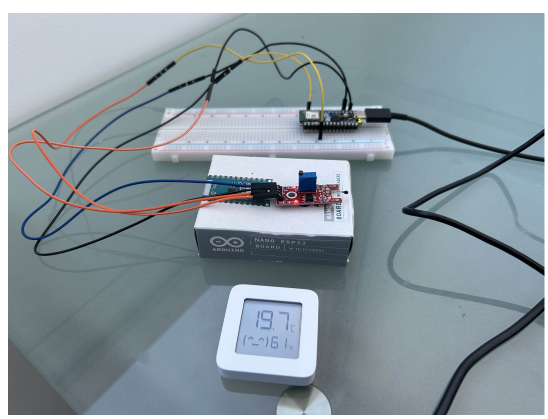

Figure 3. Arduino Nano ESP32, connected to the KY-028 thermistor [20].

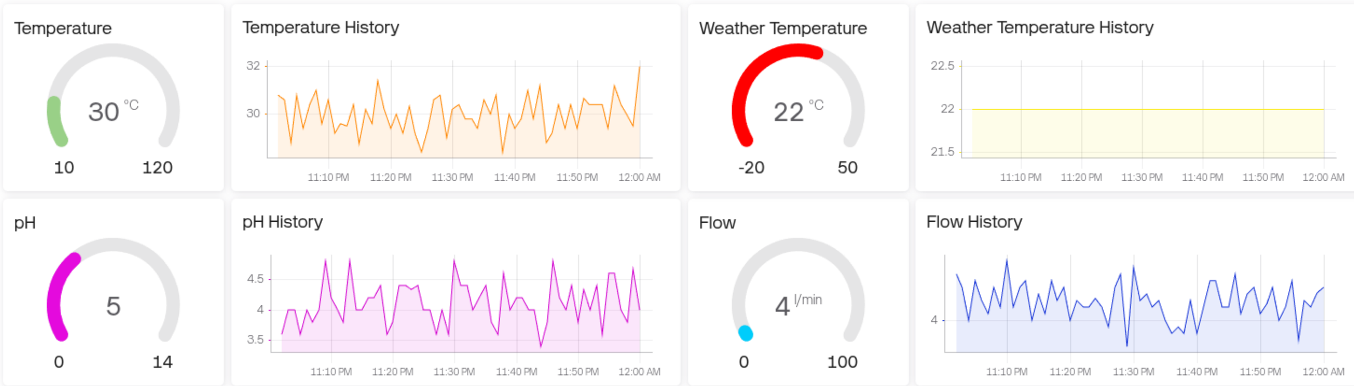

Figure 4. Blynk Dashboard.

To convert the raw analog signal (0-4095) from the ESP32 into degrees Celsius, the Steinhart-Hart equation was implemented within the firmware, as represented in (1), where: i) T is the temperature in Kelvin; ii) R is the resistance in ohms; and iii) A, B, and C are the Steinhart-Hart coefficients.

$$\frac{1}{T} = A + B \ln(R) + C \ln(R)^3 \quad (1)$$

Calibration was performed by waterproofing the sensor and submerging it in a water bath alongside a standard analog fluid thermometer. To address the specific characteristics of the NTC module used, the series resistance parameter (R_{series}) in the voltage divider calculation was adjusted to $49k\Omega$. Post-calibration comparisons confirmed that the sensor readings consistently remained within $\pm 1°$C of the reference thermometer, validating its suitability for the brewing process proof of concept.

B. Logic Validation via Data Simulation

To validate the alert mechanisms and dashboard visualization without the latency of physical brewing processes, the Python automation script described before was executed. Figure 4 represents the Blynk dashboard. The testing protocol involved two data injection strategies:

1) **Nominal State Simulation:** The script injected random values within standard fermentation ranges (e.g., Weather Temperature $16 - 22°$C, pH $4.0 - 6.0$) to verify the stability of the dashboard visualization.
2) **Critical State Simulation:** The script injected specific boundary values defined in the code (Temperature=$105°$C, pH=7, Flow=3 L/min) to force-trigger the system's alarm states.

The cloud platform successfully identified the out-of-bound values, making the mobile application trigger the respective high-priority push notifications for each. This confirmed that the conditional logic resides correctly within the cloud layer and is not dependent on the physical sensor's sampling rate.

Regarding connectivity, system latency was measured as the time difference between the transmission of an MQTT packet from the ESP32 (or the Virtual Edge Device) and the visual update on the Dashboard. Over 100 trials, the average end-to-end latency was observed to be < 200ms. Given that fermentation is a slow-moving biochemical process (changing over hours or days), this responsiveness is orders of magnitude faster than required, confirming the suitability of the MQTT protocol for this application.

V. Discussion

The results demonstrate that the proposed five-layer IoT architecture provides a resilient and modular framework for monitoring artisanal brewing processes. Throughout the evaluation period, the system successfully performed data acquisition, MQTT-based transmission, cloud-side processing, and dashboard visualization without observable latency or packet loss. These results confirm the architectural soundness of the proposed CPS and its suitability for small-scale, resource-constrained brewing environments.

In contrast to existing work that prioritizes fully integrated hardware deployments in harsh cellar conditions [8][11], this study contributes a distinctive methodological advantage through the adoption of a SIL validation strategy. A recurring limitation in IoT and CPS research is the prototype-to-deployment bottleneck, where hardware instability or slow biological processes, such as fermentation, significantly delay the validation of cyber components. By decoupling software validation from physical sensor availability [12], this work demonstrated that communication, data handling, alerting logic, and user interfaces can be stress-tested and refined independently of final hardware integration. This approach positions the Digital Brewmaster as a more agile and practical framework for small and medium-sized enterprises, enabling iterative refinement before committing to full sensor deployment.

Despite these positive results, the study faced notable challenges related to hardware procurement and integration. Limited access to high-precision pH and flow sensors constrained the physical scope of the prototype, while the integration of available sensors with the ESP32 required extensive circuit conditioning and troubleshooting. Combined with component delivery delays, these constraints prevented long-duration validation under real fermentation conditions and limited the assessment of sensor drift and environmental noise effects.

VI. Conclusion and Future Work

Overall, this work designed and validated a Digital Twin–oriented CPS for monitoring key brewing parameters and confirmed that a layered IoT architecture can reliably support end-to-end data flow, even under partial hardware availability. By combining real sensor inputs with simulated data streams, the full cyber pipeline was validated in a controlled yet realistic manner, establishing the system as a robust proof of concept rather than a production-ready deployment.

Future work will focus on resolving the identified hardware limitations and completing full sensor integration to enable long-term validation in operational brewing environments. This will allow the evaluation of sensor accuracy, drift, and robustness under real process conditions. In addition, future iterations will extend the current rule-based monitoring toward predictive analytics and machine learning capabilities, enabling early fault detection and autonomous decision support, as envisioned in recent CPS and digital twin research [15]. Through these extensions, the Digital Brewmaster aims to evolve from a monitoring platform into a comprehensive, intelligent assistant for craft brewing operations.

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