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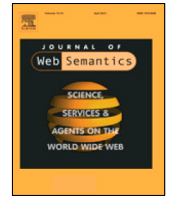
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The Jazz Ontology: A semantic model and large-scale RDF repositories for jazz[☆]



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ABSTRACT

Jazz is a musical tradition that is just over 100 years old; unlike in other Western musical traditions, improvisation plays a central role in jazz. Modelling the domain of jazz poses some ontological challenges due to specificities in musical content and performance practice, such as band lineup fluidity and importance of short melodic patterns for improvisation. This paper presents the Jazz Ontology – a semantic model that addresses these challenges. Additionally, the model also describes workflows for annotating recordings with melody transcriptions and for pattern search. The Jazz Ontology incorporates existing standards and ontologies such as FRBR and the Music Ontology. The ontology has been assessed by examining how well it supports describing and merging existing datasets and whether it facilitates novel discoveries in a music browsing application. The utility of the ontology is also demonstrated in a novel framework for managing jazz related music information. This involves the population of the Jazz Ontology with the metadata from large scale audio and bibliographic corpora (the Jazz Encyclopedia and the Jazz Discography). The resulting RDF datasets were merged and linked to existing Linked Open Data resources. These datasets are publicly available and are driving an online application that is being used by jazz researchers and music lovers for the systematic study of jazz.

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1. Introduction

Jazz is an important musical tradition with a worldwide community of millions of people enjoying, playing, and studying it. While it is primarily considered as a genre of Western music, it

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URL: <https://www.eecs.qmul.ac.uk/~simond> (S. Dixon).

occupies a special position due to the central role of improvisation, which is not common in other Western music genres [1]. Originating as a mixture of traditional African-American styles with popular American music at the beginning of the 20th Century, jazz has evolved into a highly varied and musically complex genre [2–4]. During its history of about 100 years [5], jazz has influenced and been influenced by other musical styles across cultures around the world [6–8]. With this rich tradition, jazz is a worthwhile object of semantic modelling but it also poses challenges in the construction of musical ontologies.

Jazz is recorded, produced, sold, and consumed in a similar fashion to other Western musical genres, therefore discographic and bibliographic metadata are to a significant extent in line with those. At the same time, its unique musical and performance characteristics break the limits of existing semantic models: e.g., musicians often play more than one instrument, the lineup of a band can change from performance to performance, there is a special role of improvised solos and soloists, which require

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dedicated modelling. Scores are sometimes used, but in a much looser way than in Western classical music, often in the form of lead sheets which only indicate the basic melody of the tune and its harmonic structure.

For a comprehensive modelling of the jazz domain, several subdomains have to be considered presenting a variety of data modalities and formats. Jazz as a musical sound is the subject of analysis by jazz musicians and musicologists: they study such aspects as harmonic and melodic content, improvisation, musical interaction, and stylistic characteristics of movements and epochs in jazz [9]. Jazz as a societal phenomenon has been studied by ethnomusicologists and jazz researchers, looking at jazz creators and consumers, its history and its role in society [10,11].

Given the similarities between jazz and other Western musical genres, existing ontologies of music, such as the Music Ontology [12,13] and the MusicBrainz ontology,¹ are an obvious starting point for modelling the jazz domain. Yet the centrality of improvisation, prevalence of multi-instrumentalists and changing lineups are important differences that require modelling by means of a dedicated ontology. These phenomena, while crucial for jazz, can be found in other genres and traditions: Western popular music knows multi-instrumentalists (Freddie Mercury who played guitar, piano and sang); pop bands often tour with guest musicians; improvised solos can be an important part of the musical product (Jimi Hendrix was most famous for his solos). Therefore a jazz ontology would not only borrow concepts from other genres but also contribute to other musical domains, where less salient musical practices may have escaped ontologists' attention.

Few corpora exist for systematic study of jazz on a large scale. The Weimar Jazz Database [14] comprises 456 manually transcribed and richly annotated jazz solos: it contains solo transcriptions in a score-like machine-readable format. LinkedJazz is a Linked Open Data project concerned with careers, lives, and relationships of jazz artists. It links all major open resources on jazz musicians and contains a curation tool to verify and reconcile the records [15]. Additionally, it provides a public interface to assist with semi-automatic analyses of musicians' interviews and to add new relationships [16].

