DXR: A Toolkit for Building Immersive Data Visualizations

Ronell Sicat, Jiabao Li, JunYoung Choi, Maxime Cordeil, Won-Ki Jeong, Benjamin Bach, and Hanspeter Pfister

Abstract—This paper presents DXR, a toolkit for building immersive data visualizations based on the Unity development platform. Over the past years, immersive data visualizations in augmented and virtual reality (AR, VR) have been emerging as a promising medium for data sense-making beyond the desktop. However, creating immersive visualizations remains challenging, and often require complex low-level programming and tedious manual encoding of data attributes to geometric and visual properties. These can hinder the iterative idea-to-prototype process, especially for developers without experience in 3D graphics, AR, and VR programming. With DXR, developers can efficiently specify visualization designs using a concise declarative visualization grammar inspired by Vega-Lite. DXR further provides a GUI for easy and quick edits and previews of visualization designs in-situ, i.e., while immersed in the virtual world. DXR also provides reusable templates and customizable graphical marks, enabling unique and engaging visualizations. We demonstrate the flexibility of DXR through several examples spanning a wide range of applications.

Index Terms—Augmented Reality, Virtual Reality, Immersive Visualization, Immersive Analytics, Visualization Toolkit

1 INTRODUCTION

Immersive technologies such as augmented and virtual reality, often called extended reality (XR), provide novel and alternative forms of representing, interacting, and engaging with data and visualizations [45]. The range of applications that benefit from stereoscopy, augmented reality, natural interaction, and space-filling immersive visualizations is growing, including examples in information visualization [44, 48], scientific visualization [68], immersive storytelling [14, 57, 60], immersive workspaces [50], and embedded data representations [36, 51, 72]. Eulered by the recent increase in affordable AR and VR devices, immersive visualizations have come into focus for many real-world applications and should be meant to being designed and created by a range of people not necessarily trained in XR development.

Building applications and prototyping visualization designs for immersive environments remains challenging for many reasons. It is a craft that naturally requires knowledge of concepts and technology from data visualization and analytics, 3D computer graphics, AR, and VR, as well as human-computer interaction, and human factors. Not only does this hinder fast prototyping and design exploration, especially in a real environment [36], but it creates a high bar for novice developers without background in any of these areas. On the other hand, the success and wide adoption of D3 [43], Vega-Lite [66], and VTK [29] have shown how visualization-specific toolkits and languages empower development, design, and dissemination. We believe it is timely to think about user-friendly tool-support for immersive visualizations.

In this paper, we present DXR, a toolkit for rapidly building and prototyping data visualization applications for eXtended Reality. DXR is based on the Unity development platform [24]. While Unity enables XR development, it still has limited support for rapid prototyping of
VR. Beach [60] virtually puts users in a room with dangerously increas-
ing sea levels to educate them about climate change. An application by
implementing scatter plots and parallel coordinates that are explorable
fying visual mappings and designing visualizations inside XR; comes
in X.

DXR offers multiple high-level interfaces that are easier to learn and use
than low-level Unity programming for constructing visualizations.

For instance, Plotly’s Chart Studio [20] lets users interactively ex-
determine styles of charts based on data selection in a tabular view. Similarly, Polestar [21] and RAWGraphs [22] both provide a
minimalistic drag-and-drop interface to specify a visual mapping and
programming for adapting pre-configured designs. Tableau [23] combi-
s that provide high-level abstraction for building visualizations
so that designers can focus on their data and not worry about software
ing grammar introduced by Leland Wilkinson [71] paved the way for modern high-level vis-
ich declarative specifications—enabling rapid exploration of designs albeit
with a limited set of graphical marks. Python, R, and Matlab offer their
own high-level visualization libraries that require a simple function
call with a respective parameterization to deliver data and visualization
parameters, e.g., Seaborn, Bokeh, Plotly, GGPlot. Other interactive
tools include Lyra [65], Protovis [42] and Data-Driven Guides [58].
These tools allow for novel designs but require manual specification of
shapes, style, and sometimes layout. DXR is also fully compatible with and can be ex-
tended through CSharp code in Unity.

DXR integrates several of these approaches. It uses a declarative
visualization grammar inspired by Vega-Lite; provides a GUI for speci-
fying visual mappings and designing visualizations inside XR; comes
with a set of pre-defined visualizations; and allows for individual styling
and customization. DXR is also fully compatible with and can be ex-
tended through C# code in Unity.

2.3 Authoring Non-Immersive Visualizations

Visualization authoring tools for non-immersive platforms provide a
multitude of approaches, ranging from easy-to-use charting tools to
highly flexible visualization programming libraries (Fig. 2).

