PROJECT-BASED LEARNING AS A TOOL FOR DEVELOPING INTELLECTUAL COMPETENCE IN SIGNAL PROCESSING COURSES

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ABSTRACT

Signal processing courses require students to connect mathematical representations with computational procedures and real-world data. This study examines Project-Based Learning (PjBL) as a pedagogical tool for developing intellectual competence in undergraduate signal processing education. Intellectual competence is operationalized as an integrated capacity for problem decomposition, analytical reasoning, conceptual transfer, evidence-based decision making, solution design, and metacognitive reflection. A quasi-experimental course model is proposed in which students work in small teams on authentic signal-processing problems involving signal acquisition, preprocessing, spectral analysis, filtering, algorithm validation, and technical communication. The intervention combines scaffolded project milestones, programming-based investigation, formative feedback, peer collaboration, and rubric-based assessment. To illustrate the intended analytical procedure prior to insertion of institutional data, a synthetic pilot dataset representing 64 students was analyzed. The simulated pattern showed comparable pre-test scores for the conventional and PjBL groups, followed by a larger mean gain for the PjBL group. The difference in gain scores was statistically significant in the illustrative analysis and corresponded to a large standardized effect. The pedagogical interpretation is that PjBL can create repeated opportunities for students to transform theoretical signal-processing knowledge into justified engineering decisions. The article proposes an assessment framework, a project workflow, and measurable indicators that can be adapted for empirical implementation in engineering higher education.

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Keywords: *Project-based learning; intellectual competence; signal processing education; digital signal processing; engineering education; higher-order thinking; active learning.*

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Introduction

Signal processing is a foundational area in electrical engineering, computer engineering, telecommunications, biomedical engineering, robotics, and data-intensive technologies. Yet it is also a cognitively demanding subject because students must simultaneously reason about continuous and discrete representations, time- and frequency-domain behavior, mathematical transforms, systems, sampling, filtering, noise, and implementation constraints. When instruction is dominated by derivations and routine calculations, students may successfully reproduce procedures without developing the capacity to select, justify, and adapt signal-processing methods for unfamiliar problems.

Contemporary approaches to signal-processing education therefore emphasize active engagement,

visualization, programming, design, and authentic applications. Parhi (2021) argues that digital signal processing instruction benefits when theoretical exposition is integrated with applications, programming, visualization, and collaborative in-class activity. Aboutanios et al. (2021) similarly describe a long-running design-based approach in undergraduate signal-processing curricula in which frequent and diverse design tasks are used to connect theory with practical problem solving. In a DSP-specific implementation, Deshpande (2022) reported that project-based learning increased learners' engagement, interest, self-learning, and awareness of practical applications. Earlier project-oriented work in signal processing also demonstrated gains in engagement, attendance, and course success when authentic artifacts were used to organize learning (Iriondo et al., 2019).

The broader engineering-education literature supports the relevance of PjBL while also cautioning against simplistic claims. A meta-analysis by Zhang and Ma (2023) synthesized 66 experimental or quasi-experimental studies and found a positive overall effect of project-based learning, with particularly strong applicability in engineering and technology contexts and in experimental courses. Hidayat et al. (2024) likewise reported a positive association between PjBL and higher-order thinking skills in engineering education. Recent systematic reviews emphasize that project-based approaches can develop technical and non-technical competences when projects are purposefully designed, assessed, and integrated into the curriculum (Lavado-Anguera et al., 2024; Ramírez de Dampierre et al., 2024). A 2026 umbrella review found a consistently positive direction across meta-analyses but also noted substantial methodological limitations in the existing evidence base, reinforcing the need for transparent designs and cautious interpretation of effect magnitude (Farshad & Fortin, 2026).

In this article, intellectual competence refers to the learner's integrated ability to analyze complex information, decompose problems, connect abstract concepts with observable signals, select and justify methods, generate and test solutions, evaluate evidence, and reflect on the quality of reasoning. This operational definition overlaps with higher-order thinking, critical thinking, problem solving, conceptual transfer, and metacognition, but it is organized specifically around the intellectual actions required in signal-processing practice.

