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Transforming Ancient Board Games into Interactive VR Cultural Heritage Experiences

Authors: **Arnaud Bellière, Florent Noiset**
Supervisor: **Eric Piette**
Readers: **Benoit Macq, Benoit Ronval, Nicolas Mil-Homens**

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Contents

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1

Introduction

The current era is increasingly centered around the digital world, where almost anything can be digitized. This transformation affects many aspects of daily life, ranging from simple hobbies such as reading books to traditional methods of communication, including letter writing. As society becomes more digitally oriented, many people feel increasingly disconnected from their senses and emotions.

In this context, board games now represent one of the most powerful tools for reconnecting people. Gathering around a table, handling physical pieces, and sharing the same space fosters social bonds and stimulates the mind in ways that the digital world struggles to replicate, offering something increasingly rare: genuine human connection.

Board games are among the oldest and most universal forms of human expression. From Senet to Catan, they have accompanied civilizations across millennia, serving not only as entertainment but as vectors of cultural transmission, social bonding, and strategic thinking. Their cultural significance remains recognised today, with German board game culture recently being nominated as intangible cultural heritage under UNESCO-related initiatives[1]. Ancient games are therefore far more than simple pastimes, they are tangible pieces of our shared heritage, carrying within them the values, customs, and intellectual traditions of the societies that created them.

Yet, the way they are preserved and presented in most museums today falls short of conveying this richness. More often than not, these games are reduced to static displays, encased behind glass, accompanied by brief descriptive panels that tell the visitor little about how the game was actually played.

As illustrated in Figure 1.1, even iconic artefacts such as the Senet board from Tutankhamun's tomb are presented in this way, beautiful and historically significant, yet utterly unreachable.
A board game displayed in a museum is, in many ways, a dead game: stripped of its players, its pieces untouchable, its rules unknown to most, it loses the very essence of what makes

[1] https://www.spielwarenmesse.de/en/mag/toy%2Dlab/board%2Dgames%2Drecognised%2Das%2Dcultural%2Dheritage/

Figure 1.1: Replica of the Senet board game from the Tomb of Tutankhamun, in the Grand Egyptian Museum in Giza. Source: The Egyptian Museum Mississauga.

it a game. That said, some museums have already begun to recognise this limitation and are taking steps to move beyond passive display. Bartley [1], for instance, explores how playing board games within a museum setting can serve as a powerful tool to emotionally engage adult visitors and spark meaningful discussions, demonstrating that when games are brought back to life, they regain their full cultural and educational potential.

In the academic world, significant efforts have also been made in this direction. The ERC-funded Digital Ludeme Project (DLP) was a major research initiative aimed at reconstructing and formalising the rules of thousands of ancient board games through computational methods [2].

Building on this work, the GameTable COST Action CA22145 [3] further expanded the scope of this research by bringing together an international network of researchers, historians, and game designers around the shared goal of preserving and studying traditional games.

One of the key outcomes of these efforts is the Ludii General Game System (GGS) [4], a powerful platform that allows users to play and analyse a vast collection of historical board games in a digital environment.

However, Ludii remains limited to two-dimensional interfaces, offering no ability to physically manipulate pieces or experience the spatial and social atmosphere in which these games were originally played. While it excels as a tool for game analysis and historical reconstruction [5], it stops short of providing the cultural immersion that would allow a player to truly connect with the heritage behind the game.

We hypothesize that virtual reality can provide a more experientially rich and culturally meaningful way of engaging with historical board games, while preserving the flexibility and generality offered by Ludii.

By situating the player within a reconstructed historical environment, VR has the potential to restore what both museum displays and 2D digital platforms fail to offer: the physicality of handling game pieces, a genuine sense of spatial presence, and a more natural form of situated interaction.

Beyond the experiential dimension, VR also opens the door to the capture of behavioural data, tracking how players move, hesitate, and make decisions, which could in future work inform the development of AI models that more faithfully replicate human gameplay patterns.

The primary objective of this thesis is therefore to implement a pipeline from Ludii to an interactive virtual reality experience, relying on Unreal Engine for its rendering, physics, and VR interaction capabilities.

The ultimate vision behind this work is ambitious: automatically rendering and playing thousands of ancient board games in VR, making the full breadth of human game heritage accessible in an embodied and culturally situated way.

This thesis represents a first concrete step in that direction, a system capable of adapting to a wide range of ancient board games, generating their boards and pieces procedurally in 3D, and presenting them within a culturally contextualised VR setting, while also laying the groundwork for future research into Human-Like AI modelling of gameplay.

This report will be structured as the following:

- Chapter 2 introduces the scientific and technological background of this work, including ancient board games as cultural heritage artefacts, the Ludii GGS, virtual reality, and human-like AI.
- Chapter 3 presents the Ludii Game Description Language (GDL) and its ludemic formalism.
- Chapter 4 details the main technical contribution of this thesis: a generic VR framework developed in Unreal Engine capable of transforming Ludii game descriptions into interactive 3D and VR experiences.
- Chapter 5 explores the cultural heritage applications of this framework through the case study of Ludus Coriovalli.
- Finally, Chapter 6 discusses the results, limitations, and future research directions of this work.

2

Background and Related Work

2.1 Historical Board Games as Cultural Heritage

Board games have been played across many civilizations since ancient times and constitute an important component of human cultural heritage.
Through their rules, materials, symbolism, and gameplay mechanics, they often reflect social structures, religious beliefs, military strategies, and educational practices specific to the societies in which they emerged. One of the oldest known playable board games is the Royal Game of Ur, discovered in Ancient Mesopotamia and dating from approximately 2600 BC to 2400 BC.

Beyond its entertainment value, the game appears to have played an important cultural and ritualistic role within Mesopotamian society. Historical records suggest that ancient diviners used the game as a pedagogical tool to teach pupils how to interpret anatomical patterns observed in sacrificed sheep livers during hepatoscopy rituals [6]. The Royal Game of Ur is represented in Figure 2.1.

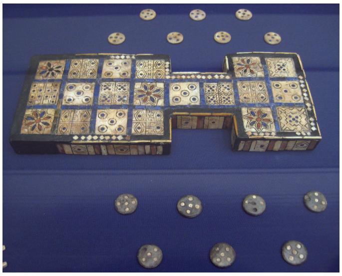

Figure 2.1: Royal Game of Ur held in British Museum. Source: The British Museum [7]

Another important example is Senet, one of the oldest known board games, whose earliest discovered versions date back to approximately 3100 BC in Dynastic Egypt. The game appears frequently in Egyptian iconography and funerary art, demonstrating its strong cultural and symbolic significance. Figure 2.2 presents queen Nefertari, wife of Pharaoh Ramesses II, playing Senet, while Figure 2.3 illustrates two individuals engaged in gameplay. Although the exact original rules of Senet remain uncertain today, historians and researchers have proposed plausible reconstructions based on archaeological discoveries, murals, and depictions of gameplay interactions.

Figure 2.2: Senet played by queen Nefertari. Source: Painting in tomb of Egyptian queen Nefertari (1295–1255 BCE).

Figure 2.3: Two people playing Senet. Source: West wall of the chapel of Nikauhor and Sekhemhathor.

These examples illustrate that board games historically represented far more than simple recreational activities. They were deeply integrated into the social and cultural life of ancient civilizations and today constitute valuable artefacts for understanding past societies and their practices.

Beyond their historical interest, traditional board games also represent valuable educational and interdisciplinary tools. Their study naturally connects fields such as archaeology, anthropology, history, artificial intelligence, mathematics, psychology, and game design. As a result, historical games are increasingly explored within broader STEAM-oriented[1]

[1]`https://store.steampowered.com/about/`

approaches, where gameplay and interaction can support both education and cultural mediation.

An example of such an initiative is Senet: Households[2], a pedagogical project inspired by the ancient Egyptian game Senet, designed to introduce players to aspects of daily life, symbolism, and social practices in Ancient Egypt through interactive gameplay experiences.

While physical artefacts such as boards and pieces can be conserved in museums, the gameplay itself, including the rules, interactions, and player experience, is often partially or entirely lost over time.

As a result, studying ancient board games frequently requires the reconstruction, formalisation, and experimentation of possible gameplay interpretations in addition to the preservation of the physical objects themselves.

2.2 Digital Preservation of Board Games

Preserving historical board games requires more than conserving their physical components. In many cases, the original rules of ancient games are partially lost, uncertain, or subject to multiple interpretations.

As a result, studying such games often requires researchers to formalise and test possible gameplay systems based on archaeological evidence, historical texts, iconography, and comparisons with related games.

Digital approaches provide valuable tools for addressing these challenges. By representing games within computational systems, researchers can simulate gameplay, compare alternative rulesets, analyse strategies, and preserve knowledge in a reproducible form. This is particularly relevant for historical games, where several plausible interpretations may coexist and where computational simulations can help evaluate their consistency.

2.2.1 Game Description Language

A central challenge in the digital preservation of board games is the formal representation of their rules, equipment, and possible interactions. This issue is closely related to the field of General Game Playing (GGP), whose objective is to develop systems and artificial intelligence agents capable of understanding and playing multiple games without requiring game-specific implementations.

To achieve this, games are represented using GDLs. A GDL provides a structured and machine-readable description of a game, including its board, pieces, rules, legal moves, and termination conditions. Ideally, such a language should be expressive enough to represent a wide range of games, descriptive enough to remain understandable to humans, and efficient enough to support gameplay simulation and AI agents [8].

The original GDL introduced by Genesereth et al. represented an important milestone for General Game Playing research [9]. It enabled the development of generic AI agents and contributed to the emergence of the International General Game Playing Competition [10]. These competitions also stimulated progress in several AI approaches for general games, including Monte Carlo Tree Search [11] and constraint-based methods for games with incomplete information [12] [13] [14].

[2] `https://store.steampowered.com/app/3457490/Senet_Households/`

However, despite its scientific importance, the original GDL is often verbose and not well suited to modelling the large diversity of equipment, variants, and rule structures found in traditional board games. This limitation is particularly important in the context of cultural heritage, where games may involve unusual board geometries, uncertain rules, regional variants, and domain experts from fields such as archaeology, history, or game studies rather than computer science.

2.2.2 The Ludii General Game System

The Ludii GGS was developed to address several of these limitations. Ludii is based on a ludemic approach, where games are described through high-level conceptual units called ludemes [4]. This allows games to be represented in a concise, modular, and human-readable way while remaining executable by computational systems. Recent work has also shown that the Ludii Game Description Language is universal, reinforcing its relevance as a formal system for representing games [8].