Easy to learn & use Polestar Lyra Vega-Lite Vega D3 JavaScript
More templated DXR GUI DXR Grammar Unity Programming More flexible

Fig. 2. Inspired by (top) 2D JavaScript-based authoring tools, (bottom) DXR offers multiple high-level interfaces that are easier to learn and use
than low-level Unity programming for constructing visualizations.

Beyond exploration, AR and VR are often used as a medium for
experiencing data-driven presentations and storytelling. For example,
LookVR [14] turns bar charts into virtual walls that can be climbed in
VR. Beach [60] virtually puts users in a room with dangerously increas-
ing sea levels to educate them about climate change. An application by
the Wall Street Journal [57] lets users virtually walk along a line chart
like a staircase to experience the rise and sudden fall of the Nasdaq
index during a stock market crash. All these examples present data-
driven scenes [38] that allow end-users to relate the data to real-life
experiences for better engagement and impact. These visualizations are
typically created by artists, storytellers, designers, and domain experts
who had to invest time to learn visualization and XR development.

Many more examples lend themselves to an exploration through
immersive technology motivated by better spatial perception, a larger
display space, or bringing together physical referents and their data [36,
69, 72]. Coupled with immersive displays, immersive interactions
beyond the mouse and keyboard allow natural and direct interaction
with data in AR [35] or VR [68] environments. Other studies have shown
the benefit of immersion for collaborative data analysis [49, 50].

2.2 Authoring Immersive Visualizations

The most common platform to develop XR applications is Unity [24],
a game engine with a large community and a range of modular and
additional assets such as 3D models, and scripting libraries. For AR,
additional frameworks exist to support object tracking and rendering in
general, e.g., ARToolkit [6], Vuforia [31], or for specific platforms, e.g.,
ARCore for Android [4], ARKit for iOS [5], and Mixed Reality Toolkit
for Microsoft’s Universal Windows Platform (UWP) [16]. A-Frame [1]
is a library that enables the creation of immersive virtual scenes in
the browser by integrating WebVR [32] content within HTML. How-
ever, none of these libraries provides specific support for developing
and designing visualization applications in XR. Moreover, designing
visualizations in immersive environments can be complex, requiring
consideration of issues such as occlusion, clutter, and user movement
and interactions in 3D [36, 46, 62].

Recent work started to enable easier authoring of immersive visu-
izations, yet still require a significant amount of low-level program-
ning or are restricted to a limited set of graphical marks. For example,
Filonik et al. [53] proposed Glance, a GPU-based framework with a focus
on rendering fast and effective abstract visualizations in AR and
VR. Donalek et al. [50] developed Viz, which provides a GUI for
specifying visualization parameters for a collaborative VR analytics
environment. Virtualitics [28] is a commercial immersive and collabo-
ration visualization platform that uses machine learning to help inform
the design of three dimensional visualizations. Operations such as
filtering, and details-on-demand are supported by virtual pointers.
2.4 Unity Core Concepts

We briefly review the core concepts of Unity as far as they are important for the understanding of DXR. In Unity, applications are represented as composable 3D scenes in which designers can add and manipulate GameObjects which encapsulate objects and their behavior. Example GameObjects include cameras, 3D models, lights, effects, input handlers, and so on. GameObjects are organized in parent-child hierarchies or scene-graphs. GameObjects can be saved as prefabs that serve as shareable and reusable templates. Unity has an on-line Asset Store [25] for sharing reusable scenes, prefabs, and other assets. A script is C# or JavaScript code that can be attached to GameObjects as components and used to programatically manipulate GameObjects at runtime. Designers can edit scenes and GameObjects interactively using the Unity Editor user interface, or programmatically using scripts via the Unity scripting API [27]. The scene can be configured to run in either AR or VR, simply by specifying the target device in Unity deployment settings. At runtime, i.e., when the scene is played, the user can see the scene through the device’s display, and interact with it using the device’s input modalities, e.g., controllers, gesture, or voice. For more information, we refer the reader to the complete Unity documentation [26].

3 DXR Overview

DXR consists of prefabs and scripts that provide a high-level interface for constructing data-driven GameObjects in a Unity scene. Figure 3 illustrates the conceptual parts of DXR. A visualization in DXR is represented as a GameObject prefab—vis-prefab—that can be added to scenes and manipulated via the Unity Editor or via scripting, just like any other GameObjects. The vis-prefab reads the visual mapping from a visualization specification file—vis-specs—in JSON format. The vis-spec file also contains a URL pointer to the respective data file which can be in CSV or JSON format. When the data or vis-specs file changes, DXR can be notified to update the visual rendering immediately.