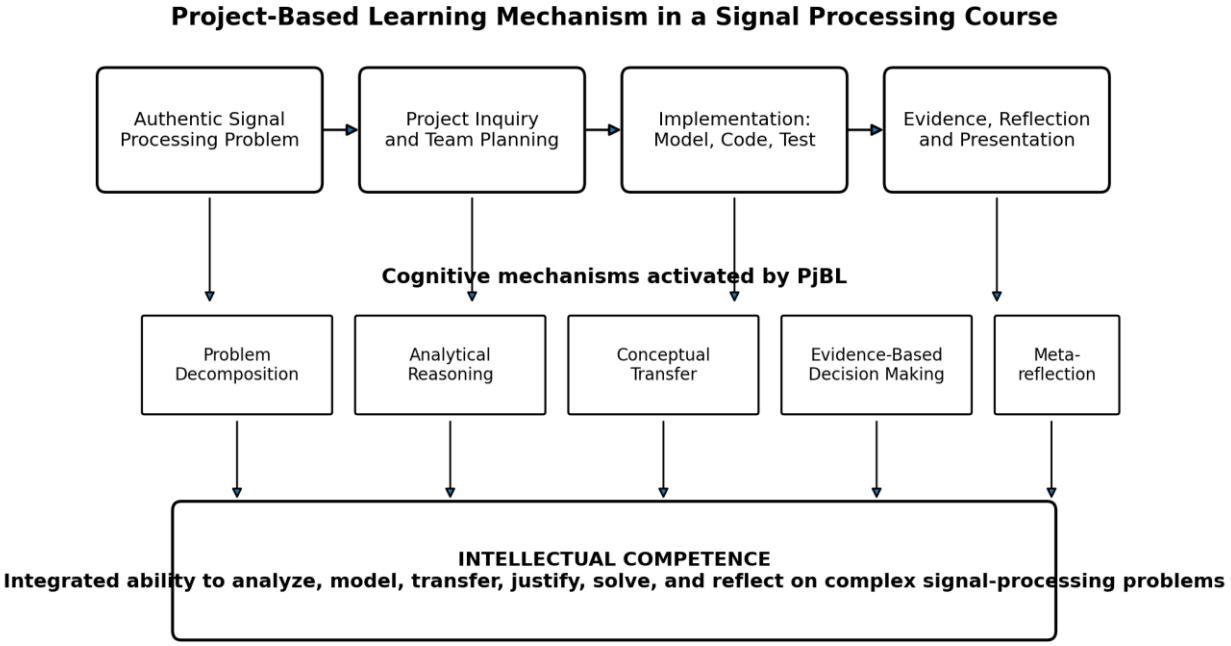


Fig 1. *Conceptual framework linking PjBL activity to intellectual competence in signal processing*

The purpose of the study is to develop and illustrate an IMRAD-compatible research model for investigating whether PjBL can support intellectual competence in an undergraduate signal-processing course. Three research questions guide the design: (RQ1) How can project activities be aligned with measurable dimensions of intellectual competence? (RQ2) What change in intellectual competence should be tested when PjBL is compared with conventional instruction? (RQ3) Which project and assessment

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features are most likely to explain observed changes? Because no institutional dataset was supplied for the present draft, the Results section uses clearly labeled synthetic pilot data only to demonstrate the statistical and graphical reporting format.

Materials and Methods

The proposed empirical study uses a quasi-experimental pre-test/post-test design with two intact undergraduate classes enrolled in a Signals and Systems or Digital Signal Processing course. One class receives conventional instruction built around lectures, worked examples, laboratory exercises, and individual problem sets. The second class receives the same core content but completes a structured PjBL intervention. A practical implementation may use approximately 60–80 students distributed across the two conditions; group equivalence should be examined using pre-test scores and relevant background variables.

The illustrative dataset in this draft contains 64 synthetic student records (32 per condition). These values were generated solely to demonstrate reporting conventions and must not be interpreted as observations from real students. In a real study, ethical approval, informed consent procedures, anonymization, and institutional data-protection rules should be documented according to the host university's requirements.

The PjBL intervention is designed for an 8–12 week period and uses teams of four to five students, consistent with evidence that small collaborative groups can be effective in project-based settings. Each team selects or receives an authentic signal-processing problem, such as denoising a sensor signal, extracting features from an audio signal, designing a digital filter, detecting events in a biomedical waveform, or classifying signal segments. The lecturer acts as a facilitator who provides milestone feedback, mini-lectures when conceptual gaps appear, and methodological constraints that preserve disciplinary rigor. Intellectual competence is assessed using a performance-based test and a project rubric.

Table 1.