Ludii was developed in the context of the DLP, whose objective was to reconstruct, classify, and analyse traditional games from around the world using computational methods [15]. It is also closely connected to the GameTable COST Action CA22145[3], which brings together researchers from artificial intelligence, digital humanities, history, archaeology, and game studies around the preservation and computational study of tabletop games heritage [3].

One of Ludii's main strengths is its capacity to represent a very large number of games and variants. The system currently includes more than 1400 games in the strict sense, while its options and parameterised rulesets make it possible to generate more than two million playable variants [16]. These variants may differ in board size, starting positions, movement rules, victory conditions, available pieces, or optional mechanics.

Beyond representation, Ludii also supports game analysis, procedural generation, and artificial intelligence research. Its formal descriptions can be used to simulate games, generate legal moves, evaluate rule hypotheses, and support general game-playing agents. This makes Ludii particularly relevant for historical board games, where the rules may be uncertain and where computational simulations can help compare different interpretations.

Several previous works illustrate this role in the study of traditional and historical games. Ludii has been used to analyse the French Military Game [17], to support computational approaches for recognising and reconstructing ancient games such as Ludus Latrunculorum [18], to study Mesopotamian games through AI-simulated play [19], and to identify plausible rules for Ludus Coriovalli using artificial intelligence-driven simulations [20]. These works demonstrate that Ludii is not only a platform for playing games, but also a research tool for cultural heritage, rule reconstruction, and computational archaeoludology.

Ludii also provides an ecosystem for AI research. It has been empirically compared with other general game systems [21], used as a competition platform [22], and extended through reusable general board game concepts that simplify the modelling of common game mechanics [23]. These characteristics make Ludii an especially suitable foundation for this thesis, as the objective is not to recreate a single game manually, but to build a pipeline capable of transferring formal Ludii game descriptions into interactive VR experiences.

[3]`https://gametable.network/index.html`

2.2.3 Limitations of Traditional 2D Systems

Despite these strengths, the current Ludii application remains primarily limited to traditional two-dimensional interfaces. While it is highly effective for describing, playing, and analysing games computationally, it does not fully reproduce the physical, spatial, and social dimensions of board game play.

First, interaction in Ludii relies mainly on standard screen-based input. Players manipulate pieces through a mouse interface rather than through direct physical interaction with boards and pieces. This limits the sense of embodiment and reduces the connection with the material dimension of board games, which is particularly important for historical and museum-oriented applications.

Second, although Ludii can model complex board geometries, it does not easily support the integration of realistic boards reconstructed from photographs, 3D scans, or archaeological artefacts. This is a significant limitation for cultural heritage applications, where the visual and material characteristics of an artefact often contribute to its historical meaning.

Finally, traditional 2D systems do not naturally capture behavioural data such as gaze direction, hand movement, hesitation, spatial attention, or physical interaction patterns. Such information is particularly relevant for studying how players perceive and understand game situations, and may support future research on gameplay analysis and human-like AI.

These limitations motivate the use of virtual reality as a complementary medium. By combining Ludii's formal and general game descriptions with immersive 3D interaction, it becomes possible to preserve the computational strengths of the system while extending historical board games toward more embodied, interactive, and culturally meaningful experiences.

2.3 Virtual Reality

Virtual Reality (VR) refers to a digital environment in which users can be immersed and interact with virtual objects as if they were physically present within the scene. In the context of this thesis, VR is not considered only as a visualisation technology, but as an interaction medium capable of restoring some of the physical and spatial dimensions that are essential to board game play.

A first important aspect of VR is embodied interaction. Unlike traditional screen-based interfaces, VR allows users to interact with virtual objects through hand movements and motion controllers. In the case of board games, this makes it possible to reproduce actions such as grasping a piece, moving it across the board, and placing it on a target position. These interactions are particularly relevant for historical board games, since the manipulation of material components is part of the way such games are understood and experienced.

A second important aspect is spatial immersion. VR places the user inside a three-dimensional environment rather than in front of a flat interface. This changes the relationship between the player and the game space, transforming the user from a passive observer into an active participant. For board games, this spatial dimension can help reproduce the feeling of being physically present around a table or in a culturally contextualised environment.

VR also offers opportunities for cultural immersion. Historical games are not only defined by their rules, but also by the contexts in which they were played. By situating a game within an appropriate virtual environment, VR can help users better perceive the cultural setting associated with the artefact. This is especially relevant for museum-oriented applications, where the objective is not only to display an object, but also to support interpretation, engagement, and cultural mediation.

Finally, VR provides valuable possibilities for behavioural capture. Modern immersive systems can record information such as head position, hand movements, gaze direction, spatial attention, and interaction patterns during gameplay. Such data can help researchers analyse how players perceive a board, hesitate before making decisions, manipulate pieces, and adapt to unfamiliar rules. This aspect is particularly relevant for future studies on player behaviour and human-like AI, as discussed in the next section.

In this thesis, VR is therefore used as a complementary medium to formal game descriptions. While systems such as Ludii provide a powerful way to describe and analyse games computationally, VR extends this representation toward physical interaction, spatial presence, and behavioural observation. This combination is central to the proposed framework, which aims to transform formal board game descriptions into playable and immersive 3D experiences.

2.4 Human-Like AI

Although competitive board games are often associated with performance and optimisation, most people primarily play board games for entertainment, social interaction, and enjoyment. However, playing against an artificial agent is often perceived as less engaging than playing against another human player, since most game-playing agents are designed primarily to maximise their chances of winning [24] [25]. Even when difficulty levels are adjusted, the underlying objective of these systems generally remains the same: selecting strong or optimal moves.

In recent years, the concept of human-like AI has emerged as an alternative approach to traditional performance-oriented game AI. Rather than focusing exclusively on victory, human-like AI aims to reproduce behaviours, decisions, and play styles that resemble those of human players. This is particularly challenging because human behaviour is diverse and context-dependent. For example, different players may adopt aggressive, defensive, cautious, exploratory, or highly personal strategies depending on their experience, preferences, and understanding of the game[4] [26].

Human-like AI is therefore a multidimensional research topic involving artificial intelligence, cognitive science, psychology, behavioural analysis, and human-computer interaction [27]. It cannot be reduced to the simple imitation of optimal play, since human players do not always act rationally or consistently. Instead, modelling human-like gameplay requires understanding how players perceive the board, evaluate possible moves, hesitate, learn from previous actions, and interact physically with the game environment.

In the context of traditional and historical board games, human-like AI could have several important applications. Previous works have already shown how AI-driven simulations can support the analysis of historical games, the exploration of possible rulesets,

[4] `https://www.chess.com/forum/view/general/chess-styles`

and the reconstruction of uncertain gameplay dynamics [17] [18] [19] [20]. Human-like agents could further improve such approaches by producing simulations that more closely resemble how real players might interact with these games, potentially leading to more realistic interpretations of historical gameplay.

The development of such systems requires behavioural data collected from real gameplay situations. This data may include decision-making patterns, move sequences, reaction times, gaze direction, hand movements, physical interactions with pieces, and player hesitation. Capturing how humans naturally perceive, analyse, and interact with board games is essential for designing AI systems that reproduce realistic gameplay behaviour rather than only optimised strategies.

Virtual reality offers a valuable opportunity in this context. Unlike traditional 2D interfaces, VR allows players to interact with game elements in a more natural and embodied way, while also enabling the collection of detailed behavioural information. By observing how players move around the board, focus their attention, manipulate pieces, and react during gameplay, researchers can build datasets that better reflect real human behaviour during play.

This thesis does not aim to develop a complete human-like AI system. However, by creating a VR environment in which players can interact naturally with historical board games, it contributes indirectly to the acquisition of behavioural gameplay data that may support future research on player modelling and human-like AI.

Previous research on chess expertise provides an example of how behavioural data can contribute to the understanding of human gameplay. Studies on Long Term Memory (LTM) and chunk-based information processing suggest that experienced players do not analyse the board as a collection of isolated elements, but instead recognise meaningful configurations of pieces and spatial relationships[5] [28]. Such findings highlight the importance of visual attention and perception in board game decision-making.

Modern VR equipment equipped with tracking technologies can help extend this type of analysis to other games, including historical board games whose gameplay remains less studied. Figure 2.4 illustrates how the peripheral vision of expert chess players contributes to the recognition of meaningful patterns during gameplay.

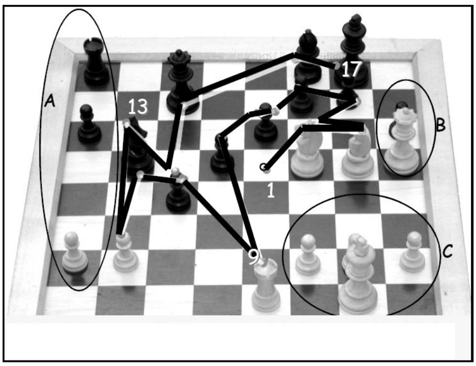

Figure 2.4: Eye movements of a chess champion. Source: [29].

[5] https://www.chessprogramming.org/index.php?title=Eye_Movements

3
The Ludii Game Description Language

Throughout this thesis, the Ludii language is used to describe and represent the board games integrated into the VR environment. This chapter therefore introduces the main structural elements of the Ludii Game Description Language that are relevant to our framework.

Ludii represents games as structures composed of ludemes, which are high-level, human-understandable game concepts. This ludemic approach allows games to be described in a concise, modular, and readable manner while remaining executable by computational systems. The elements introduced in this chapter correspond to the main components later extracted by our parser and translated into interactive 3D and VR representations.

3.1 Game rules and equipment

A Ludii game description is organised around a small number of main components that define how the game is structured and played. As illustrated in Example 3.1 with Tic-Tac-Toe, a game description generally specifies the name of the game, the number of players, the equipment used during gameplay, and the rules governing player actions and game termination.

Example 3.1 illustrates how the rules of Tic-Tac-Toe are represented in Ludii.

Example 3.1: rules of Tic-Tac-Toe.lud.

```
(game "Tic-Tac-Toe"
    (players 2)
    (equipment {
        (board (square 3))
        (piece "Disc" P1)
        (piece "Cross" P2)
    })
    (rules
        (play (move Add (to (sites Empty))))
        (end (if (is Line 3 #1) (result Mover Win)))
    )
)
```

The `game` ludeme defines the game itself and contains the main information required to execute it. It includes the game name, which allows the game to be identified by the user, as well as the number of players, the equipment, and the rules.

