# Declarative Computing with Shapes and Shadows

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**Abstract.**

We present a preliminary concept and a prototypical implementation of a declarative computing framework that is capable of reasoning about 3D physical entities, and the shadows that they cast in open or uniformly lit environments. For this paper, we restrict our scope of 'uniform lighting' to sunlight, and its incidence on a given geospatially and temporally referenced location.

The model extends traditional techniques from computational geometry and computer graphics that are primarily motivated by simulation or visualisation. In particular, our declarative framework is capable of deriving and reasoning about the objects and their cast shadows in a knowledge processing sense, e.g., involving qualitative abstraction and semantic specification of requirements, query capability, ensuring conceptual consistency of design requirements. Our ontology of objects and shadows, and the resulting computational framework serves as a foundational engine for high-level conceptual (spatial) design assistance technology.

The capabilities demonstrated in this paper are aimed at applications in spatial design, chiefly encompassing Computer-Aided Architecture Design (CAAD), Urban Planning, and Interior Design.

**Keywords.** declarative languages, knowledge representation and reasoning, geometric and spatial representation and reasoning, computational geometry, shadows, CAAD, design

## 1. Introduction

The way in which direct sunlight falls on surfaces in the built environment has a tremendous impact on its atmosphere, character, and affordances. Consider the role of sunlight in fostering a golden autumnal scene, the mood established by acutely angled sun rays in the early morning, or headache-inducing glare in a work place.

The *absence* of direct sunlight is shadow. Shadows and sunlight partition *empty space*; they are not objects in the sense of having a material extension in the way that walls, doors, and other physical objects do. Yet architects are centrally concerned with the play between shadows and sunlight, and reason about the physical *geometric forms* and arrangements of shadows and sunlight, for example, to achieve a visual balance, to focus or accentuate aspects of the design, or to create a visual flow through a hierarchy of illumination.

Questions surrounding the behaviour of sunlight come to the fore in urban-scale designs. Architects need to determine how the orientation, shape, and positioning of buildings and large environment features influence the geometric forms of shadows. How can we manipulate the objects in the environment to achieve a desired atmosphere through shadows and sunlight? Would it be possible to manipulate shadows *directly* in our design?

Various numerical techniques have been developed for computing the effects of lighting in an environment. One method is detailed *ray tracing* where a large number of simulation rays are emitted from the light source and reflected from intercepting surfaces.[1] While being very accurate and precise, there are significant limitations with these detailed numerical approaches.

Firstly, they require an enormous amount of computational resources, and may take hours or even days to produce a lighting model for large-scale urban designs. This makes it infeasible to repeatedly re-run the simulation after making minor changes to the design.

Secondly, the results do not emphasise the essential form of shadows *as objects*. For example, they may produce a complex point cloud of luminance values that requires yet further complex calculations to answer basic questions about sunlight and shadow. By applying a uniformly high degree of numerical precision to every aspect of the building design, these methods hide those critical *qualitative* aspects of the design that play the most important role in natural lighting.

Thirdly, these methods require a detailed numerical building design before the lighting model can be generated. But very often, particularly in the early stages of a design, many numerical details are simply not available, such as the exact lengths of certain walls or the precise orientation of certain buildings.

We present a qualitative approach for generating shadows and sunlight regions as first-class objects using appropriate abstractions of building information models and natural lighting. Our objective is to extend and enrich standing design information models with different types of natural lighting *space*. We accomplish this within the paradigm of constraint logic programming so as to support declarative queries and high-level analysis about sunlight and shadows.

## 2. The Shape of Shadows

Seen as mathematical objects, shadows are a product of the interaction between opaque geometric forms and light. The placing and orienting of walls and windows is *sculpting* the forms of shadows and sunlight, and thus shaping yet another layer of experience from the environment, beyond the material objects and the perceived empty space [Bhatt et al., 2012]. Figure 1 comparatively illustrates these three layers of a scene.

[1] Each ray might have a maximum number of allowable reflections before the simulation of the ray is terminated. Properties of the ray are recorded, such as the complete path or just the intersection points, and this data is used to generate a detailed surface lighting model.