Suggested project sequence and its intellectual-competence targets

	Identify signal source, noise, objective, and constraints		
	Collect or select real/simulated signals		
	Visualize waveform; compute spectrum/features		
	Choose filter, transform, detector, or feature method		
	Develop MATLAB/Python code and test cases		
	Compare alternatives with quantitative metrics		
	Explain limitations and alternative solutions		Technical report; oral defense; reflection

The performance-based test should contain unfamiliar problems requiring interpretation, method selection, justification, transfer, and evaluation rather than only routine calculation. The project rubric provides complementary evidence from authentic performance. To reduce construct contamination,

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teamwork and presentation quality should be scored separately from intellectual competence when the primary outcome is analyzed.

Table 2. *Operational indicators of intellectual competence*

	Separates a complex task into relevant variables, constraints, and sub-problems	Identify what must be known before designing a filter for a noisy sensor stream	
	Uses mathematical and computational evidence to explain signal behavior	Explain why aliasing occurs and support the explanation with spectral evidence	
	Applies principles to a novel signal, domain, or constraint	Adapt a method learned for audio to a biomedical waveform and justify changes	
	Compares methods using explicit metrics and limitations	Select between two filters using SNR, phase, complexity, and application constraints	
	Evaluates assumptions, errors, and alternative approaches	Describe which assumptions failed and how the design would be improved	

A signal-processing project should require students to produce inspectable technical artifacts rather than only a final presentation. Figure 2 illustrates a simple example in which a noisy measured waveform is processed using a frequency-selective method. In an actual student project, the artifact would be accompanied by a sampling rationale, spectral analysis, filter specification, quantitative quality metrics, code, tests, and a written interpretation of trade-offs.

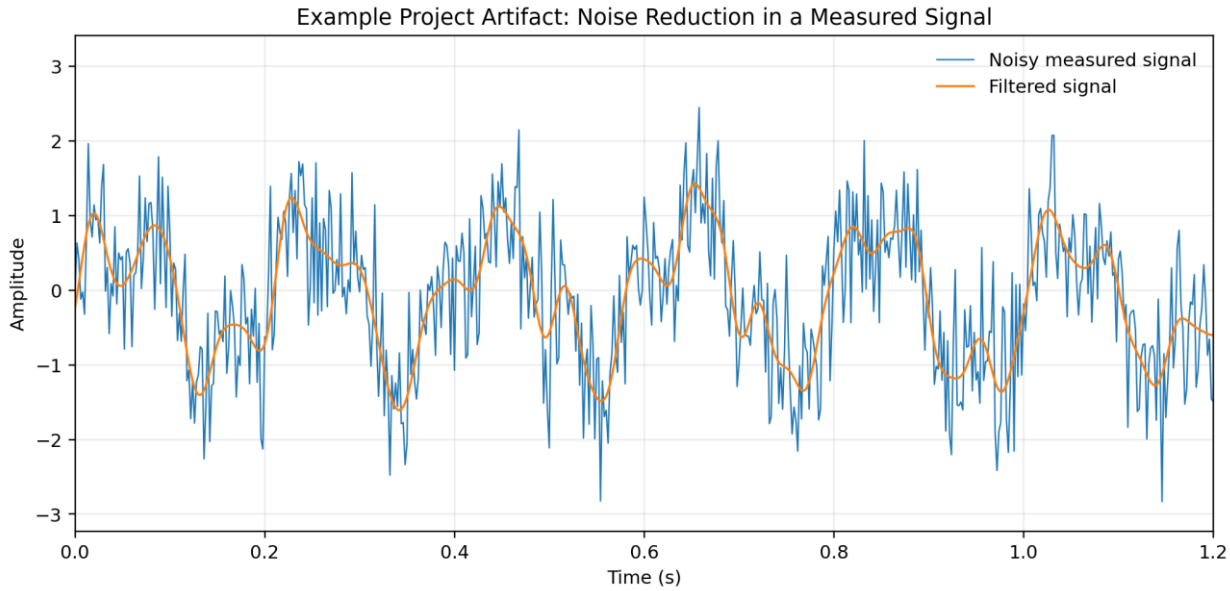


Fig 2. *Example technical artifact that can be used as evidence in a signal-processing project.*

The primary analysis should compare pre-to-post change in intellectual competence across conditions. Descriptive statistics are reported as mean and standard deviation. Baseline equivalence is checked with an independent-samples test or, preferably, through a regression/ANCOVA model that controls for pre-test scores. Gain scores may be used as a transparent supplementary analysis. Effect sizes and confidence intervals should accompany p-values. Dimension-level results are interpreted as secondary outcomes. Qualitative reflections may be coded to identify recurring reasoning processes, misconceptions, and metacognitive changes. Reliability of multi-item instruments should be assessed before composite

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scores are calculated.

