

Crystallographic Principles Explored via Immersive and Non-Immersive Virtual Reality Tools

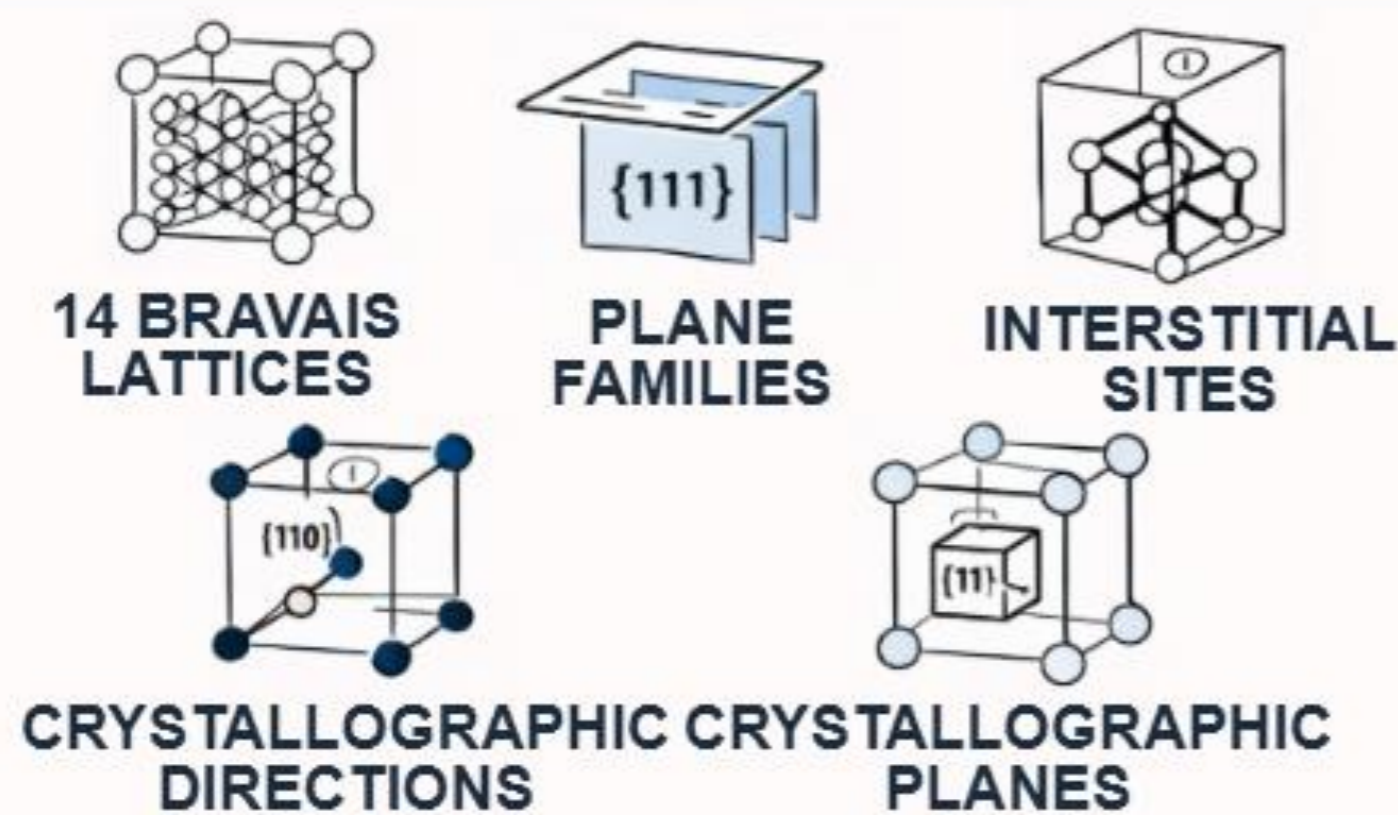
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INTRODUCTION & AIM

Crystallographic structures require spatial understanding to correctly interpret lattice geometry, symmetry, and atomic arrangement, something that 2D representations often limit. To overcome this barrier, a **Virtual Reality Learning Environment** (immersive and non-immersive) has been developed that facilitates the interactive exploration of fundamental 3D concepts: **the 14 Bravais lattices, crystallographic directions, planes and families of planes, and interstitial sites.**