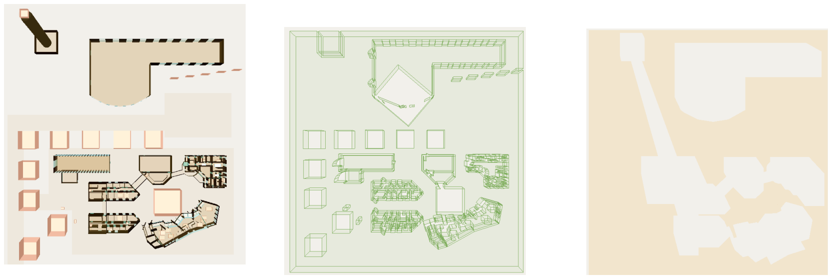


**Figure 1.** A design represented as the *material*, *perceived empty space*, and resulting *shadows*.

### *2.1. Spatial Patterns and the Subjective Experience*

Within each layer the designer can specify spatial patterns that they deem to evoke salient user experiences or induce certain behaviours. Consider the following brief extracts from Seidler's opening statements about the role of sunlight and shadow in architecture [Seidler, 1959]:

> *"Solid form is accentuated and added to by the shadow it casts which recalls design form."*
>
> *"Spidery elements, adjuncts to buildings and sculpture increase the interest of their own forms by the complex pattern of their shadows which must be considered as an integral part of the elements that cast them."*
>
> *"The oscillation between light and shade gives richness to building in contrast [..]"*

In these excerpts the architect identifies a number of relationships: shadows *accentuate* the experience of material forms; complex patterns of shadow *increase interest* in architectural forms; oscillation patterns add *richness* to the experience of the environment.

For example, a small patch of sunlight can be accentuated by a much larger region of surrounding shadow. Such a pattern may function as a visual attractor for user wayfinding, and the visual emphasis and focus may provide a heightened sense of *excitment* and *drama*. We argue that these patterns are *qualitative*, rather than metric, in nature, and that they can be successfully formalised within first-order logic expressions over semantically rich building information models.

### *2.2. The dynamic nature of shadows and sunlight*

There is an inherent dynamism in the nature of sunlight that operates at numerous levels. The location of the sun in relation to the environment clearly has an immediate impact on the forms of shadows. Although this relationship is constantly changing throughout the day, the induced patterns of sunlight and shadow can *appear* fixed at a given moment, especially at an urban scale. Thus, an environment can exhibit distinct visual states from sunlight at various times of the day.

The seasonal variations of the sun's trajectory across the sky also has a clear impact in many countries: the low arc of the sun's path during winter can cast long shadows throughout a day and may leave some parts of the environment without any direct sunlight for months.[2]

This dynamism gives rise to two basic questions: what are the shapes of shadows and sunlight *at a given moment*, and what are those shapes *across periods of time*? For example, the designer may need to know whether a given room *ever* has direct sunlight during the day, or whether a certain cafe zone has direct sunlight at each midday period throughout the year.

Computationally answering each one of these questions requires the capability to handle conceptual, spatial, and temporal concepts in an expressive knowledge processing and inferencing environment. From an application viewpoint, this is the objective of the ongoin work reported in this paper.

## 3. A Qualitative Model of Sunlight and Shadows

In this section we describe the abstractions of our sun model. Our model provides the necessary information for determining the regions of space covered in shadow, it is flexible enough to work with both highly under-specified early designs and detailed numerical designs, and generates shadows in real-time. Thus, our model allows the designer to quickly experiment with a large number of designs to determine how shadows broadly behave.

In this model we focus explicitly on direct sunlight (and ignore ambient illumination [Schultz et al., 2009]), i.e. regions of space in which there is an uninterrupted straight line from the sun to every point in the region; shadows are the absence of direct sunlight.