DXR’s main target users are visualization developers with varying expertise in XR programming (Unity/C#) and whose goal is to rapidly prototype and build immersive visualizations.

- **Non-programmers (beginners)** include users with little to no programming experience, e.g., architecture or biology students, artists, and storytellers. In DXR, they can build visualizations without programming. To do this, they can place their data file into the StreamingAssets/DXRData directory. Then, they can add a DXR vis-prefab into their scene using the Unity menu or by dragging it into their scene window. They can then set the vis-specs filename parameter of the vis-prefab to an empty file (to start from scratch) or to one of the example vis-specs files in the StreamingAssets/DXRSpecs folder containing templates for common visualizations such as bar charts, scatter plots, vector field plots, and many more. At runtime, DXR generates the visualization, and a GUI gives the user control over the data and visual mappings that can be changed (Fig. 4).

- **Non-XR-developers (intermediate)** include users with general programming experience, e.g., with JSON and visualization grammars, but without experience with Unity and C# specifically. With DXR, intermediate users can edit the vis-specs file and directly manipulate the visualization grammar to add or remove visual mappings and fine-tune the design (Sect. 4.1). For example, they can adjust scale domains and ranges, change color schemes, etc. Intermediate users can also create custom graphical marks with generic visual channels without programming (Sect. 6).

4 DXR’s Visualization Pipeline

Fig. 5 shows DXR’s visualization pipeline, consisting of four steps: specify, infer, construct, and place. First, the designer describes the visualization design in a concise specification (vis-specs) using DXR’s high-level visualization grammar. DXR then infers missing visualization parameters with sensible defaults. Based on this complete specification, DXR then programatically constructs the 3D visualization that the designer can place in a real or virtual immersive scene.

4.1 Design Specification

We designed DXR’s visualization grammar to be similar to Vega-Lite [66] because it is intuitive, making it easier to learn and modify representations, and concise, making it efficient to iterate over designs. Furthermore, there are many visualization designers who are familiar with Vega, Vega-Lite, and Polaris who will find it easier to learn and use DXR and transition their designs to immersive environments.

A single visualization in DXR, which we call dxrvis, is a collection of graphical marks (Unity GameObjects) whose properties (position, color, size, etc.) are mapped to data attributes according to the declarative specification in the vis-specs file. Following the notation of Vega-Lite, a dxrvis is a simplified equivalent of a unit that “describes a single Cartesian plot, with a backing data set, a given mark-type, and a set of one or more encoding definitions for visual channels such as position (x, y), color, size, etc.” [66]:

\[
\text{dxrvis} := (\text{data, mark, encodings, interactions})
\]

The input data consists of a “relational table consisting of rows” with named attributes (columns)” [66]. The mark specifies the graphical object (Unity prefab) that will encode each data item. DXR’s built-in marks include standard 3D objects like sphere, cube, cone, and text, as well as user-provided custom graphical marks (Sect. 6). The encodings describe what and how properties of the mark will be mapped to data. Interactions that can be added to the visualization are discussed in a later section. The formal definition of an encoding is:

\[
\text{encoding} := (\text{channel, field, data-type, value, scale, guide})
\]
The channel describes which geometric or visual property of the graphical mark will be mapped to the data attribute specified by the field. DXR provides a set of generic channels that generally apply to any Unity GameObject, namely x, y, z, width, height, depth, color, opacity, size, length, rotation, zrotation, xdirection, ydirection, and zdirection. The size channel rescales the object’s width, height, and depth equally, while the length only rescales the object along a user-defined forward direction. This forward direction is defined by default to set the (0,1,0) 3D vector, and is used to orient marks that show direction, e.g., arrow and cone. DXR also provides (x,y,z)offsetpc channels that translate the mark by a percentage of its width, height, or depth for styling and to handle prefabs with different center or pivot points. The data-type describes the attribute that can be quantitative, nominal, or ordinal. A channel can also be mapped to a fixed setting using the value property. The scale describes the type of mapping (linear, categorical, etc.) from data attribute values to visual channel properties, as well as the mapping’s domain and range. The guide properties describe the axis or legend specifications such as tick values, labels, and the like.

Fig. 5 (a-e) and Fig. 5 show examples of declarative specifications using DXR’s grammar. A detailed grammar documentation with tutorials is provided on-line at https://sites.google.com/view/dxr-vis/grammar-docs. Thanks to the syntax similarity, some Vega-Lite visualizations can be ported with little effort into immersive environments using DXR. Unlike Vega-Lite, DXR does not provide data transforms, yet. We plan to add them in future versions.