The `players` ludeme specifies how many players are involved in the game. In the case of Tic-Tac-Toe, the game is played by two players.

The two most important components for our VR framework are the equipment and rules sections. The equipment determines which physical elements must be represented in 3D, such as the board and pieces, while the rules define the legal actions that players and AI agents can perform during gameplay. These two components are therefore central to the parser described in Chapter 4, since they provide the information required to generate the board, instantiate the pieces, validate moves, and evaluate the end of the game.

The following subsections describe these two components in more detail.

3.1.1 Equipment

The `equipment` ludeme describes the physical elements required to play a game, including the board and the components manipulated by the players, such as pieces, dice, or cards. In this thesis, this section is particularly important because it defines the elements that must later be translated into 3D objects within Unreal Engine.

The `board` ludeme defines the structure of the game board. Ludii can represent boards through predefined structures, such as square, rectangular, or hexagonal boards, as well as through more complex graph-based structures [30]. For instance, (square 3) defines a 3×3 square board. This information is used by the VR framework to generate the corresponding board layout in 3D.

The `piece` ludeme defines the game elements that players manipulate during gameplay. A piece may belong to a specific player, such as P1 or P2, or be shared between all players depending on the rules of the game. In the VR environment, these pieces are represented as 3D objects that can be selected, moved, or physically manipulated.

3.1.2 Rules

The `rules` ludeme defines how the game progresses and how players can interact with the equipment. It generally contains three main parts: the initial state of the game, the legal actions available during gameplay, and the end conditions.

The `start` ludeme specifies the initial configuration of the game, including the pieces already placed on the board at the beginning of the game.

The `play` ludeme defines the legal moves that players can perform, such as placing a piece on an empty cell, moving a piece from one position to another, removing a piece, or promoting a piece into another component. In the VR framework, this information is used to validate player interactions.

The `end` ludeme specifies the conditions under which the game terminates, such as a win, a loss, or a draw. These conditions are evaluated after each move to determine whether the game should continue or whether a final result should be displayed.

Together, these rule components provide the core gameplay logic that must be interpreted by the parser and executed within the VR environment.

3.2 Metadata

In Ludii, metadata provides descriptive information about a game that is not directly required for gameplay execution. This information may include the game description, aliases, rules explanation, historical origin, classification, credits, and visual properties.

Example 3.2 presents the metadata associated with Tic-Tac-Toe.

Example 3.2: metadata of Tic-Tac-Toe.lud.

```
(metadata
    (info {
        (description "Tic-Tac-Toe is a game of alignment popular among children. It
          is known from the nineteenth century in England and the United States, but
          may be older.")
        (aliases {"Noughts and Crosses" "Oughts and Crosses" "Tik Tak Tol" "Tripp
          Trapp Trull" "Tick-Tack-Toe"})
        (rules "Play occurs on a 3x3 grid. One player places an X, the other places
          an O and players take turns placing their marks in the grid, attempting to
          get three in a row of their colour.")
        (source "Murray 1951: 40.")
        (id "100")
        (version "1.3.14")
        (classification "board/space/line")
        (credit "Eric Piette")
        (origin "This game was played in Unknown, from around 1850 to 1883.")
        }
    )
    (ai "Tic-Tac-Toe_ai" )
)
```

Unlike the equipment and rules sections, metadata does not define how the game is played. However, it remains important for documentation, analysis, and user interfaces. In the context of this thesis, metadata can be used to display useful information to the player, such as the game rules, credits, or historical context, within the 3D or VR environment.

Metadata may also include visual information through the graphics section. This allows Ludii descriptions to specify visual properties such as the colour of pieces, the style of the board, or other graphical aspects that can later be reflected in the virtual representation of the game.

3.3 Options and Definitions

Ludii can represent not only individual games, but also many variants of these games. This is particularly important for traditional board games, which often evolved differently across regions, cultures, and historical periods. Variants may differ in board size, starting positions, movement rules, victory conditions, available pieces, or optional mechanics.

To support this diversity, Ludii provides an option system. Options allow specific parts of a game description to be replaced depending on the configuration selected by the player. They are represented through placeholders such as `<OptionName>`, as illustrated in Example 3.3.

Example 3.3: Example usage of the options in TrafficLights.lud.

```
(game "Traffic Lights"
    ...
    (equipment {
        (board <Board:size>)
        ...
    })
)

(option "Board Size" <Board> args:{ <size> } {
    (item "3x3" <(square 3)> "The game is played on a 3x3 board.")
    (item "3x4" <(rectangle 3 4)> "The game is played on a 3x4 board.")+
})
```


Depending on the selected option, the placeholder is replaced by the corresponding rule or equipment configuration. Each option is associated with a description explaining its effect on gameplay, making it easier for players and researchers to understand the differences between variants.

Ludii also provides the define ludeme, which allows reusable rule structures or keywords to be declared once and referenced multiple times in a game description. This helps reduce code duplication and improves the readability and maintainability of Ludii files.

Some definitions are local to a specific game, while others are globally available in Ludii. For example, predefined concepts such as `"Line3Win"`, which indicates that placing 3 pieces in a row automatically ends the game with a win for the mover, can be reused across multiple games without needing to redefine the corresponding rule manually.

Together, options and definitions make Ludii highly modular and extensible. They allow game designers to represent families of related games, capture historical variants, and reuse common game concepts efficiently.

4

A Generic Framework for Ludii Games

This chapter presents the main contribution of this work through the example of one of the simplest games, Tic-Tac-Toe. It explains the process of translating a Ludii game description into a 3D environment using Unreal Engine, as well as the subsequent transition from a standard 3D experience to a virtual reality experience.

The complete Unreal Engine VR project is available here.

4.1 Unreal Engine and Development Environment

Unreal Engine[1] is a 3D computer graphics game engine developed by Epic Games in 1998. Originally developed for first-person shooters on PC, it has progressively evolved into a versatile engine used across many domains, including video games, virtual reality, and television production. Unreal Engine provides extensive tools for creating, managing, and interacting with complex 3D environments.

Unlike Ludii, which is developed in Java, Unreal Engine is primarily written in **C++** [31], requiring a different programming approach and interoperability considerations between the two environments.

Unreal Engine provides several tools to facilitate the development of interactive 3D and virtual reality applications. In this work, the engine was mainly used to create interactions between the player and the game environment, such as moving within the virtual space, manipulating objects, and interacting with game elements.

To accelerate the development process, Unreal Engine offers predefined templates for different types of applications, including virtual reality projects. This VR framework was used as a starting point for the implementation of our prototype, as it already provides core functionalities such as player movement, camera control, object interaction, and object manipulation. These built-in systems allowed us to focus primarily on the integration of Ludii games into an immersive VR environment rather than on low-level VR mechanics.

[1] `https://www.unrealengine.com/`

It was important to support both traditional 3D interaction and virtual reality interaction throughout the development of the project. In practice, VR applications are significantly more difficult and time-consuming to debug than standard 3D applications, as developers must repeatedly wear and remove the headset for each testing iteration. Consequently, implementing a non-VR 3D mode greatly simplifies the development and debugging process by allowing rapid testing of gameplay logic directly within the Unreal Engine editor.

To determine whether the application is currently running in VR mode or in a traditional 3D environment, Unreal Engine provides the built-in function IsHeadMountedDisplayEnabled(). This function returns a boolean value indicating whether a VR headset is connected and active, allowing the system to dynamically adapt the interaction mechanisms depending on the execution mode.

4.2 System Architecture

Before implementing the different components of the project, it was necessary to design a clear architecture describing both the sources of the data and assets used in the system, as well as the interactions between the different software and hardware components involved in the VR experience.

Figure 4.1 illustrates the overall architecture of the master thesis project.

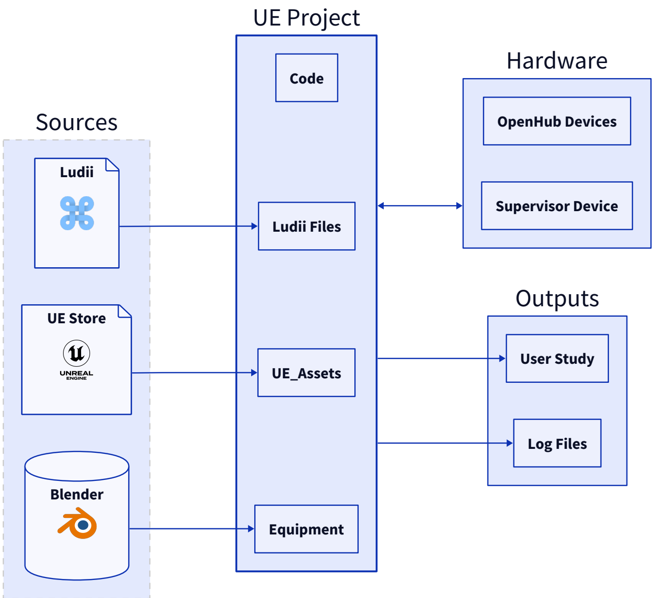

Figure 4.1: Architecture of our master thesis.

The system combines several complementary elements. First, game descriptions are retrieved from Ludii and translated into an interactive 3D environment. In parallel, graphical assets are integrated from multiple sources, including environments from the Unreal Engine Marketplace. Additional 3D assets and modifications are created using Blender in order to adapt the content to the needs of the VR application.

The architecture also relies on dedicated VR hardware, enabling immersive interaction with the virtual environment. These devices allow users to navigate within the scene, manipulate game elements, and interact naturally with the application.

Finally, the developed system is designed not only as a playable experience, but also as a research platform for conducting user studies. During each session, the application records gameplay information and interaction data in log files, allowing the collection of user feedback and behavioral observations for later analysis.

4.3 Translation of Ludii Games into Unreal Engine

4.3.1 Ingestion and Runtime File Processing

A key challenge of this project was enabling the dynamic integration of Ludii games into a 3D and virtual reality environment. To achieve this, it was first necessary to import Ludii game descriptions into Unreal Engine and process them in a format compatible with the engine's execution pipeline.

Unreal Engine provides tools allowing external files to be loaded and converted into character strings at runtime. This mechanism makes it possible to dynamically import any Ludii file simply by specifying its filename, opening the possibility for both traditional 2D interfaces and immersive VR interfaces to load games interactively. Figure 4.2 illustrates the integration process used to import Ludii files within the engine.