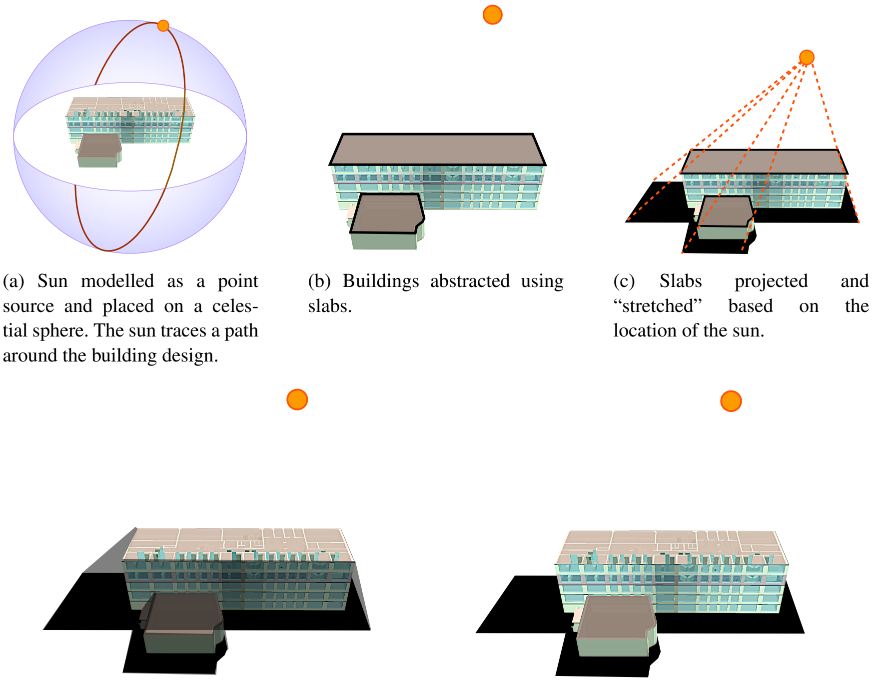
### *3.1. Modelling Outdoor Sunlight*

When modelling sunlight on an urban scale we only take large objects into account such as buildings, large trees, and billboards.[3] We use a highly abstracted model of buildings to determine how they cast outdoor shadows: while buildings can consist of thousands of objects, the single most informative features are the geometries, elevations, and heights of *slabs* (i.e. rooves and floors).

Shadows are generated from slabs by making the qualitative generalisation that walls and other objects holding up slabs are *effectively opaque*. This provides a rapid approximation of the *building envelope*. Other large outdoor objects are modelled using very abstract geometries such as bounding boxes. Thus, the designer only needs to provide a very rough outline of buildings and amenities to begin experimenting with shadows.

[2]The interference of other objects such as clouds can also influence the form of shadows, but these external conditions are not relevant for our qualitative model.

[3]Modelling the shadows of an outdoor park bench is too fine-grained and will not contribute to an understanding of how shadows influence and shape the environment on a large scale.



(a) Sun modelled as a point source and placed on a celestial sphere. The sun traces a path around the building design.

(b) Buildings abstracted using slabs.

(c) Slabs projected and "stretched" based on the location of the sun.

(d) 3D shadow volumes.

(e) 2D shadow footprints.

**Figure 2. Generating shadows with a qualitative sun model.**

As is typical for planetary models [Roderick, 1992], we model the sun as a point source placed on a celestial sphere centred on the design. The sun is positioned using altitude and azimuth angles.[4] We generate a model of shadows by "stretching" each vertex of each slab polygon according to the elevation and height of the slab, and location of the sun. This results in 2D shadow *footprints* (useful for top-down plan analysis) and 3D shadow *volumes*. The process is illustrated in Figure 2.

If the sun's altitude is within a certain range then indoor direct sunlight can be approximated using the isovist of a point derived from the sun's location,[5] as illustrate in Figure 3. This abstracts from the height information of the windows, and other precise design parameters, to provide the designer with information on the rooms that are exposed to direct sunlight.

[4]Standard formulae for converting latitude, longitude, calendar date, and time of day into approximate sun coordinates are usable; for details, refer to [Ast, 1996] page C24.

[5]More specifically, the sun point is projected onto a plane that is parallel to the ground and set to the elevation of the relevant building floor. The isovist is then taken from this projected point in that plane.

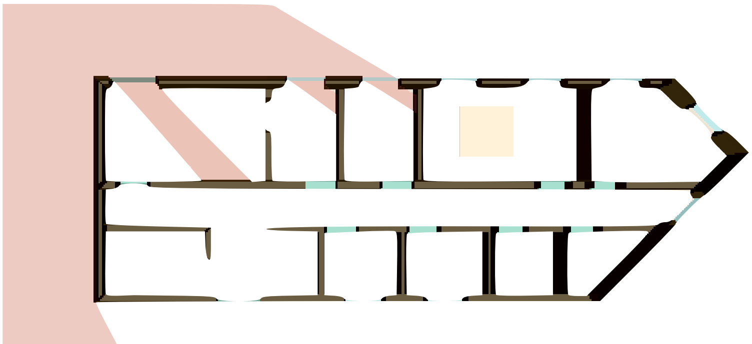


**Figure 3.** Direct sunlight in the building interior (the sun is located in the upper left area of the plan).

## 4. Declarative High-level Design Specifications for Shadows

In this section we present an assortment of declarative programming logic specifications in the domain of urban and indoor design for art galleries, academic sites, and other public spaces. These example rules are processed using our general purpose spatial reasoning framework CLP(QS) [Bhatt et al., 2011]; CLP(QS) provides domain-independent geometric and qualitative spatial and temporal reasoning functionality within a Constrain Logic Programming (CLP) setting .