4.2 Inference
Concise specifications are intuitive and succinct, making them easy to learn and modify, as well as reduces the tedious setting of all tunable visualization parameters. DXR’s inference engine sets missing visualization parameters to sensible defaults based on the data types and visual channels informed by the Vega-Lite model. Originally, the resulting inferred specification was hidden from the designer by default and only used internally by DXR. However, feedback from new users indicated that all the possible tunable parameters can be difficult to remember, leading to frequent visits to the on-line documentation. To address this, we provide designers direct access to DXR’s inferred specifications so they can see and tweak them directly. This option exposes all tunable parameters to improve debugging, customization, and learning. Inference rules are documented on the DXR website.

4.3 Construction
A DXR specification is not translated to Unity code. Instead, a specification acts as a complete list of parameters for DXR’s visualization construction pipeline that gets executed at runtime by the vis-prefab.

Visualizations in DXR are most similar to glyph-based visualizations [41]. A graphical mark in DXR is a glyph whose visual properties are mapped to data (independently of other glyphs) and then rendered within a spatial context. Thus, we modeled DXR’s construction pipeline after Lie et al.’s glyph-based visualization pipeline [61], adapting it to match Unity’s scripting API for prefab instantiation and modification. First, DXR parses the data and constructs the necessary internal data structures. Then it loads the specified mark as a GameObject prefab which is instantiated for each data record. Each instance starts with the prefab’s default properties with initial positions at the vis-prefab’s origin. Then, DXR goes through each encoding parameter in the specifications and changes visual channel properties of the mark instances according to the data attribute or a given fixed value. This instantiation and encoding is performed by a C# Mark base class that encapsulates functionalities of a graphical mark. For example, to set the position, rotation, and size channels, the class programmatically modifies each instance’s local transform property. Scale parameters in the specification instantiate one of several pre-programmed scaling functions for mapping data attribute values to visual channel values. Finally, DXR constructs optional axes, legends, and query filters. These steps result in an interactive 3D visualization represented as children of the vis-prefab GameObject—a collection of data-driven instances of the mark prefab, with optional axes, legends, and filters. Similar to how glyph instances are rendered in their spatial context, this 3D visualization can be placed in an AR or VR scene for immersion.

We designed this construction pipeline to be as agnostic as possible to the graphical mark prefab’s type and complexity in order to support the use of any Unity prefab as graphical mark (Sect. 6).

4.4 Placement
DXR facilitates the placement of visualizations within real or virtual worlds. DXR provides an anchor—a red cube near the visualization origin that allows a user to drag-and-drop the visualization in a fixed position relative to the real-world or a virtual scene at runtime. When the anchor is clicked on, the visualization’s position and orientation get attached to that of the user’s view. By moving around, the user effectively drags the visualization in 3D space. Clicking on the anchor again drops the visualization. This feature is particularly useful for aligning embedded visualizations with their object referents [72] or spatial contexts such as the examples in Fig. 1. In these embedded visualizations, physical positions of the referents need to be measured and encoded in the data. The anchor can then be aligned to the real-world origin used for measuring these positions. In the future, aligning of graphical marks with (non-)static referents could be enabled with computer vision and tracking.

Furthermore, DXR visualizations are GameObjects that can be composed and placed within a Unity scene either manually using the Unity Editor, or programmatically via scripts, or through libraries such as Vuforia, e.g., for attaching a GameObject to a fiducial marker. In some cases, designers may want to set the size of their visualization to match...
A channel can also be mapped to a fixed setting using the visualization parameters to sensible defaults based on the data types. Specification acts as a complete list of parameters for DXR's visualizations [41]. A graphical mark in DXR is a glyph whose visual properties are mapped to data attributes that can be quantitative, nominal, or ordinal. This forward direction is by default set to the (0,1,0) 3D vector, and only used internally by DXR. However, feedback from new users has shown that generally designers may want to set the size of their visualization to match the size of their intended canvas when overlaying them together. For example, in Fig. 5, the width and height of the visualization is set to that of the width and height of a basketball court (DXR size units are in millimeters). Moreover, multiple visualizations can be arranged in a scene to enable side-by-side comparison, or building of compound charts, e.g., simple stacked bar charts (Fig. 1h).

4.5 Interactions

In order to support multi-visualization workspaces, DXR allows the creation of query filters and linking of visualizations via vis-specs, illustrated in Fig. 6. Interactive query filters [56] control the visibility of graphical marks according to data using threshold and toggle interfaces. Linked visualizations within the same scene get filtered together.