Results

The following results are an illustrative analysis of synthetic pilot data and are included only to show how a completed empirical article could report findings. They do not constitute evidence collected from real participants.

Table 3. Illustrative pre-test, post-test, and gain scores (synthetic data).

The two synthetic groups showed nearly identical baseline performance (conventional M = 62.25, SD = 5.49; PjBL M = 62.18, SD = 4.69). After the instructional period, the conventional group reached M = 69.37 (SD = 5.60), whereas the PjBL group reached M = 73.22 (SD = 6.32). The corresponding mean gains were 7.12 and 11.04 points.

An illustrative Welch independent-samples t test on gain scores produced $t = 3.94$, $p < .001$, with a standardized mean difference of approximately $d = 0.99$. In a real dataset, the preferred inferential model should be selected based on design assumptions, baseline balance, clustering, missing data, and the measurement properties of the competence instrument. The large effect shown here is not a claim about the true magnitude of PjBL; it is a demonstration of the reporting format.

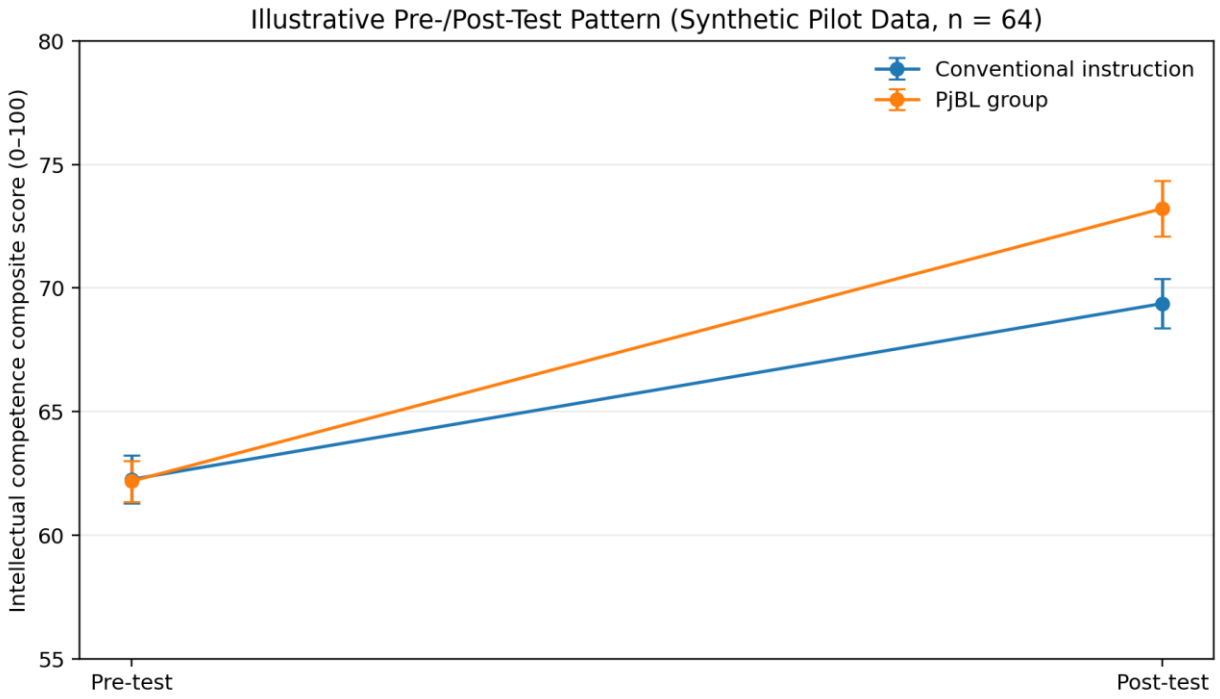


Fig 3. *Illustrative pre-/post-test pattern for the conventional and PjBL groups. Error bars represent standard errors; all values are synthetic*

The hypothetical pattern is consistent with the proposed mechanism: students in a project environment repeatedly encounter situations in which formulas are insufficient by themselves. They must identify what information matters, inspect real signal behavior, choose representations, compare alternative algorithms, interpret quantitative metrics, justify parameter choices, and explain limitations. These actions map directly onto the operational dimensions of intellectual competence.

Table 4.

Illustrative dimension-level post-test profile (synthetic summary values).