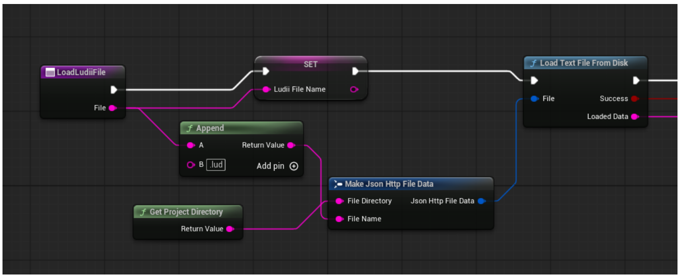

Figure 4.2: LoadFileFromDisk takes a file name as input and returns a string corresponding to the content of the file.

4.3.2 Syntactic Parsing and Rule Extraction

Once a Ludii game description has been loaded into Unreal Engine as a string, it must be interpreted and transformed into executable game logic.
This process requires a *parser*: a system capable of reading the structured syntax of Ludii

descriptions and translating it into concrete game rules, board configurations, and interaction behaviours within the engine.

Ludii already provides a fully functional parser, implemented in Java as part of its original architecture. However, rather than attempting to reuse this existing implementation, we chose to develop a native parser directly within Unreal Engine using C++ and Blueprint.
This decision was driven by several technical and architectural considerations:

Absence of Java support in Unreal Engine: Unreal Engine is fundamentally built around C++ and Blueprint and does not natively support a Java runtime. Integrating the original Ludii parser would have required embedding a Java Virtual Machine [2] inside the engine, managing cross-language communication through JNI bridges, and synchronising two separate memory and threading models. Furthermore, while experimental Java-to-C++ conversion tools exist, none provide reliable results for large and architecturally complex projects such as Ludii. As noted by [32], even semi-automated migration between similar languages requires significant manual intervention, particularly regarding memory management and complex object hierarchies. Given that the Ludii parser relies on a dynamic, reflection-heavy Java architecture, such a conversion would likely have produced code difficult to maintain and poorly integrated with Unreal Engine, ultimately costing more effort than a targeted native reimplementation.

Real-time performance constraints of VR: Virtual reality applications impose strict performance requirements. To ensure a comfortable and immersive experience, the application must maintain a stable frame rate of 90 to 120 frames per second, with minimal latency on all interactions [33]. Introducing a permanent communication layer between a Java process and the Unreal Engine rendering pipeline would have created non-deterministic delays, thread synchronisation issues, and potential frame drops. A native C++ implementation eliminates this overhead entirely, as game logic and rendering operate within the same execution environment.

Maintainability and extensibility: A self-contained native implementation is easier to debug, profile, and extend within a single development environment. Having the parser, the game logic, and the VR interaction systems coexist within the same codebase reduces the cognitive overhead for future developers and avoids the versioning and dependency issues that would arise from maintaining a parallel Java component alongside an Unreal Engine project.
Although integrating Ludii directly through a JVM and JNI bridges was theoretically conceivable, the cumulative cost in terms of complexity, performance risk, and maintainability made a native reimplementation the more robust and pragmatic choice for a real-time VR application.

With this architecture decision established, the focus shifted to the practical challenge of interpreting Ludii game descriptions within Unreal Engine. Since Ludii's syntax follows

[2] https://docs.oracle.com/en/java/javase/26/vm/java%2Dvirtual%2Dmachine%2Dtechnology%2Doverview.html

a structured, recursive format, the parsing process had to be adapted to the constraints of a real-time 3D/VR environment rather than directly mirroring the original Java implementation.

To validate this approach, Tic-Tac-Toe was selected as an initial case study because of its relatively simple Ludii description. The game file was used to identify the core structures and rules necessary to execute a game in real time within the VR application.

Beyond gameplay execution, the parser also had to extract metadata information contained in Ludii files. These metadata elements, defined as key-value pairs, include information such as the game name, description, and other contextual elements useful for the user interface. Dedicated extraction functions were therefore implemented to retrieve and display this information dynamically within the application interface.

Overall, this processing pipeline constitutes the transformation of abstract Ludii game descriptions into interactive and immersive experiences executable in real time within Unreal Engine.

4.3.3 Runtime Game Representation and Gameplay Logic

The rules described through Ludii ludemes directly determine both the types of game pieces involved and the actions that players are allowed to perform during gameplay. As presented in Chapter 3, these actions may include placing a piece on the board, moving a piece between cells, replacing one piece with another, or removing a piece from the game. In order to represent these interactions in a generic manner within Unreal Engine, we defined a dedicated C++ structure named *FSTMove*, which encapsulates all the information required to describe a move independently of the specific game being played.

This structure stores several parameters associated with a move, including: the type of move being performed, the piece involved in the action, an optional secondary piece interacting with the first one, the type of target cell affected by the move, the index of the affected board cell, and the index of the manipulated piece.

Both the human player and the AI maintain access to a dynamically generated list of all legal moves available in the current game state. Since all move categories supported by Ludii, such as adding, moving, removing, or replacing pieces, are represented through the same generic structure, the system can uniformly process player actions across different games without requiring game-specific implementations.

This move list therefore acts as a constraint system defining the set of authorized actions for each player. Whenever a player performs an action, the corresponding move is transmitted to the Game Manager, which validates and applies the modification to the board state. The Game Manager then updates the active player state by disabling the current player's interactions and enabling those of the opponent, thereby ensuring correct turn alternation and synchronization of the gameplay state.

4.4 Procedural Materialization and Spatial Interaction

4.4.1 Procedural Board Generation

In order to have a working board in 3D, we opted for a procedural generation approach where the board is constructed dynamically. In the case of Tic-Tac-Toe, the user can directly change the board size within the Ludii file. Therefore, the 3D representation needed to dynamically adapt to such modifications.

To address these requirements, we designed a structure called *LogicalCell* to represent each type of cell for any board-based game [30]. This structure contains game-related information such as:

- The index of the cell,
- The type of piece currently occupying it,
- The geometric shape of the cell (e.g., square, hexagonal, etc.),
- The list of connected cells for the current cell.

These pieces of information are initially defined in the Ludii file and are then translated into Unreal Engine using the parser we implemented. Once parsed, the data is provided to the game manager. This procedural approach ensures flexibility and scalability. It allows the board to automatically adjust to changes defined in the Ludii file without requiring manual modifications in Unreal Engine.

Moreover, this system facilitates adaptation to other types of board games such as **Aboyne**, visible in Figure 4.3, simply by replacing the cell shape with a hexagonal model instead of a square one, even though the indexes have to be interpreted differently as the number of adjacent pieces differs from a traditional square board.

Example 4.1 presents the creation of a board using hexagonal pieces.

Example 4.1: board rules of Aboyne.lud.

```
(game "Aboyne"
    (players 2)
    (equipment {
        (board (hex 5))
        ...
    })
    ...
)
```

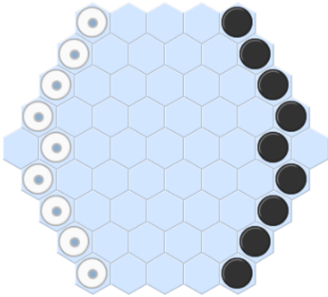

Figure 4.3: The board of the game Aboyne implemented in Ludii. Source: Ludii Portal Aboyne

4.4.2 Interaction Paradigms in 3D and VR

In the standard 3D version, the player interacts with the board through mouse-based inputs. A piece can be placed by selecting it and clicking on the target cell while looking at the board from a traditional camera perspective.

In the VR implementation, interactions rely on the motion controllers provided by the headset. To enable physical manipulation, each 3D game piece must contain a Grab Component, allowing it to be attached to and held in the player's virtual hand when the corresponding controller input is pressed. Figure 4.4 illustrates a cross piece configured with this component.

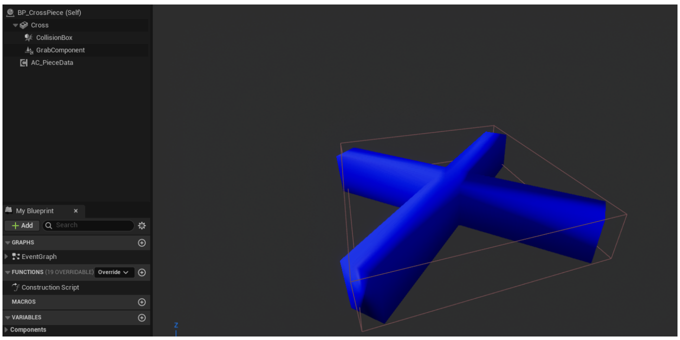

Figure 4.4: The grab component must be present for each models of pieces imported in Unreal.

Once a piece is grabbed, the player can physically move and release it onto the desired board cell. When the piece comes into contact with a cell, the system evaluates whether the action is valid according to the current game rules parsed from the Ludii description. If the move is authorized, the piece is placed on the board and the internal game state is updated accordingly by replacing the previous cell state with the newly placed piece.

4.5 Runtime Game Execution

4.5.1 End-Game Rule Evaluation and AI agents

Before allowing the next player to perform an action, the Game Manager evaluates whether the current board state satisfies any game-ending condition. As explained in Section 3.1.2, these conditions are defined through the end ludeme, which specifies both the termination criteria of the game and the corresponding outcome.

In Ludii, end-game conditions are generally represented using sub-ludemes of the form:

```
(if (condition) (result ...))
```

where the first part defines the condition that must be satisfied, while the second part specifies the resulting game outcome.

For example, in Tic-Tac-Toe, the rule:

```
(if (is Line 3 #1) (result Mover Win))
```

indicates that if three identical pieces are aligned, the player who performed the last move wins the game.

Since the Game Manager continuously maintains the current board state, it can evaluate these victory conditions after each action performed by a player. If a terminal condition is detected, the game state is updated accordingly and further interactions are disabled, thereby ending the game.

4.5.2 Generic AI Integration

A key requirement for a generic AI capable of playing any Ludii game was to define a representation of moves and board states that is entirely independent of the specific game being played. To this end, we previously defined the *FSTMove* structure, which encapsulates all parameters necessary to describe a move.

The board state is represented as an array of *LogicalCell*, where each entry corresponds to a cell on the board and stores its current occupancy and connectivity information. This representation is entirely derived from the Ludii parser: legal moves are generated at runtime by iterating over the *FSTMove* array produced by the parser for the current game, and for each move type, enumerating all valid instantiations given the current board state.

Crucially, neither the move generation nor the state evaluation logic contains any game-specific knowledge. Win condition checking is encapsulated in a dedicated function that evaluates solely the end ludeme parsed from the Ludii file, with no hardcoded game-specific logic. This abstraction means that the AI operates identically regardless of the game: it receives a board state, generates legal moves, applies them to a copy of the state, and evaluates the result, all through the same generic pipeline.