VIRTUAL REALITY LEARNING ENVIRONMENTS FOR CRYSTALLOGRAPHY



METHOD

The application was implemented in two complementary modes—**immersive and non-immersive EVR**—to adapt to different usage contexts and levels of technological familiarity. The environment was designed as a **virtual museum** composed of five interactive stations, each dedicated to a specific crystallographic topic, so that learning is structured as a progressive journey that guides the user from identifying structures to interpreting more complex geometric elements. At each station, users can explore and compare three-dimensional models using **direct manipulation tools (rotation, translation, and zoom)**, which fosters the development of a spatial understanding that is often difficult to achieve with two-dimensional representation.

IMMERSIVE APPLICATION



RESULTS & DISCUSSION

The application successfully conveys geometric and structural features that are often difficult to interpret using **traditional representations**, especially when it is necessary to simultaneously **integrate symmetry, periodicity, and spatial relationships**. Through direct interaction, users can switch between unit cell analysis and extended lattice inspection, moving from a global view to local details to recognize **repeating patterns and distinctive elements of each structure**.

Furthermore, the tool allows for the clear **visualization of crystallographic directions and planes, the comparison of different orientations, and the exploration of families of elements indexed by Miller indices**, facilitating the connection between the notation and its geometric meaning. Additionally, the dynamic representation of **tetrahedral and octahedral voids** offers a particularly **intuitive illustration of their distribution, coordination, and role as potential interstitial sites within the lattice**.

ADVANTAGES OF THE VR LEARNING ENVIRONMENT FOR THE SPATIAL VISUALIZATION OF CRYSTALLOGRAPHIC STRUCTURES

GLOBAL AND LOCAL EXPLORATION



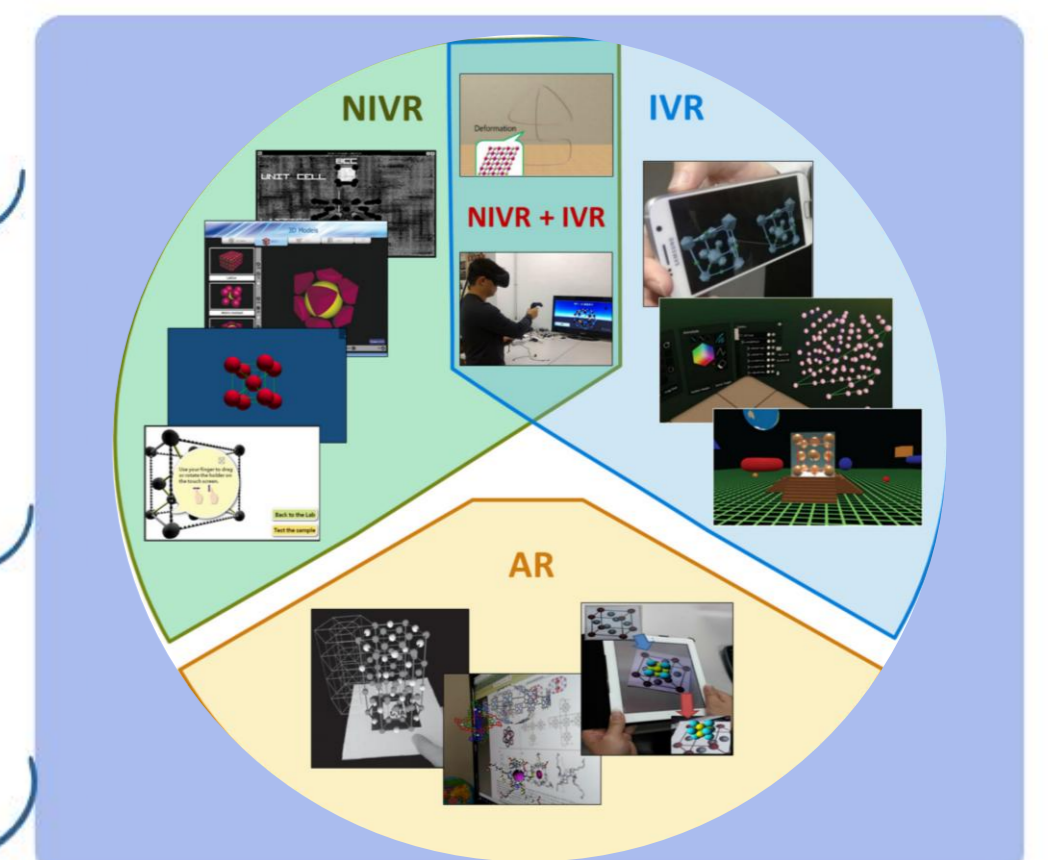
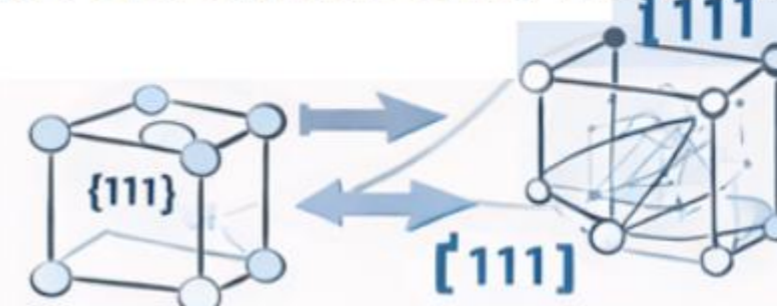
SYMMETRY AND SPATIAL RELATIONSHIP