By default, DXR provides details-on-demand with a tooltip that shows a textual list of data attributes when the user’s gaze pointer hovers on a graphical mark. DXR’s GUI (Sect. 5) also provides view manipulation (scaling up and down, rotating along x, y, z-axis) and view configuration controls. DXR’s grammar for interaction can be extended to further exploit device-dependent affordances of tangible [35] or direct manipulation [48] interfaces, as well as gesture- and voice-based input. Furthermore, any existing Unity asset for manipulating GameObjects and navigating scenes can apply to DXR visualizations. For example, hand tracking devices, e.g., leap motion [13], can be utilized to move, rotate, and rescale DXR visualizations using hand gestures. Similarly, device-dependent navigation features such as tracked headsets allow walking around DXR visualizations in AR or VR.

Out of the many options for immersive input modalities, e.g., touch, gaze, gesture, voice [37], we decided to use gaze and click for filtering, GUI interactions, and object placements. This makes them compatible with many common immersive devices because they are typically supported. Their similarity to mouse interactions in WIMP-based interfaces also make them familiar and easy to learn.

5 In-situ Graphical User Interface (GUI)

Fig. 7 shows a typical XR development set-up. It often requires testing a visualization within an immersive environment while tuning the design on a desktop or laptop computer running the Unity Editor. Initially, we designed DXR so that designers can only modify vis-specs in a text editor, typically running side-by-side with the Unity Editor. However, we found that in some cases this led to tedious switching between the two contexts. Furthermore, we found that the JSON syntax and grammar-based specification were overwhelming to non-programmers. To address these challenges, we designed and implemented DXR’s in-situ GUI—an intuitive interface that is embedded in the Unity scene with the vis-prefab so it runs in-situ within the immersive environment at runtime (Fig. 7:left).

The GUI provides drop-down menus, similar to WIMP interfaces, for selecting data, graphical marks, and visual encoding options from pre-defined sets of parameters. This removes the need to deal with JSON syntax. Moreover, designers no longer need to memorize possible parameter values since the GUI’s drop-down menus already provide lists of usable marks, channels, and data attributes. GUI interactions directly modify the underlying specification, as illustrated in Fig. 1(a, b) and Fig. 7, updating the output visualization instantly for rapid immersive prototyping.

Using the in-situ GUI, a designer can stay in the immersive environment to try different combinations of data, marks, and channels until an initial prototype has been reached. Instant preview of the visualization...
gives the designer immediate feedback for rapid design iterations. The
g design can then be fine-tuned back on the computer using a text editor.
the GUI also enables adapting and reusing existing DXR visualizations
as pre-configured templates similar to interactive charting applications.
With only a few clicks in the GUI, an existing visualization’s data can
be easily changed, instantly updating the visualization with the new
data—all without programming or additional scene configuration.

Our initial GUI design included drop-down menus for creating query
filters. However, we noticed that in practice they were seldom used,
yet made the GUI crowded. In our current design we removed these
menus since filters can be easily added via the grammar (Fig. 6). In
the future, we plan to make the GUI reconfigurable such that designers
can add and arrange menus for features they use the most. Another
design we considered was to make the GUI tag-along and follow the
user’s peripheral view. However, multiple GUIs overlap when there are
multiple visualizations in a scene, rendering them unusable. In
the current design, the GUI is fixed on the side of the visualization by
default and simply rotates along the y-axis to always face the user.

6 Custom Graphical Marks and Channels

We made it easy to use any Unity prefab as custom graphical mark in
DXR in order to leverage their wide availability and variety to support
flexible and engaging visualization designs. Fig. 8 illustrates how DXR
enables this by leveraging Unity’s object-oriented representation of
graphical marks. As discussed in Sect. 4.3, DXR has a Mark base
class that encapsulates all mark-related graphical functionalities such
as instantiation and visual encoding. This base class treats any mark
prefab in the same way, regardless of their type—as a shaded 3D box
model. DXR uses the bounding box of this model to modify standard
geometric properties like position and size, and its material shader to
change color and opacity. This base class is automatically applied to
any prefab within a designated marks directory.

Any Unity prefab can be converted into a graphical mark in DXR sim-
ply by placing it in the marks directory. During construction (Sect. 4.3),
DXR uses the mark parameter in the specifications as the unique prefab
filename to load from the marks directory. Once loaded successfully,
the prefab becomes a DXR graphical mark that can be instantiated and
modified according to data via the base class implementation. This
simple model makes it easy to extend the system with arbitrary Unity
prefabs as custom marks. For example, when a 3D model of a book
is saved as a prefab in the marks directory, it automatically becomes
a DXR graphical mark with the generic channels. Instead of a plain
bar chart, this book graphical mark can now be used to generate an
embellished bar chart (Fig. 8d).