Building on this game-agnostic representation, we implemented two AI algorithms: Alpha-Beta pruning and Monte Carlo Tree Search (MCTS) [34].

Both algorithms operate exclusively on *FSTMove* and *LogicalCell* structures, with no modification required between games. Alpha-Beta explores the game tree up to a configurable maximum depth, pruning branches that cannot affect the outcome. MCTS builds a search tree through repeated cycles of selection, expansion, random simulation, and backpropagation, guided by the Upper Confidence Bound (UCB1) [35] formula to balance exploration and exploitation.

In both cases, the algorithms are oblivious to the rules of the game being played: legal moves come from the parser, terminal states are detected by the rule evaluator, and the board representation is uniform across all games. This makes both AIs fully reusable across any board game defined in Ludii and loaded into the VR prototype, without requiring any game-specific adaptation.

5

Cultural Heritage Applications of the VR Framework

This chapter presents the application of our VR framework to the domain of cultural heritage and museum-oriented experiences. While the previous chapter focused on the design of a generic pipeline capable of translating Ludii games into interactive 3D and VR environments, the objective here is to evaluate how such a system can be used to transform historical board games into immersive and interactive cultural experiences.

Historical board games displayed in museums are most often presented as static artefacts that visitors can observe but not directly interact with. However, board games are inherently interactive objects whose cultural and social significance emerges through gameplay, physical manipulation, and player interaction. As a result, traditional museum presentations often fail to fully convey the experiential dimension of these artefacts.

One of the main objectives of this work is therefore to investigate how virtual reality can help bridge this gap by allowing visitors to interact with historical games in a more natural and immersive way. Beyond simple visualisation, VR makes it possible to recreate physical interactions with game elements while preserving the historical and cultural context associated with them.

In this chapter, we explore this perspective through the integration of a historical board game into our VR framework, highlighting both the technical challenges and the cultural heritage applications of such an approach.

5.1 Ludus Coriovalli

To explore the cultural heritage applications described in the previous section, we selected Ludus Coriovalli as a case study for the integration of a historical board game into our VR framework. This choice was motivated by several factors. First, the scientific work surrounding the discovery and analysis of this artefact is particularly recent and includes contributions from researchers at UCLouvain, notably through the participation of Prof.

Eric Piette, supervisor of this thesis. In addition, the artefact is exhibited at the Het Romeins Museum in Heerlen, located just across the Belgian border in the Netherlands, making it a realistic and locally relevant application scenario. Following the ongoing renovation of the museum, such a VR experience could potentially be explored in the future as an interactive tool for museum visitors.

Another important motivation behind this choice is the nature of the artefact itself. The original stone is relatively small and fragile, which naturally limits direct interaction by museum visitors. Furthermore, understanding the gameplay and cultural significance of such an object remains difficult through simple observation or textual explanations alone. As a result, immersive and interactive experiences represent an interesting opportunity not only to improve visitor engagement, but also to help preserve and transmit the cultural heritage associated with the artefact by allowing people to experiment with and better understand its possible gameplay.

Ludus Coriovalli is associated with a stone artefact originating from the Roman settlement of Coriovallum and currently exhibited at the Het Romeins Museum in Heerlen [20]. The object has been interpreted as a potential game board following detailed archaeological analyses combining use-wear analysis and artificial intelligence simulations [36]. The objective of these studies was to determine whether the wear patterns observed on the artefact could realistically result from repeated gameplay interactions under candidate rulesets.

Because the original rules of the game are unknown, several possible board geometries and starting configurations were reconstructed from the artefact. Figure 5.1 presents the different candidate board geometries identified during the archaeological analysis, while Figure 5.2 illustrates example starting positions generated through AI-driven simulations. According to the conclusions presented in [20], the most plausible interpretation suggests an asymmetrical blocking game in which one player controls black pieces, referred to as hounds, whose objective is to block the movement of the opposing white pieces, referred to as hares.

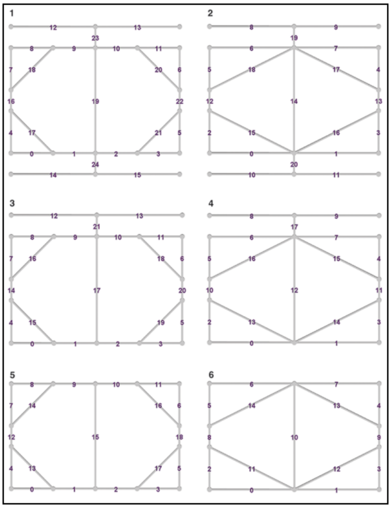

Figure 5.1: Possible board geometries based on the lines seen on the surface of the stone. Source: [20]

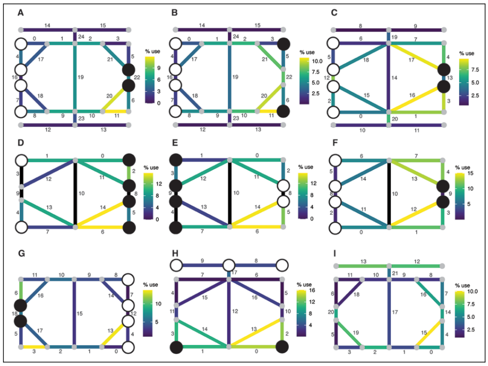

Figure 5.2: Results of the AI-driven simulation that produced asymmetrical play along the relevant diagonal line. Source: [20]

The game was implemented in Ludii, which was also the framework used in the original research to analyse the different hypotheses surrounding the game. The Ludii implementation integrates the various candidate board geometries together with multiple rulesets inspired by existing historical blocking games[1] such as Haretavl, Jeu Militaire, and Janes Soppi. This makes Ludus Coriovalli particularly relevant for this thesis, as it not only represents a historical artefact, but also a complex reconstruction problem involving uncertainty, gameplay interpretation, and AI-assisted cultural heritage analysis.

5.2 Interactive VR Adaptation of Ludus Coriovalli

The objective of this section is not only to digitally reproduce Ludus Coriovalli, but to transform an archaeological artefact into an interactive and playable VR experience allowing museum visitors to directly experiment with its possible gameplay. In this context, the development of the VR experience involves both technical and cultural heritage considerations: the system must remain flexible enough to represent the uncertainties surrounding the game while also providing an immersive and understandable experience for non-expert users.

One of the main challenges surrounding Ludus Coriovalli lies in the uncertainty of its original gameplay configuration. Since several candidate board geometries and starting positions were proposed during the archaeological analysis, the VR framework initially aimed to support all possible interpretations of the game. To achieve this, players were allowed to manually place the pieces at the beginning of the game, making it possible to reproduce any of the proposed starting configurations directly within the VR environment.

[1] `https://ludii.games/details.php?keyword=Ludus%20Coriovalli`

In addition, the system was designed to support all six candidate board geometries identified during the original research. Rather than manually modelling each board individually, we implemented a procedural generation pipeline based on the graph representation generated from the Ludii description of the game. Starting from a rectangular stone block spawned within Unreal Engine, the system generates a graph corresponding to the board topology by retrieving the coordinates of vertices and edges defined in the Ludii ruleset.

The graph generation process relies on the procedural creation of rectangular structures whose adjacent vertices are automatically connected. These structures are then merged together and completed by adding the remaining missing edges required to obtain the final board geometry. Once the graph is generated, the corresponding board layout can be carved directly into the stone model using boolean operations within Unreal Engine.

Example 5.1 presents the Ludii rules used to describe one of the candidate Ludus Coriovalli boards. Figure 5.3 illustrates the resulting graph representation in 2D, while Figure 5.4 presents its implementation as a 3D board within the VR environment.

Example 5.1: A type of board from Ludus Coriovalli written in Ludii.

```
(define "NoExtensionJoinedDiagonal"
    (board
        (add
            (merge {
                (scale 2 1 (rectangle 1 3))
                (rectangle 2 1)
                (shift 4 0 (rectangle 2 1))
                (shift 4 1.5 (rectangle 2 1))
                (shift 0 1.5 (rectangle 2 1))
                (scale 2 1 (shift 0 2.5 (rectangle 1 3)))
            })
            edges:{{3 7} {5 4} {9 1} {3 1} {1 4} {5 9} {9 7}}
        )
        use:Vertex
    )
)
```

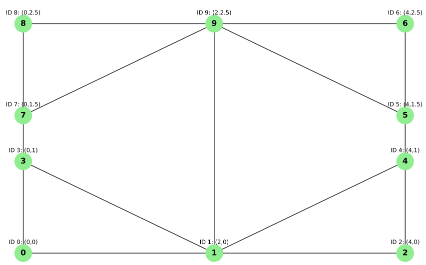

Figure 5.3: Graph of a board created from Ludus Coriovalli's rules.

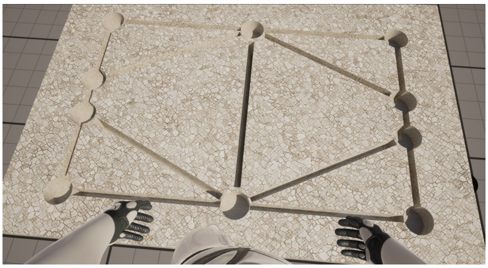

Figure 5.4: Creation of a board from Ludus Coriovalli's rules in 3D.

Although this procedural carving approach successfully reproduced all candidate geometries, it did not fully satisfy the museum-oriented objectives of the project. Indeed, when museum visitors attempt to understand the purpose and usage of an archaeological artefact, interacting directly with a representation of the original object is often more

5

meaningful than interacting with an abstract generated board. As a result, we decided to replace the procedural stone block with a faithful 3D representation of the original artefact itself, allowing players to directly manipulate and play on the historical object displayed in the museum.

This choice significantly strengthened the cultural heritage dimension of the experience by reinforcing the visual and physical connection between the VR application and the real artefact. However, it also introduced an important limitation: only one of the candidate board geometries could realistically be integrated onto the original stone model. Since the selected geometry corresponded to the interpretation considered the most plausible from a gameplay perspective, this limitation was considered acceptable for the final prototype.

Figure 5.5 presents the final interactive VR implementation of Ludus Coriovalli, allowing users to manipulate pieces and experiment with the proposed gameplay directly on the digitalised artefact.