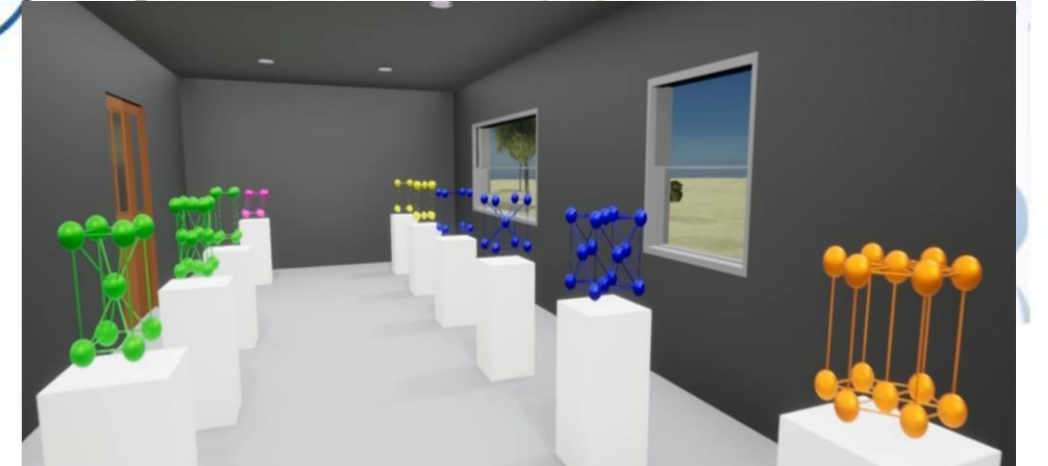
VISUALIZATION OF INTERSTITIAL GAPS



VISUALIZATION OF DIRECTIONS AND CRYSTALLOGRAPHIC PLANS



PROMOTES ACTIVE LEARNING AND IMPROVES SPATIAL UNDERSTANDING



This combination of three-dimensional visualization and interactive manipulation **reduces common ambiguities of planar interpretation** (e.g., apparent parallelism or intersections) and **promotes more active, exploration-based learning**. Its preliminary use in educational settings suggests an improvement in spatial understanding and greater conceptual retention, by promoting **immediate visual verification and the direct connection between concept, representation, and structure**.

CONCLUSION

- **VRLE offers an effective and accessible platform** for understanding crystallographic principles with high spatial requirements.
- It allows the direct **manipulation of three-dimensional models**, facilitating the development of geometric intuition regarding symmetries, periodicity, and relationships between structural elements.
- It allows the environment to be **adapted to different levels and objectives**, from conceptual introduction to comparative exploration.
- It is a valuable tool for **both guided instruction in practical activities and independent learning**, as it promotes exploration, immediate verification, and self-paced learning.