Optionally, the designer can expose more complex prefab parameters
as custom encoding channels by implementing a derived class that
inherits from DXR’s Mark base class. For example, using this approach,
the intensity property of a flame particle system prefab can be used as
an encoding channel, in addition to the generic channels inherited from
the base class. This custom mark can be used to visualize forest fires in
Montesinho park [17] overlaid on a virtual geographical map (Fig. 8e).

Custom marks and channels are represented as a mark prefab with
an optional script of the derived class. These formats can be packed
into a Unity package file that allows their easy sharing and reuse. Once
imported, custom marks and channels just work, without the need for
additional set-up or programming. A drawback of this approach how-
ever, is that unlike grammars with a fixed set of marks with predictable
behavior, DXR users will have to be conscious about imported marks
to make sure that they understand how the channel encodings work,
to avoid unexpected behavior. In the future, we envision that well
documented DXR mark prefabs with accompanying examples will be
made available in the Asset Store similar to D3 blocks [8] and Vega
or Vega-Lite specifications that will facilitate informed sharing and
reuse. Consequently, designers must be conscious when using complex
prefabs that could extend construction times or limit frame rates with
increasing data size (Sect. 9).

7 Layered Authoring Support

Studies of visualization design workflows show that designers typically
iterate and switch between tools [39,40]. For example, a designer may
use high-level tools like Polaris or Vega-Lite to create an initial vis-
ualization, and then switch to more advanced D3 or Vega to fine-tune
the design. This type of workflow benefits from layered authoring
support [54], i.e., cross-compatible tools along the spectrum of simplic-
ity to flexibility illustrated in Fig. 2. This spectrum of tools can also
support the collaboration of designers and domain experts with varying
expertise in design, visualization, and programming.

DXR naturally supports layered authoring by providing multiple
alternative interfaces for design specification and graphical mark cus-
tomization. For design specification (Fig. 7:top) the GUI is easy to learn
and use, but is limited to pre-configured designs since the designer can
only change some parameters. The text editor allows tweaking of all
tunable parameters but requires familiarity with the grammar and JSON
syntax. Similarly, for graphical mark customization (Fig. 8:top), the
designer has three options: built-in graphical marks only allow simple
designs, custom marks with generic channels are easy to create but
only offer standard geometric and visual channels, and custom marks
and channels via derived class implementation are more complex to
create but are more flexible. With these options, DXR is able to support
iterative workflows as well as collaborations among users with varying
expertise as illustrated in the following examples.

8 Application Examples

We demonstrate the usage of DXR with a range of representative appli-
cation examples. Table 1 categorizes them by a variety of characteris-
tics. These and additional examples can be found on the DXR website
at https://sites.google.com/view/dxr-vis/examples.

Immersive information visualization. DXR can be used to create
bar charts (Figs. 1h and 8d), scatter plots (Figs. 1i and 6), and space-
time cubes (Fig. 10b) [33]. Without DXR, this would involve writing
custom programs to load data, instantiate marks, calculate and apply
visual mappings, and create axes, legends, and interactive query filters.
With DXR, particularly non-programmers, can easily prototype
We made it easy to use any Unity prefab as custom graphical mark in the GUI. With only a few clicks in the GUI, an existing visualization's data can be adapted and reused. The GUI also enables adapting and reusing existing DXR visualizations. Consequently, designers must be conscious when using complex visualizations that could extend construction times or limit frame rates. An additional set-up or programming is needed. A drawback of this approach is that unlike grammars with a fixed set of marks with predictable behavior, custom marks and channels are represented as a mark prefab with optional script of the derived class. These formats can be packed into a Unity scene template, in addition to the generic channels inherited from DXR's Mark base class.

The current design, the GUI is fixed on the side of the visualization by default. However, multiple GUIs overlap when there is only one visualization on the screen. Immersive visualizations require a different design, where the viewer can place the visualization anywhere by aligning its anchor with the shelf's lower left corner. To do this, the user can then download 3D models of a glass of milk and sugar cubes from Unity's Asset Store and compose a custom graphical mark implementing new channels such as milkheight, milkcolor, and sugarcubes via C# programming. Using the GUI or vis-specs, these channels are then mapped to milk content, days to expiry date, and sugar content, respectively. Scale and color schemes are then fine-tuned in the vis-specs, e.g., the color range for the milk is changed from the default white-to-red into brown-to-white reflecting the freshness of the milk. For an advanced user, the complete design and specification process can take approximately 15-20 minutes.