Our recent project, *Dig That Lick: Analysing Large-Scale Data for Melodic Patterns in Jazz Performances*² (DTL) was a two-year endeavour within the fourth *Trans-Atlantic Program Digging into Data Challenge*. It addressed jazz on a larger scale, combining various aspects of jazz and data modalities in an interdisciplinary approach. The work was concerned with automatic analysis of melodic patterns ("licks") in jazz improvisations, aiming to trace musical influence based on borrowing of licks [17]. The analysis workflow included automatic melody extraction from 50K audio recordings [18,19]; segmenting tracks into solo and other parts; and advanced pattern search on symbolic representations of solos [20]. This paper describes modelling, collecting, integrating, correcting, enriching metadata and linking it to audio.

In the next section, we outline previous work in semantic modelling and dataset development relevant to music (FRBR, Music Ontology) and in particular to jazz (Weimar Jazz Database, LinkedJazz). We lay out a methodological framework that guided us during planning, modelling and populating the Jazz Ontology in Section 3. Section 4 presents the semantic model of the Jazz Ontology: the basic model which represents and relates the discographic and the sessionographic information about jazz, as well as further additions modelling jazz-specific phenomena. Section 5 describes the process of ontology population for three jazz datasets, including dataset merging and enrichment, while

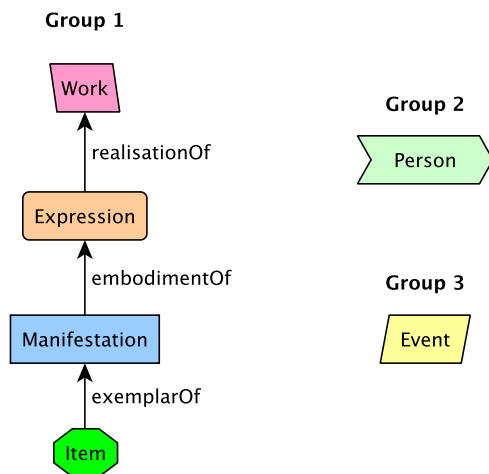


Fig. 1. FRBR conceptual model. The shape and colour coding exemplified here is used throughout this paper to indicate classes implementing FRBR concepts. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Section 6 discusses the assessment of the ontology in terms of formal requirements and in-use validation. We wrap up with a discussion and future work suggestions.

2. Related work and datasets

One of the main standards for semantic modelling in cultural heritage is FRBR (Functional Requirements for Bibliographic Records). It is a conceptual model for describing entities and relationships in libraries, museums, and archives [21]. FRBR was developed by the International Federation of Library Associations and Institutions (IFLA) and is widely used by cultural institutions around the world, in particular for electronic cataloguing of physical and digital objects. As a conceptual model, it is separate from the language, cataloguing standards, or the actual implementation system and provides the basis for interoperability between holdings, collections, and datasets [22]. FRBR Group 1 defines four main entities to represent the products of intellectual or artistic endeavour: "Work (a distinct intellectual or artistic creation) and expression (the intellectual or artistic realisation of a work) reflect intellectual or artistic content. Manifestation (the physical embodiment of an expression of a work) and item (a single exemplar of a manifestation) reflect physical form". Group 2 includes persons and corporate bodies responsible for the custodianship of Group 1 intellectual or artistic endeavours (e.g., creators, consumers). Group 3 includes events and places [23] (Fig. 1). While too general in its pure form, FRBR is relevant for music [24] and in particular for jazz, and has been widely implemented or referred to in existing semantic models of music. It has been represented as an OWL ontology.³

The Music Ontology (MO) [12,13] is among the most comprehensive ontologies for the music domain, providing a vocabulary for publishing and linking a wide range of music-related data on the Web.⁴ It extends the FRBR model and provides an event-based conceptualisation of music creation, performance, production and consumption, including aspects such as discographic information, production processes as well as music-related events. The Music Ontology builds upon four broadly accepted domain models adapted to the music domain:

¹ <https://wiki.musicbrainz.org/LinkedBrainz>.