			Using mathematical and computational evidence
			Applying principles in unfamiliar contexts
			Selecting methods through explicit criteria
			Evaluating assumptions, errors, and alternatives

Discussion

The proposed model positions PjBL not as an additional assignment at the end of a signal-processing course but as a structured environment for intellectual activity. Its central pedagogical value is the requirement that students move repeatedly between abstract representations and observable system behavior. A student who designs a denoising method, for example, must interpret a waveform, reason about frequency content, select a filter family, choose parameters, evaluate distortion, compare metrics, and defend the final trade-off. This sequence combines disciplinary knowledge with analysis, transfer, judgment, and reflection.

This interpretation is consistent with signal-processing education research. Parhi (2021) emphasizes applications, programming, visualization, and collaborative engagement as ways to strengthen DSP learning. Aboutanios et al. (2021) demonstrate how repeated design activities can anchor theoretical concepts in authentic engineering tasks. Deshpande (2022) reports benefits for engagement and self-learning in a DSP course using PjBL, while Iriondo et al. (2019) show how a complex project artifact can integrate signal-processing knowledge with project-management and collaborative skills. The recent DSP study by Xie et al. (2026) further supports the movement toward collaborative inquiry, project work, and simulation-hardware integration rather than exclusively teacher-centered instruction.

At the broader level, the model is aligned with systematic evidence on PjBL in engineering. Zhang and Ma (2023) found that PjBL effects vary according to subject, course type, group size, and duration, with engineering and experimental contexts showing favorable patterns. Reviews by Lavado-Anguera et al. (2024) and Ramírez de Dampierre et al. (2024) emphasize authentic engineering contexts, program alignment, and assessment quality. Hidayat et al. (2024) specifically connect PjBL with higher-order thinking in engineering education. However, Farshad and Fortin (2026) caution that available meta-analyses have methodological weaknesses, so local studies should report design, instruments, implementation fidelity, and uncertainty transparently rather than assuming a universal effect size.

The most important design implication is that intellectual competence must be assessed through tasks that actually require intellectual decisions. If the final test consists only of familiar calculations, the study may fail to capture the competence that PjBL is designed to develop. Assessment should therefore include unfamiliar signals, incomplete problem statements, alternative valid approaches, explicit justification prompts, and opportunities to interpret errors. The project rubric should reward reasoning quality and evidence, not merely whether code runs or a visually attractive presentation is produced.

Scaffolding is equally important. Novice students may experience open-ended projects as cognitively overwhelming. A milestone structure—problem proposal, data justification, preliminary analysis, algorithm design, prototype, validation, final defense—preserves learner autonomy while preventing the project from becoming unstructured trial and error. Short targeted mini-lectures can be inserted when teams encounter common conceptual barriers. This combination of autonomy and scaffolding is particularly suitable for signal processing because project work exposes misconceptions that may remain invisible during routine exercises.

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The current manuscript has an explicit limitation: its numerical Results section uses synthetic data. No causal or empirical conclusion about a specific student population should be drawn from those numbers. A future implementation should use validated instruments, document participant characteristics, report reliability, check baseline equivalence, account for instructor and class effects, and include confidence intervals. Where feasible, multiple cohorts or replication across institutions would strengthen generalizability. Qualitative evidence from project reports, code reviews, oral defenses, and reflective journals can also help explain how intellectual competence changes, rather than only whether a composite score changes.

Conclusion

Project-Based Learning provides a strong pedagogical structure for aligning signal-processing theory with the intellectual practices required in engineering. When projects are authentic, scaffolded, technically rigorous, and assessed through evidence-centered rubrics, students are required to decompose problems, analyze signals, transfer concepts, compare algorithms, justify decisions, and reflect on limitations. These processes offer a defensible pathway for developing intellectual competence beyond procedural mastery. The proposed IMRAD framework can be used as the basis for a real quasi-experimental study in Signals and Systems or Digital Signal Processing courses. Before publication, the synthetic results in this draft should be replaced with institutional data, and the methods should be adapted to the actual course context, sample, ethics procedure, assessment instrument, and statistical design.

A practical semester implementation can begin with short guided mini-projects and progress toward one integrative team project. Useful topics include audio denoising, vibration analysis, ECG/PPG preprocessing, speech feature extraction, image-frequency filtering, event detection, and sensor-fusion preprocessing. MATLAB, Python/NumPy/SciPy, or equivalent environments can be used. The project should culminate in a reproducible notebook or code repository, a technical report, an oral defense, and an individual reflection so that both collective engineering work and individual intellectual development are visible.

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