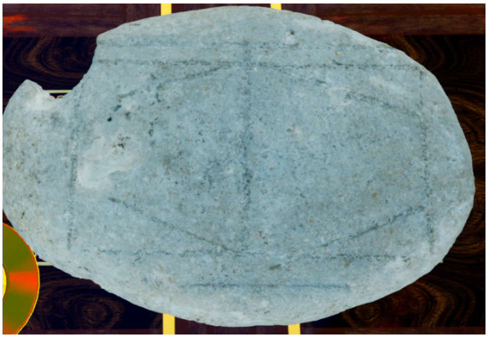

Figure 5.5: Board on which one can play Ludus Coriovalli in 3D and VR.

Importantly, the objective of this implementation is not limited to producing a visual representation of the artefact. The 3D model becomes a playable support through which users can test the proposed rules, manipulate the game pieces, and experience the gameplay directly on the digitised object. In this sense, the VR prototype transforms the artefact from a static object of observation into an interactive medium for cultural interpretation.

To preserve the authenticity of the cultural transmission, it was crucial to pay deep attention to the realism of physical interactions within the virtual environment. Users can interact naturally with the game components using a physics-based grabbing system paired with a precise piece-snapping mechanism. Collisions, gravity and friction are simulated to faithfully replicate the tactile sensations of real-world gameplay. This approach allows visitors to intuitively grasp the physical presence of the ancient game, while completely removing the risk of degradation inherent to handling genuine historical artefacts.

Figure 5.6 summarises the complete pipeline used to transform the original artefact into an interactive VR experience. The process is divided into five main stages:

1. **Physical Heritage:** the pipeline starts from the archaeological artefact preserved in the museum.

2. **Ludii Description Language:** the possible rules and board structures of the game are formalised through Ludii.
3. **VR Framework Pipeline:** the Ludii description is processed by the VR framework, which extracts the rule logic and board topology required to create a playable environment.
4. **Enhancement Layer:** additional visual and interaction elements are integrated, including the digitised stone model and VR gameplay interactions.
5. **Experience and Telemetry:** users can play the game in VR while interaction data is collected for future analyses of player behaviour.

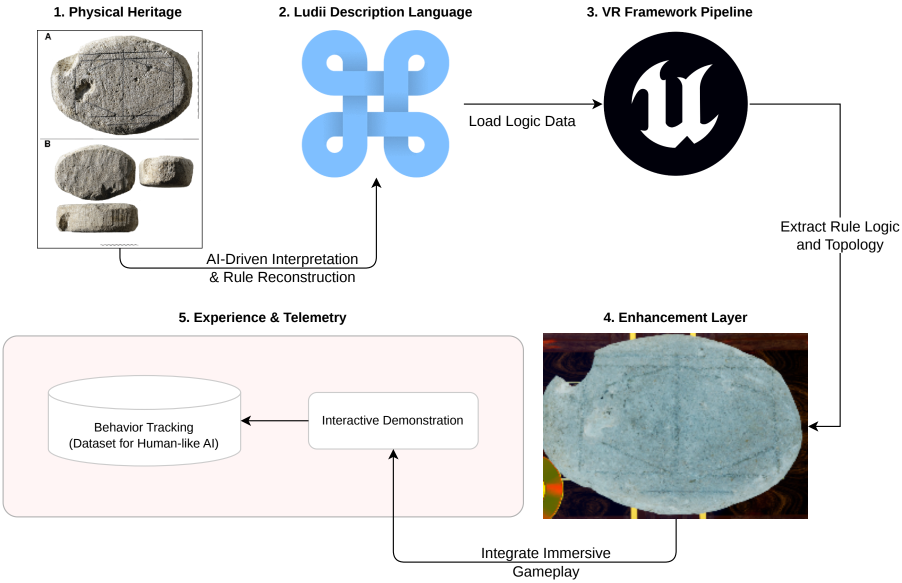

Figure 5.6: Complete architecture of the pipeline from the initial stone object to its integration and usage in VR.

5.3 Museum Impact and Human Behaviour in Ancient Games

The VR adaptation of Ludus Coriovalli changes the relationship between museum visitors and the archaeological artefact. In a traditional exhibition setting, such objects are usually protected behind glass displays, which preserves the physical artefact but prevents visitors from interacting with it. By providing a playable virtual version of the game, the proposed framework allows users to move from passive observation to active experimentation.

This interaction is particularly important for historical board games, since their cultural meaning cannot be fully understood through visual observation alone. Gameplay, piece manipulation, rule exploration, and player decision-making are central to the experience of the object. In this sense, the VR prototype does not simply present the artefact visually, but uses gameplay itself as a medium for cultural transmission.

The system also allows users to explore possible gameplay hypotheses in an interactive way. By testing different starting positions and playing directly on the digitised artefact, visitors can better understand how the game may have functioned and why it may have been meaningful in its historical context. This makes the prototype relevant not only as a museum installation, but also as a tool for experimentation and cultural mediation.

Beyond its museological value, the framework also opens perspectives for behavioural analysis [37]. Since VR interactions can be tracked during gameplay, the system may collect information such as gaze direction, movement patterns, decision times, and interactions with the pieces and board. Such data could support future research on how players perceive and understand unfamiliar historical games.

However, this contribution should be considered exploratory. The current prototype does not aim to provide a complete dataset for Human-Like AI, but rather to demonstrate that VR environments can serve as a promising medium for collecting behavioural gameplay data in more natural interaction conditions. In future work, larger user studies and more systematic telemetry pipelines could make this data valuable for player modelling and Human-Like AI research.

6

Results and Discussion

This chapter presents an overview of the users who participated in our evaluation demonstrations, outlines the experimental protocol deployed, and provides an in-depth empirical analysis of the data collected. Finally, it engages in an academic discussion regarding the broader implications of these findings, the limitations of the current prototype, and the pathways towards museum deployment and advanced telemetry capture.

6.1 User Study Design

To evaluate the efficacy, usability, and cultural impact of the developed framework, two distinct user evaluation demonstrations were conducted at the conclusion of the development cycle. The evaluations were intentionally performed on two highly contrasted cohorts to observe variations in user adaptation and cultural engagement:

1. **The UCLouvain Cohort:** Composed of 11 university students and academic staff specialising in civil engineering and informatics within the ICTEAM research institute[1]. This sample represents individuals with profound technical knowledge but low prior exposure to cultural heritage transmission.
2. **The Heritage Action Cohort (GameTable COST Action CA22145[2]):** Conducted in Cork, Ireland, this cohort was composed of 9 specialised researchers from interdisciplinary backgrounds tied to tabletop game heritage, including mathematics experts, digital humanists, and archaeologists. This cohort represents expert individuals deeply embedded in the domain of cultural heritage.

The experimental protocol was kept uniform across both evaluation samples and was structured into three sequential phases:

- **Phase 1 (2D Baseline Exploration):** Participants observed or interacted with a game of *Ludus Coriovalli* being played on the standard 2D desktop interface of the Ludii application to familiarise themselves with the ruleset and mechanics.

[1] https://www.uclouvain.be/en/research-institutes/icteam
[2] https://gametable.network/index.html

- **Phase 2 (Immersive VR Interaction):** Participants were equipped with a *Meta Quest Pro* VR Headset and played under identical game rules within our custom virtual environment, manipulating pieces directly on the digitalised model of the artefact.
- **Phase 3 (Post-Evaluation Survey):** Users completed a structured survey split into three categories: profile demographics, usability feedback, and cultural reception. The exact phrasing of these questions is presented below.

- *1.a*: How often do you play board games?
- *1.b*: How often do you play video games?
- *1.c*: Have you already used VR? How many times?
- *1.d*: How often do you go to the museums?

- *2.a*: Was the game enjoyable?
- *2.b*: Was it entertaining to be able to directly interact with the board and pieces?
- *2.c*: Were the controls intuitive?
- *2.d*: Did you experience eye pain, headache, or motion sickness while in the VR environment?

- *3.a*: Does this game board touch your interest enough to make you want to learn more about it?
- *3.b*: Would this game make you interested in learning more about the environment and culture from which this game board comes?
- *3.c*: Would you play the game if it were available in a museum, for example in front of the original stone object?

6.2 User Feedback and Observations

The data collected from the post-evaluation surveys yielded encouraging results across both cohorts, with a total of 20 participants, providing valuable empirical evidence validating the ergonomics and educational potential of the framework.

Regarding baseline profiles, pre-evaluation metrics confirmed the expected divergence between the two groups. On one hand, the UCLouvain Cohort exhibited regular board gaming habits but moderate museum attendance, averaging 1 to 2 visits per year. On the other hand, the GameTable Cohort demonstrated highly specialized profiles, while board game consumption varied, their museum attendance was substantially higher, with several participants visiting multiple times a month or daily. Prior VR experience was highly polarized: 3 out of 11 UCLouvain participants had zero prior exposure, whereas the GameTable Cohort presented a broader spectrum, ranging from complete novices, with

3 participants having zero VR experience, to highly proficient users, with 3 users having experienced VR more than 10 times.

The system's interactive mechanics achieved remarkably high scores regarding enjoyment and usability. When evaluating game enjoyment, 19 out of 20 total participants gave a decisively positive response, characterizing the prototype as fun and highly engaging; only one expert from Cork remained neutral, citing a personal distaste for abstract strategy games but special interest in exploring the environment instead. Direct interaction with the board and pieces was an overwhelming success: 10 out of 11 UCLouvain users and 100% of the Cork cohort found it exceptionally rewarding and playful, with comments highlighting the accuracy of the physics interaction and the potential for advanced haptic feedback. Furthermore, the grab-and-snap control scheme was categorized as intuitive by 9 UCLouvain and 8 GameTable users. A minor subset (3/20 overall) reported tracking or depth perception issues, noting that depth evaluation felt slightly unusual or that seeing the full virtual hand model was a bit distracting when only two fingers should be needed to grab the pieces. Physiological side effects were minimal, with 18 out of 20 users reporting absolutely no symptoms. However, mild eye strain was recorded in 2 UCLouvain users, which was explicitly attributed to the high luminosity settings and bright lighting of the virtual scene. Notably, zero participants from the GameTable Cohort experienced headaches, eye pain or motion sickness.

The metrics focusing on cultural heritage transmission strongly validated the core hypotheses of this thesis. When questioned if the game board triggered curiosity, users noted that the stone object acted as a catalyst to master the underlying rules, moving away from viewing the asset as a mere static adaptation. Regarding broader cultural and environmental interest, participants affirmed that playing directly on top of the photo-scanned stone model generated a heightened sense of cultural value, moving the artifact far beyond a mundane scene and sparking a desire to research its historical context. Finally, the willingness to play the game as a free-access installation in front of the original stone object in a museum received a virtually unanimous response: 19 out of 20 participants answered favourably. Multiple users explicitly highlighted that an immersive VR setup is vastly superior to observing a flat 2D screen or a static glass display case, validating the core vision of interactive archaeological mediation.