² <http://dig-that-lick.eecs.qmul.ac.uk>.

³ <http://vocab.org/frbr/core#>.

⁴ <http://musicontology.com>.

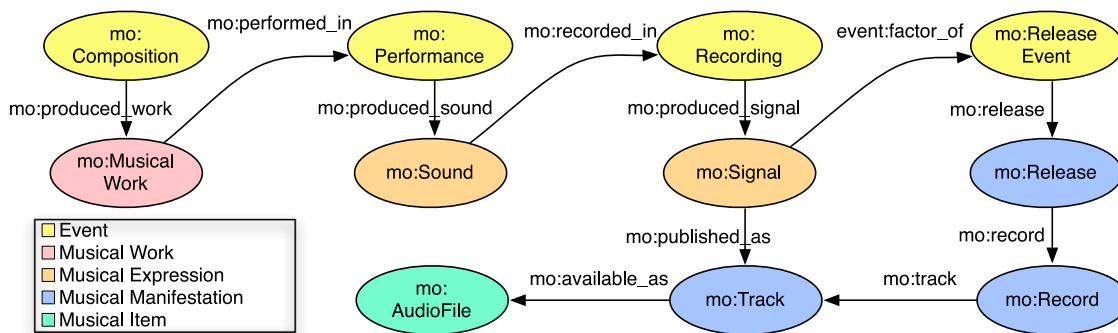


Fig. 2. A fragment of the Music Ontology: key concepts and selected properties describing the music production workflow, showing the FRBR layers. Source: Reproduced from [47].

- FRBR Ontology⁵ (Fig. 1),
- the Timeline Ontology,⁶
- the Event Ontology,⁷
- FOAF.⁸

Fig. 2 illustrates how the Music Ontology classes implement FRBR.

A broad range of applications [25,26] have been implemented based on the Music Ontology, from recommendation systems [27, 28] to live performance [29], and numerous extensions covering music production⁹ [30–33], audio effects [34,35], audio features¹⁰ [36], musical instruments [37], transformation and redistribution of audio content¹¹ [38,39], music theoretical concepts [40–42], live music archives [43], smart instruments and more generic “Musical Things” [44]. The Music Ontology has been successfully applied to a variety of musical content including many commercial pop music genres, electronic and classical music. Moreover, it was found to generalise well to a number of non-Western musical traditions [45,46].

Our model builds strongly on the Music Ontology as its main reference, yet some aspects like frequently changing band lineups and the prevalence of multi-instrumentalists are specific for the genre and need more detailed modelling.

Turning our attention to data sources relevant in the jazz domain, MusicBrainz is the largest crowd-sourced collection of music metadata online, mainly focused on discographic information about published CDs. It is widely used by applications and music consumers to automatically add metadata to their downloaded digital tracks^{12,13,14} [48,49]. The data is ingested according to detailed guidelines, and curated by volunteers, therefore it is quite consistent, though errors cannot be excluded. An API is provided for data retrieval and sharing. The MusicBrainz data model has been expressed in OWL and the data is available in RDF format. MusicBrainz is an important Linked Open Data resource for us even though its focus on releases and CD metadata

does not meet the core needs of our ontology and its applications. For interoperability, we kept our data model consistent with MusicBrainz where possible. Another important aspect of MusicBrainz is its fingerprinting algorithm,¹⁵ which we use to identify track duplicates in our collection.

The Weimar Jazz Database is a collection of manually transcribed and richly annotated jazz solos. It was produced as part of the Jazzomat Project at the University of Music “Franz Liszt” Weimar in Germany between 2012 and 2017 and has become an important corpus for systematic jazz research [14]. The database comprises 456 instrumental jazz solos from 343 different recordings, and provides musical content annotations for meter, structural segmentation, measures, beats, chord labels, style, solo instrument and more. Discographic metadata is also included with the tracks. The Jazzomat data model has been developed with a detailed manual analysis of musical content as the main goal. Data is disseminated as an SQLite database; it has been represented in OWL as part of the JazzCats project [50]. The data released as part of Dig That Lick (see Section 1) and used to evaluate the Jazz Ontology builds on the findings and experience from the Jazzomat project, taking its approach into the realm of big data (tens of thousands of tracks) by automating manual tasks such as solo transcription.