**Sunlight and Shadow predicates**. The location of the sun is defined by altitude and azimuth, which in turn can be computed from a calendar date and time. We can determine the sun location based on a given time, or the time that corresponds to a given location, by using the predicate:

```
sun(DateTime, Azi, Alt).
```

**Painting damage**. There may be a risk that paintings are damaged if they are exposed to direct sunlight. This occurs if there is *some* period in which the sunlight overlaps the painting.

```
riskOfSunDamage(Painting) :-
      physical_space(Painting,_,PPolygon),
      sunlight(sun(DateTime,_,_),_,SPolygon),
      topology(SPolygon,PPolygon,overlaps).
```

**Rooms with sunlight**. We can determine whether particular rooms in our design get direct sunlight during winter.

```
sunRoom(Room) :-
      movement_space(_,Room,MPolygon),
      winter(DateTime),
      sunlight(sun(DateTime,_,_),_,SPolygon),
      topology(SPolygon,MPolygon,overlaps).
```

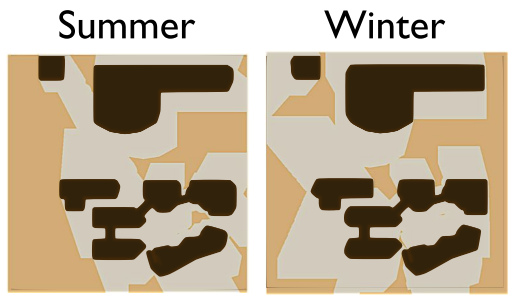



**Figure 4.** Regions of space that are always in shadow (brown), and always in sunlight (orange), throughout the entire day, during summer and winter.

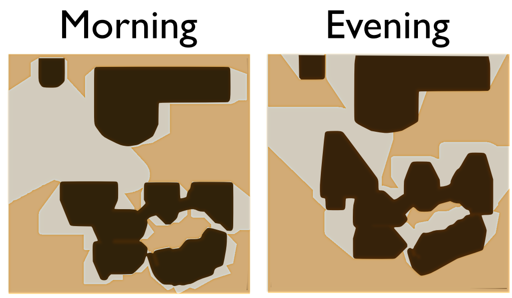



**Figure 5.** Regions of space that are always in shadow (brown) and always in sunlight (orange) for every morning (left) and evening (right) across the entire year.

**Uncomfortable cafe garden**. At around midday throughout the year, the area where people relax and enjoy lunch should not be completely covered in shadow.

```
uncomfortableCafeArea(CafeOutdoorArea) :-
    movement_space(CafeOutdoorArea,_,MPolygon),
    midday(DateTime),
    shadow(sun(DateTime,_,_),_,SPolygon),
    topology(SPolygon,MPolygon,contains).
```

**Shadow forms across periods of time**. The dynamism of shadows as a product of the changing relationship between environment and sun results in patterns and forms that can be captured and analysed. For example, as in the *uncomfortable cafe* example, the architect may need to study the topology of regions that are always in shadow over a period of time.

Figure 4 shows the areas throughout summer (left) and winter (right) that are always in sunlight (orange), and always in shadow (brown). We can observe that, during winter, certain areas of sunlight in the central portion of the design grow and become disconnected from the larger sunlit region to the right. This “island” of sunlight is highlighted by the surrounding colder shadowed regions, and thus could be utilised as an area for outdoor winter activities such as winter markets, events, or a shared cafe area.

The periods of time do not need to be temporally contiguous. Figure 5 shows the areas of sunlight and shadow from every morning and evening throughout the entire year.

## 5. Discussion and Future work

In our current prototypical implementation, we compute dynamic forms of sunlight and shadow regions by sampling sun locations within the specified period, generating the sunlight or shadow regions for each sample, and combining the results. One future research aim is to fully encode the *relationship* between calendar date, sun location, and sunlight and shadow regions within the framework of Constraint Logic Programming. Furthermore, based on our preliminary foundations in [Schultz et al., 2009], we are also investigating the incorporation of non-uniformly lit ambient lighting conditions, which are more suited for interior design scenarios, and in cases where the internal composure of a building is controlled via artificial light sources.

This leads into the next core future research aim of generating *metric instantiations* from qualitative (spatial) relational specifications – that is, automatically adjusting designs in order to satisfy certain high-level qualitative properties. Given certain shadow properties that must be satisfied in the design such as "the painting must not be exposed to direct sunlight", our reasoning system (i.e., underlying constraint solver) will find solutions by rotating and translating the objects on the ground-plane in a manner that the derived transformation satisfies the desired topological relationships between the physical entities and their cast shadows.

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