Using a custom flame graphical mark's intensity channel, we show the remaining life of referent organic materials hanging on a wall (Fig. 1g), adding a virtual dimension to the existing artwork. With DXR to create a 3D vector field plot using built-in cone graphical marks to show locations of photographs (Fig. 1) of an exhibit. To build this example, 3D real-world positions and orientations were encoded in the data and mapped to the cone mark's x, y, z, xdirection, ydirection, and zdirection channels. Embedded data visualizations can reveal insights about physical objects and spaces, as well as enhance our experience in the real-world.

### Immersive geospatial visualizations

To visualize forest fire data on a virtual map, we use DXR to create a 3D bar chart (Fig. 10e) that can be flown-over or walked-through in AR or VR showing heights and ages of several buildings in Manhattan. Furthermore, we downloaded a 3D population visualization from the Asset Store and converted it into a reusable DXR template (Fig. 10f) with minimal effort.

### Embedded data visualizations

Table 1. Summary of examples authored using DXR. Mark type can be a generic type (cube, sphere, or cone) or a custom prefab; spatial dimension is 2D if the visualization uses both x, y position channels, and 3D if it uses all x, y, z channels; scale is the size of the visualization (small: hand size, medium: table size, or large: room size); the runtime environment can be AR or VR; and anchor specifies whether the visualization is anchored in the real or virtual world.

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<th>Examples</th>
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<td>AR Workspace: Fig. 1d</td>
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<td>Buildings: Fig. 1e</td>
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<td>Population: Fig. 1f; Flow: Fig. 1g</td>
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<td>Basketball: Fig. 1k</td>
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<td>childbirth: Fig. 1l; Fire: Pref: Fig. 1m</td>
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Table 1: Summary of examples authored using DXR. Mark type can be a generic type (cube, sphere, or cone) or a custom prefab; spatial dimension is 2D if the visualization uses both x, y position channels, and 3D if it uses all x, y, z channels; scale is the size of the visualization (small: hand size, medium: table size, or large: room size); the runtime environment can be AR or VR; and anchor specifies whether the visualization is anchored in the real or virtual world.

virtual glass of milk on top of each milk carton on a grocery shelf. An advanced user would iteratively build this visualization as follows. First, the physical positions of each milk carton are measured (in millimeters, with respect to a real-world origin, e.g., lower left corner of shelf) and are then added as x and y columns in the data. Then, a 2D scatter plot template is used to visualize the data, using the GUI to map the measured positions to x, y dimensions, milk content to size, and days before expiration to color. Next, the width and height parameters in the vis-specs are set to match that of the shelf. At runtime, DXR constructs the visualization where scale parameters and color schemes are generated automatically with default values. The user can then place the visualization by aligning its anchor with the shelf's lower left corner (Fig. 9c). Then, the user downloads 3D models of a glass of milk and sugar cubes from Unity’s Asset Store and composes a custom graphical mark implementing new channels milkheight, milkcolor, and sugarcubes via C# programming. Using the GUI or vis-specs, these channels are then mapped to milk content, days to expiry date, and sugar content, respectively. Scale and color schemes are then fine-tuned in the vis-specs, e.g., the color range for the milk is changed from the default white-to-red into brown-to-white reflecting the freshness of the milk. For an advanced user, the complete design and specification process can take approximately 15-20 minutes.

Using a custom flame graphical mark’s intensity channel, we show the remaining life of referent organic materials hanging on a wall (Fig. 1g), adding a virtual dimension to the existing artwork. With DXR, we can create a 3D vector field plot using built-in cone graphical marks to show locations of photographs (Fig. 1) of an exhibit. To build this example, 3D real-world positions and orientations were encoded in the data and mapped to the cone mark’s x, y, z, xdirection, ydirection, and zdirection channels. Embedded data visualizations can reveal insights about physical objects and spaces, as well as enhance our experience in the real-world.

**Immersive visualization workspaces** consist of multiple linked visualizations in custom AR and VR environments. In an example scenario, users with varying backgrounds can collaboratively develop a VR workspace that visualizes a multi-variate hurricane data through a set of 3D and 2D scientific and abstract visualizations. For example, data points encode position, orientation, temperature, pressure, etc. A domain expert on hurricanes without experience in XR-programming, for example, can use a 3D vector field plot template to visualize wind velocity. The GUI can be used to quickly try out different variable combinations to find interesting correlations in the data via scatter plot templates. Working with an advanced immersive visualization designer, the domain expert can then customize the layout, link visualizations, and add query filters to support custom analytical workflows. The arrangement of the visualizations can be easily modified using the Unity Editor or direct manipulation, e.g., such that they surround a physical workstation.