LinkedJazz¹⁶ is a research project at the Pratt Semantic Lab concerned with Linked Open Data, and in particular documents and data related to the personal and professional lives of jazz artists [15,16,51]. The researchers crawled all the main Linked Open Data resources such as DBpedia,¹⁷ Library of Congress authority files,¹⁸ MusicBrainz,¹⁹ Virtual International Authority File,²⁰ to collect and link all entries related to jazz artists. The outcomes of automatic discovery (around 9,000 artists) were curated by researchers and volunteers by means of a dedicated application. LinkedJazz researchers created a data model specifically describing jazz artists and relationships between them, implementing FOAF and the Music Ontology, and extending these further. We build upon the findings and the data model of this pioneering project, which enables us to easily link our ontology to existing Linked Open Data on jazz musicians. Only a small proportion of musicians in our data are currently referenced online – we hope to change that with our datasets.

The JazzCats²¹ [53] project successfully interlinked disparate jazz-related datasets by means of Semantic Technologies. The

⁵ <http://vocab.org/frbr/core.html>.

⁶ <http://purl.org/NET/c4dm/timeline.owl>.

⁷ <http://purl.org/NET/c4dm/event.owl>.

⁸ Friend of a Friend ontology, describing relationships between persons: <http://xmlns.com/foaf/spec/>.

⁹ <http://isophonics.net/content/studio-ontology>.

¹⁰ <https://w3id.org/afo/onto/>.

¹¹ <https://w3id.org/ac-ontology/aco>.

¹² “The BBC partners with MusicBrainz for Music Metadata” <https://blog.metabrainz.org/2007/06/28/the-bbc-partners-with-musicbrainz-for-music-metadata/>, accessed on 14/05/2022.

¹³ MusicBrainz Tagger https://www.foobar2000.org/components/view/foo_musicbrainz, accessed on 14/05/2022.

¹⁴ Blog on MusicBrainz use by Aiir <https://blog.aiir.com/what-was-that-song-c9ff8a93d9c4>, accessed on 14/05/2022.

¹⁵ AcoustID: <https://acoustid.org>.

¹⁶ <https://linkedjazz.org>.

¹⁷ <https://wiki.dbpedia.org>.

¹⁸ <http://id.loc.gov/authorities/names.html>

¹⁹ <https://musicbrainz.org>.

²⁰ <https://viaf.org>.

²¹ <http://jazzcats.oerc.ox.ac.uk/sparql>.

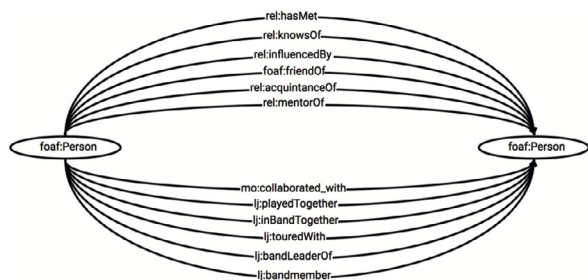


Fig. 3. LinkedJazz properties describing relationships between jazz artists [52].

datasets in question were the Weimar Jazz Database, the Linked-Jazz repository and the Body&Soul dataset²² which provides a discography for over 200 performances of “Body and Soul” recorded between 1930 and 2004 [54]. A follow-up project further added connections to two other musicological datasets describing concert life in London in the 18th and 19th centuries [50, 55]. The goal was to connect existing datasets, not to model the domain of jazz with its specific characteristics which differentiate it from other musical domains. Whereas Body&Soul implemented the Music Ontology for its discographic relationships, LinkedJazz extended the Music Ontology properties with further relevant relationships among musicians (Fig. 3). In contrast, the Weimar Jazz Database did not implement existing ontologies or schemas and many classes were project specific. In this case, RDF was produced from an SQLite3 database via an automated process. Given the very rich solo annotations produced in the Jazzomat project, most of them would not normally be available for other data sources, or different types of content annotations might be used.