6.3 Discussion and Limitations

The empirical results confirm that migrating historical board games from static, passive display cases into a physical-virtual interaction environment successfully transforms the museum visitor from a passive spectator into an active participant. The high levels of immersion, combined with the nearly unanimous desire to engage with the system inside museums, prove that playful interaction can serve as a potent medium for cultural transmission.

However, it is crucial to characterise the current state of this system as an experimental prototype. The empirical data allows us to assert certain successes, but it also highlights clear methodological and technical boundaries:

The evaluation firmly establishes that a seamless data bridge can be maintained between Ludii's GDL and our rendering pipeline. It also proves that physical-virtual interaction achieves high user satisfaction across the two cohorts, significantly increasing a user's desire to learn about the underlying history of an archaeological artifact.

Despite these positive indicators, the current study design possesses specific limitations that prevent broader generalizations. The study lacks the statistical power to generalize across the broader public, such as elderly visitors and families with children, as well as populations suffering from vision deficiency.

The prototype suffers from several technical constraints that currently hinder independent museum installation. As noted in the user feedback, the high ambient luminosity settings of the virtual environment triggered eye strain in two users, indicating that the pipeline lacks user-adjustable settings.

6.4 Future Work

The evaluation data, paired with the identified methodological and technical limitations, outline clear pathways for future research and development, structured into four core pillars: pipeline generalisation, contextual historical environments, advanced telemetry, accessibility and an expanded user study.

Pipeline Generalisation The current prototype relies on a specialised workflow tailored to the specific rules and geometries of a select few Ludii games, such as Tic-Tac-Toe[3], Traffic Lights[4], and Ludus Coriovalli[5]. Currently, the Ludii rulesets for 93 games are fully implemented, meaning that the additional integration of Ludii's core ludemes is required to further scale this pipeline. Future work must focus on integrating a broader subset of Ludii's core ludemes, to instantiate even more board games into the virtual environment.

6

Contextual Historical Environments The current digital environment is not yet fully tailored to each implemented game. For instance, since *Ludus Coriovalli* originates from a Roman settlement in the Netherlands, an environment depicting this specific historical era would be more in keeping with the game's identity. Additionally, culturally specific environments should be included for other historical games, such as Senet[6] and Mehen[7], both of which stem from Dynastic Egypt.

Advanced Telemetry and Human-Like AI training The current telemetry framework can be significantly enhanced to support Human-Like AI training. This includes integrating hand tracking to record finger velocity and hesitation curves, as well as eye gaze tracking to map user attention zones on the board layout. This richer behavioural data may serve to further study Human-Like AI.

Accessibility and Expanded User Study To transition this framework into a viable public museum installation, the framework must accommodate diverse user physics and accessibility requirements. Future work must focus on introducing automated height-calibration

[3]https://ludii.games/details.php?keyword=Tic-Tac-Toe
[4]https://ludii.games/details.php?keyword=Traffic%20Lights
[5]https://ludii.games/details.php?keyword=Ludus%20Coriovalli
[6]https://ludii.games/details.php?keyword=Senet
[7]https://ludii.games/details.php?keyword=Mehen

and visual filters tailored to specific conditions such as colourblindness, alongside audio guidance cues to assist players with visual or cognitive impairments. Finally, a large-scale user study must be deployed across highly diverse demographics to gather the necessary quantitative data to fully validate the framework's accessibility and long-term educational impact, which will as well provide a more representative user sample for Human-Like AI training.

7 Conclusion

This master's thesis presented the design and implementation of a virtual reality framework connecting Ludii game descriptions with interactive 3D environments in Unreal Engine. The objective was to investigate how historical board games can be transformed into playable VR experiences while preserving both their gameplay structure and cultural heritage value.

Through this framework, Ludii descriptions are used to extract game information such as board structures, pieces, rules, moves, and end conditions. These elements are then translated into procedural 3D representations and interactive gameplay components within Unreal Engine. This demonstrates the feasibility of extending the formal and computational strengths of Ludii toward more embodied and immersive forms of interaction.

The case study of Ludus Coriovalli illustrated the cultural heritage potential of this approach. By using a digitised model of the original artefact, the prototype allowed users to interact with a fragile archaeological object without physically manipulating it. More importantly, it showed how gameplay can become a medium for cultural interpretation, allowing visitors not only to observe a historical board game, but also to experiment with its possible rules and interactions.

This work also opened perspectives for behavioural analysis and Human-Like AI research. By capturing interaction data during VR gameplay, such as movement patterns, decision times, gaze behaviour, and piece manipulation, future versions of the framework could support the study of how humans perceive and play historical games. However, this aspect remains exploratory in the current prototype and would require larger user studies, more systematic telemetry, and broader game coverage to become fully exploitable.

Overall, this thesis demonstrates that combining Ludii, virtual reality, and cultural heritage offers a promising direction for the preservation and transmission of historical board games. While the current implementation remains a prototype, it provides a foundation for future work toward more general, accessible, and museum-ready systems capable of transforming ancient games from static artefacts into interactive experiences.

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Glossary

AI Artificial Intelligence.

CP Constraint Programming.

DLP ERC-funded Digital Ludeme Project.

GDL Game Description Language.

GGP General Game Playing.

GGS General Game System.

LTM Long Term Memory.

MCTS Monte Carlo Tree Search.

UCB1 Upper Confidence Bound.

VR Virtual Reality.

8

Appendix

8.1 Ludii files

In Ludii to represent the favourite option of a game, a "*" is used, as it is used as a typeset character in LaTeX, all "*" are replaced by "+" instead.

Example 8.1: Tic-Tac-Toe.lud

```
(game "Tic-Tac-Toe"
    (players 2)
    (equipment {
        (board (square 3))
        (piece "Disc" P1)
        (piece "Cross" P2)
    })
    (rules
        (play (move Add (to (sites Empty))))
        (end ("Line3Win"))
    )
)

//------------------------------------------------------------------------------

(metadata

    (info
        {
        (description "Tic-Tac-Toe is a game of alignment popular among children. It
          is known from the nineteenth century in England and the United States, but
          may be older.")
        (aliases {"Noughts and Crosses" "Oughts and Crosses" "Tik Tak Tol" "Tripp
          Trapp Trull" "Tick-Tack-Toe"})
        (rules "Play occurs on a 3x3 grid. One player places an X, the other places
          an O and players take turns placing their marks in the grid, attempting to
          get three in a row of their colour.")
        (source "Murray 1951: 40.")
        (id "100")
        (version "1.3.14")
        (classification "board/space/line")
        (credit "Eric Piette")
        (origin "This game was played in Unknown, from around 1850 to 1883.")
        }
    )

    (ai
```

```
        "Tic-Tac-Toe_ai"
    )

)
```

Example 8.2: GONNECT.LUD

```
(game "Gonnect"
    (players 2)
    (equipment {
        (board <Board> use:Vertex)
        (piece "Marker" Each)
        (regions P1 {(sites Side N) (sites Side S) })
        (regions P2 {(sites Side W) (sites Side E) })
    })

    (rules
        (meta {
            (swap)
            (no Repeat)
        })
        (play
            (do
                (move Add
                    (to (sites Empty))
                    (then ("EncloseCapture" Orthogonal))
                )
                ifAfterwards:("HasFreedom" Orthogonal)
            )
        )

        (end {
            (if (is Connected Mover) (result Mover Win))
            ("BlockWin")
        })
    )
)

//------------------------------------------------------------------------------

(option "Board Size" <Board> args:{ <size> }
    {
    (item "9x9"  <(square 9)>  "The game is played on a 9x9 board")
    (item "13x13" <(square 13)> "The game is played on a 13x13 board")**
    (item "15x15" <(square 15)> "The game is played on a 15x15 board")
    (item "19x19" <(square 19)> "The game is played on a 19x19 board")
})

//------------------------------------------------------------------------------

(metadata

    (info
        {
        (description "Gonnect was invented by Joao Pedro Neto in 2000. It is played
           with a Go board and pieces, with the goal of creating a group that connects
           two opposite sides of the board.")
        (rules "All the rules of Go apply, except that passing is not allowed. A
           player loses if he has no legal move. A player wins if they successfully
           connect two opposite sides of the board.")
        (source "<a href=\"https://en.wikipedia.org/wiki/Gonnect\" target=\"_blank\"
           class=\"style1\" style=\"color: #0000EE\" />Wikipedia</a>")
        (id "467")
        (version "1.3.14")
        (classification "board/space/connection")
        (author "Joao Pedro Neto")
        (credit "Eric Piette")
```

```
        (date "2000")
        }
    )

    (graphics {
        (board Style Go)
        (player Colour P1 (colour Black))
        (player Colour P2 (colour White))
    })

    (ai
        "Gonnect_ai"
    )

)
```

Example 8.3: Traffic Lights.lud

```
(game "Traffic Lights"
    (players 2)
    (equipment {
        (board <Board:size>)
        (piece "Square" Shared)
        (piece "Triangle" Shared)
        (piece "Disc" Shared)
    })
    (rules
        (play
            (or {
                (move Add (piece "Square") (to (sites Empty)))
                (move Select
                    (from (sites Occupied by:Shared component:"Square"))
                    (then
                        (promote (last To) (piece {"Triangle"}) Shared)
                    )
                )
                (move Select
                    (from (sites Occupied by:Shared component:"Triangle"))
                    (then
                        (promote (last To) (piece {"Disc"}) Shared)
                    )
                )
            })
        )
        (end ("Line3Win"))
    )
)

//------------------------------------------------------------------------------

(option "Board Size" <Board> args:{ <size> } {
    (item "3x3" <(square 3)> "The game is played on a 3x3 board.")
    (item "3x4" <(rectangle 3 4)> "The game is played on a 3x4 board.")+
})

//------------------------------------------------------------------------------

(metadata

    (info
        {
        (description "Many variants on the concept of noughts and crosses exist. This
          version was created by Alan Parr. It is played on a 3x3 or 3x4 board with a
          supply of red, yellow, and green markers.")
        (rules "The object is to get a line of three of the same color.

            On each turn, you may do ONE of the following:
```

```

            (1) Put a red counter in an empty square.
            (2) Replace a red counter with a yellow one.
        (3) Replace a yellow counter with a green one.")
        (id "1973")
        (source "<a href=\"https://boardgamegeek.com/boardgame/1893/traffic-lights\" target=\"_blank\" class=\"style1\" style=\"color: #0000EE\" />BGG</a>")
        (version "1.3.14")
        (classification "board/space/line")
        (author "Alan Parr")
        (credit "Eric Piette")
        (date "1985")
        }
    )

    (graphics {
        (piece Colour Shared "Square" fillColour:(colour Red))
        (piece Colour Shared "Triangle" fillColour:(colour Yellow))
        (piece Colour Shared "Disc" fillColour:(colour Green))
    })

    (ai
        "Traffic Lights_ai"
    )
)
```