**Immersive sports data analytics** is a growing trend with more and more companies leveraging AR and VR for immersive training and strategizing. Our baseball (Fig. 1e) and basketball (Figs. 1h, 5, and 7) examples were scaled to life-size and blended with real-world or virtual courts. The full immersion potentially makes it easier for players to assimilate and translate the data into actionable insights. With a HoloLens, a baseball batter can, for example, view life-size virtual pitched balls of an opponent for immersive training within a real-world baseball field, similar to an existing immersive training

![Fig. 9. Prototypes for (a,b) forest fire and (c) milk data visualizations.](image-url)
Fig. 10. Examples of immersive visualizations built using DXR include (a) embedded representations, (b, c, d, e, f) 2D and 3D information and geospatial data visualizations, (c, d) immersive workspaces, and (g, h) 3D flow fields and streamlines. Prototyping each example took 10-30 minutes using DXR’s GUI and grammar-based interfaces. Custom graphical marks are based on Asset Store prefabs and 3D models from on-line repositories. All examples presented in this paper are available on the DXR website as templates for designers.
application [30]. Since most sports data are similar across players and teams, once their visualizations are implemented in DXR, they can be reused as templates by non-programmer players and coaches.

We also used DXR to create immersive flow field (Fig. 10g) and streamlines (Fig. 10h) visualizations using arrow and paper airplane graphical marks, respectively. Fig. 10h shows direct manipulation of DXR visualizations using a leap motion controller.

9 Performance Evaluation
As DXR is meant for prototyping and exploring designs, scalability was not an explicit design goal. This section reports on performance measures of the current implementation. Fig. 11 shows construction times and frame rates for varying data sizes and graphical mark complexities running on Unity Desktop, HoloLens [15] (HL), and ACER VR headset [2] (VR). The Unity Desktop experiments were performed using Unity Editor 2017.2.1 on a PC with an Intel Xeon CPU (2 processors @ 2.10 GHz), 128 GB RAM, and a GTX Titan X graphics card. The ACER VR headset was tethered to the same PC, while the HoloLens used its own standalone processor and GPU. For the Random_Cube and Random_Fire examples, we generated random 3D points and plotted them in a 3D scatter plot. We used the built-in cube graphical mark and more complex fire particle system similar to Fig. 8e. We used these two examples as representative visualization examples with both simple and complex marks on all devices. The Flow_Cone and Flow_Arrow examples use the flow simulation data shown in Fig. 10g at different subsampling levels plotted as a vector field. We used the built-in cone and custom arrow graphical marks, respectively. Note that the flow visualization examples used 8 channels (x, y, z, color, opacity, xdirection, ydirection, zdirection), while the scatter plot used only 3 channels (x, y, z).

To measure construction time, we ran DXR’s visualization construction pipeline (Sect. 4) 11 times for each example. We discarded the first one as warm-up and report the average of the remaining 10. Construction times remain below 12 seconds even for complex examples. As data size goes up, construction times increase as an effect of increasing graphical mark prefab instantiation calls.

When measuring frame rate, we kept the visualization fully visible within the viewport and continuously rotated it along the y-axis with respect to its center. Frame rates drop more or less exponentially with increasing graphical mark prefab instantiation calls. We also provided specially optimized custom graphical marks and use level-of-detail techniques that have been developed to handle large-scale scientific visualizations [63]. Eventually, designers can build on DXR to implement more scalable custom visualization techniques, e.g., multi-resolution approaches, by aggregating data via external tools, combining multiple visualizations, and customizing mark behavior.

10 Conclusions and Future Work
DXR makes rapid prototyping of immersive visualizations in Unity more accessible to a wide range of users. By providing a high-level interface and declarative visualization grammar, DXR reduces the need for tedious manual visual encoding and low-level programming to create immersive data-driven content. We believe DXR is an important step towards enabling users to make their data engaging and insightful in immersive environments.

DXR opens up many directions for future work. On one hand, we look forward to developing new immersive visualization applications for shopping, library-browsing, office productivity systems, or collaborative analysis. On the other hand, we encourage the user community to improve and extend DXR’s functionality. In addition to the GUI, alternative immersive interfaces can be explored for specifying and interacting with data representations, e.g., using gesture, voice, or tangible user interfaces. We envision the development of immersive visualization recommender systems, similar to Voyager, providing better support for designing in the AR-CANVAS [36] and to suggest designs that can alleviate potential cluttering and occlusion issues. DXR may also enable perception and visualization researchers to streamline user studies for a better understanding of the benefits and limitations of immersive visualization in various domains.

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