In contrast to previous works with a stronger emphasis on interlinking data, we took a top-down approach, aiming to model the domain of jazz, first concentrating on elements which most jazz-related projects and datasets would have in common. We also focus on jazz-specific characteristics which have not been covered by more general models, such as fluidity of band line-ups and prevalence of multi-instrumentalists, as well as the centrality of live performance, soloing and improvisation. The ontological models and knowledge organisation approach proposed in this paper may transfer over a range of domains and applications that makes use of semantic models of music data. These include frameworks that bind applications targeting different stakeholders in music production and consumption, for instance, to navigate music collections or reproduce music recordings adaptively using metadata [56,57]. Our work may also contribute to broader efforts supporting music informatics research through semantic integration of datasets [58–60].

3. Methodology and scope

In this section, we describe the Jazz Ontology in accordance with the MIRO Guidelines for Ontology Reporting [61]. We address the compulsory sections of the Guidelines keeping their numbering (such as A.1: Ontology owner or E.5: Entity naming convention), and, where relevant, optional descriptions (e.g., D.1: Knowledge acquisition method). Please refer to the MIRO Guidelines for the list of required and optional descriptions.²³

The Jazz Ontology (A.1), owned and developed by the Dig That Lick consortium²⁴(A.2, C.2), is licensed under CC BY terms, which

allow anyone to adapt and build upon it as long as they credit its creators (A.3). The ontology can be accessed at the permanent URL <https://w3id.org/JazzOntology/> (A.4), and it is represented in OWL (E.1). The ontology is versioned and issues are tracked on GitHub: <https://github.com/ppquadrat/JazzOntology> (A.5, C.3). All documentation, semantic model diagrams and RDF datasets based on the Jazz Ontology can be found in the Open Science Framework repository associated with Dig That Lick.²⁵

The semantic model and the ontologies presented in this paper were developed to enable systematic study of jazz, in particular queries across large, heterogeneous metadata repositories; to support metadata correction and disambiguation; to track workflows and provenance in manual and automatic content metadata creation; to support linking audio and other media to clean metadata (B.1). The main aim of the Jazz Ontology is to provide interoperability between ontologies and datasets. It was not conceptualised as an explicit knowledge representation model. Related work is presented in Section 2 (B.2). The target audience are jazz researchers and enthusiasts, libraries, archives, and jazz discographers (B.3).

In developing our ontology, we broadly followed the METHONTOLOGY methodological framework [62] that identifies six phases: 1. specification; 2. knowledge acquisition; 3. conceptualisation of an informal model (e.g., formalisation of the ontology in OWL); 4. integration of existing ontologies; 5. implementation of the ontology; and 6. evaluation.

No plan has been made to develop the ontology further beyond the lifetime of Dig That Lick, however its publication and documentation allows interested parties to take on further development, while further projects on related topics are planned by consortium partners (F.1). Minor changes such as qualifying a property or adding an attribute would amount to a new subversion; more substantial additions (e.g., a new class) or deletions require a new version (F.2, F.3). Versioning and discussion can take place on GitHub.

3.1. Specification (C.1)

For the aims of the Dig That Lick project we were broadly interested in questions such as:

- When, where and by whom was a given lick/pattern played?
- Were licks based on a given pattern popular at a particular time and place?
- If two musicians played the same lick, could they have influenced each other? Have they played together, recorded together, or toured together?
- Does a given lick/pattern appear more often during certain stages of a musician’s career?

Beyond these research-specific goals, we also aimed to be able to answer general questions about discography and sessionography, as well as relationships between the artists involved. These included:

- Where and when were the tracks on this CD recorded?
- What is the band line-up for the given performance? Who played which instruments?
- Which bands have played/recorded a given tune?

The full list of competency questions is given in Section S1 of the Supplement.