Example 8.4: Chess.lud

```
// Defines used to model the castling Moves.
(define "HasNeverMoved"
    (= (state at:(mapEntry #1 (mover))) 1)
)

(define "PieceHasMoved"
    (set State at:#1 0)
)

(define "RememberPieceHasMoved"
    (then
        (if
            (= (state at:(last To)) 1)
            ("PieceHasMoved" (last To))
        )
    )
)

(define "KingNotCheckedAndToEmpty"
    (and
        (is Empty (to))
        (not ("IsInCheck" "King" Mover at:(to)))
    )
)

(define "DecideToCastle"
    (move Slide
        (from (mapEntry #1 (mover)))
        #2
        (between
            (exact #3)
            if:#4
        )
        (to
            if:True
            (apply ("PieceHasMoved" (from)))
        )
        #5
    )
```

```
)

(define "CastleRook"
    (slide
        (from (mapEntry #1 (mover)))
        #2
        (between
            (exact #3)
            if:#4
        )
        (to
            if:True
            (apply ("PieceHasMoved" (from)))
        )
    )
)

(define "SmallCastling"
    ("DecideToCastle" "King" E 2 "KingNotCheckedAndToEmpty" (then ("CastleRook"
      "RookRight" W 2 True)))
)

(define "BigCastling"
    ("DecideToCastle" "King" W 2 "KingNotCheckedAndToEmpty" (then ("CastleRook"
      "RookLeft" E 3 True)))
)

(define "Castling"
    (if (and
            ("HasNeverMoved" "King")
            (not ("IsInCheck" "King" Mover))
        )
        (or
            (if (and
                    ("HasNeverMoved" "RookLeft")
                    (can Move ("CastleRook" "RookLeft" E 3 (is Empty (to))))
                )
                "BigCastling"
            )
            (if (and
                    ("HasNeverMoved" "RookRight")
                    (can Move ("CastleRook" "RookRight" W 2 (is Empty (to))))
                )
                "SmallCastling"
            )
        )
    )
)

// Defines used to model the extra Pawn moves.
(define "SetEnPassantLocation"
    (then
        (set Pending (ahead (last To) Backward))
    )
)

(define "InLocationEnPassant"
    (and
        (is Pending)
        (= (to) (value Pending))
    )
)

(define "EnPassant"
    (move Step
        (directions {FR FL})
        (to if:"InLocationEnPassant")
        (then
```

```
            (remove
                (ahead (last To) Backward)
            )
        )
    )
)

(define "InitialPawnMove"
    (if (is In (from) (sites Start (piece (what at:(from)))))
        ("DoubleStepForwardToEmpty" "SetEnPassantLocation")
    )
)

//------------------------------------------------------------------------------

(game "Chess"
    ("TwoPlayersNorthSouth")
    (equipment {
        (board (square 8))

        ("ChessPawn" "Pawn"
            (or
                "InitialPawnMove"
                "EnPassant"
            )
            (then
                (and
                    ("ReplayInMovingOn" (sites Mover "Promotion"))
                    (set Counter)
                )
            )
        )
        ("ChessRook" "Rook" (then (set Counter)) ("RememberPieceHasMoved"))
        ("ChessKing" "King" (then (set Counter)) ("RememberPieceHasMoved"))
        ("ChessBishop" "Bishop" (then (set Counter)))
        ("ChessKnight" "Knight" (then (set Counter)))
        ("ChessQueen" "Queen" (then (set Counter)))

        (map "King" {(pair 1 "E1") (pair 2 "E8")})
        (map "RookLeft" {(pair 1 "A1") (pair 2 "A8")})
        (map "RookRight" {(pair 1 "H1") (pair 2 "H8")})
        (regions "Promotion" P1 (sites Top))
        (regions "Promotion" P2 (sites Bottom))
    })
    (rules
        (start {
            (place "Pawn1" (sites Row 1))
            (place "Pawn2" (sites Row 6))
            (place "Rook1" {"A1" "H1"} state:1) (place "Knight1" {"B1" "G1"}) (place "Bishop1" {"C1" "F1"}) (place "Queen1" coord:"D1") (place "King1" coord:"E1" state:1)
            (place "Rook2" {"A8" "H8"} state:1) (place "Knight2" {"B8" "G8"}) (place "Bishop2" {"C8" "F8"}) (place "Queen2" coord:"D8") (place "King2" coord:"E8" state:1)
        })

        (play
            (if "SameTurn"
                (move Promote (last To) (piece {"Queen" "Knight" "Bishop" "Rook"}) Mover)
                (do
                    (or
                        (forEach Piece)
                        ("Castling")
                    )
                    ifAfterwards:(not ("IsInCheck" "King" Mover))
                )
            )
```

```
        )

        (end {
            ("Checkmate" "King")
            (if (or (no Moves Mover) (= (counter) 99)) (result Mover Draw))
        })
    )
)

//------------------------------------------------------------------------------

(metadata

    (info
        {
        (description "Ultimately originates from Indian Chaturanga, arrived in
          Western Europe during the Middle Ages as Shatranj. Over several centuries,
          after seeming experimentation with movement, the adoption of the modern
          movement of the queen and bishop made chess what it is today. Modern Chess
          appeared sometimes during the fourteenth or fifteenth Century, when the
          vizier piece was replaced by the queen. It since has become perhaps the
          most popular game in the world, with massive international competitions.")
        (aliases {"Mad Queen’s Chess" "Queen’s Chess" " checs " "Schach" "Ajedrez"
          "Xadrez" "Scacchi"})
        (rules "Played on an 8x8 board with pieces with specialized moves: Pawns (8):
          can move one space forward; Rooks (2): can move any number of spaces
          orthogonally; Bishops (2): can move any number of spaces diagonally; Knight
          (2): moves in any direction, one space orthogonally with one space forward
          diagonally; Queens (1): can move any number of spaces orthogonally or
          diagonally; Kings (1): can move one space orthogonally or diagonally.
          Players capture pieces by moving onto a space occupied by an opponent’s
          piece. Player wins when they checkmate the other player’s king.")
        (source "<a href=\"https://en.wikipedia.org/wiki/Rules_of_chess\"
          target=\"_blank\" class=\"style1\" style=\"color: #0000EE\"
          />Wikipedia</a>")
        (id "44")
        (version "1.3.14")
        (classification "board/war/replacement/checkmate/chess")
        (credit "Eric Piette")
        (origin "This game was played in Europe, from around 1475 to 2022.")
        }
    )

    (graphics {
        (show Check "King")
        (piece Scale "Pawn" 0.825)
        (piece Families {"Defined" "Microsoft" "Pragmata" "Symbola"})
        (board Style Chess)
    })

    (ai
        "Chess_ai"
    )

)
```

Example 8.5: Aboyne.lud

```
(define "GoalCell"
    (if (is #1 P1)
        34
        26
    )
)

//---------------------------------------------------------------------------

```

```
(game "Aboyne"
    (players 2)
    (equipment {
        (board (hex 5))
        (piece "Marker" Each)
    })
    (rules
        (start {
            (place "Marker1" (sites { 0 5 11 18 27 35 43 50 56 }))
            (place "Marker2" (sites { 4 10 17 25 33 42 49 55 60 }))
        })
        (play
            (forEach Piece
                (or {
                    (move Step
                        (from
                            if:(= (count Sites in:(intersection (sites Around (from))
                              (sites Occupied by:Next))) 0)
                        )
                        (to
                            if:(and
                                (not ("IsFriendAt" (to)))
                                (!= (to) ("GoalCell" Next))
                            )
                            (apply
                                if:("IsEnemyAt" (to))
                                (remove (to))
                            )
                        )
                    )
                    (move Hop
                        (from
                            if:(= (count Sites in:(intersection (sites Around (from))
                              (sites Occupied by:Next))) 0)
                        )
                        (between
                            (max 7)
                            if:("IsFriendAt" (between))
                        )
                        (to
                            if:(and
                                (not ("IsFriendAt" (to)))
                                (!= (to) ("GoalCell" Next))
                            )
                            (apply
                                (if ("IsEnemyAt" (to)) (remove (to)))
                            )
                        )
                    )
                })
            )
        )
        (end {
            (if
                (is Mover (who at:("GoalCell" Mover)))
                (result Mover Win)
            )
            (if (no Moves Next)
                (result Mover Win)
            )
        })
    )
)

//------------------------------------------------------------------------------

(metadata
    (info
```

```
        {
        (description "Aboyne is played on a 5x5 hexagonal board.")
        (rules "Aboyne is a two-player strategy game played on a 5x5 hexagonal board.
          Each player has a set of stones, and the goal is to move one of your stones
          into your own goal cell, located on the opposite side of the board, or to
          stalemate your opponent. A stone is considered blocked if it is adjacent to
          an enemy stone, and a blocked stone cannot be moved. At each turn, a player
          must move one of their non-blocked stones to an adjacent empty cell or jump
          over a line of friendly stones, landing on the immediate next cell. If the
          landing cell is occupied by an enemy stone, that stone is captured. A stone
          cannot move into the opponent’s goal cell. The game ends when one player
          achieves their goal or when neither player can make a legal move, resulting
          in a stalemate.")
        (id "4257")
        (source "<a href=\"https://jpneto.github.io/world_abstract_games/aboyne.htm\"
          target=\"_blank\" class=\"style1\" style=\"color: #0000EE\" />The World of
          Abstract Games</a>")
        (version "1.3.14")
        (classification "board/race/reach")
        (author "Paul Sijben")
        (credit "Achille Morenville")
        (date "1995")
        }
    )
)
```

UNIVERSITÉ CATHOLIQUE DE LOUVAIN
École polytechnique de Louvain
Rue Archimède, 1 bte L6.11.01, 1348 Louvain-la-Neuve, Belgique | **www.uclouvain.be/epl**