The model should also account for the heterogeneity of the resources, varied data quality, and possible uncertainties in the data. Alongside conventional provenance, the origin of the annotations is also important in musicological research. The above use cases were expressed in the following formal requirements (FR):

²² <http://josebowen.com/body-and-soul/>.

²³ <https://link.springer.com/article/10.1186/s13326-017-0172-7>.

²⁴ contact: Prof. Simon Dixon, s.e.dixon@qmul.ac.uk.

²⁵ <https://osf.io/rqk7z/>.

- FR1** Represent discographic concepts such as Track, Release, Album, Label.
- FR2** Represent sessionographic information: Session with attributes for Date, Place, Band, Band Lineup, Musical Instruments; Tunes played in the Session.
- FR3** Represent musician relationships, such as pairs of musicians who played together, toured together, or where one was band leader of the other.
- FR4** Represent jazz performance segmentation, in particular, the Solo, as well as the concept of the Lick.
- FR5** Represent provenance of the data, in particular the origin of annotations, and the workflow for automatically created data.

The entities of our semantic model are defined in Section S2 of the Supplement. For a detailed semantic model description see Section 4.

3.2. Knowledge acquisition (D.1)

Knowledge acquisition was conducted by means of literature reviews and focus groups with jazz experts. Literature reviews were compiled by the project partners to scope the overall domain of jazz with the focus on Dig That Lick's objectives [63–68], in particular, to understand the perceptual process and the practicalities of improvisation in jazz [69–72], lick creation and borrowing, stylistic influence [1,17,73,74], and the discographic and the sessionographic documentation of jazz.²⁶ Additionally, focus groups with jazz experts were conducted at the initial stage to formulate ontology specifications (Section 3.1) [75,76]. The main themes that emerged from the initial stage of knowledge acquisition were the importance of sessions and sessionography, the prominence of band leaders, the fluidity of band lineups, the prevalence of multi-instrumentalists among jazz musicians. At more advanced stages of the research, focus groups with jazz experts were used to confirm the broader concepts (Section S2 of the Supplement), to discuss, test and improve the models illustrated by the entity-relationship diagrams presented in this paper (Section 4) to ensure the correct modelling of the datasets metadata (Sections 5.1 and 5.2), and to validate data inference, merging (Section 5.4) and enrichment (Section 5.6).

3.3. Ontology content

The integration of relevant models listed in Section 2 is achieved through re-use or subclassing. We directly reuse entities from relevant external ontologies, which makes the Jazz Ontology dependent on them and might require remodelling if any of the incorporated ontologies change [77]. For musical entities, Music Ontology classes are re-used or, where further constraints are present, are expressed as subclasses of Music Ontology classes (E.8). This approach ensures the compliance with the FRBR general model, since it is the basis for the Music Ontology. A shortcut was introduced between Performance and Signal, omitting Sound and Recording, permitting appropriately rich data to be captured using fewer triples optionally. The details of the recording process are less important in jazz than possibly in other genres. The events and agents layers differ significantly from the Music Ontology – see Section 4.1.

The Event²⁷ and Timeline²⁸ ontologies were re-used where possible. One notable exception includes subclassing `timeline:Instant` and `timeline:Interval` to express approximate date spans – see Section 4.3.

The Ordered List Ontology²⁹ was used to retain the order of tunes within a medley – see Section 4.2.

Relationships were added to express specifics of jazz sessionography, e.g., a band having a leader. In particular, a variety of relationships between a performance and a tune were reflected in properties like `has_intro`, `variations_of`, `theme_of` and `changes_of` (E.4), see Section 4.2. For music artist relationships, properties from the LinkedJazz model are re-used, see Section 5.6).

Camel case is used for class names and lower case for properties, with the exception of imported ontologies (e.g. LinkedJazz uses camelCase for properties) (E.5). Entity identification is only based on existing identifiers where these are unambiguously unique and are expected to remain unique in future; otherwise new unique identifiers are created (E.6). For example, identifiers for Sessions and Musicians from the Jazz Discography (see Section 5.2) are re-used; while musician names are not unambiguous and are not used for identification: a name can have different spellings or refer to more than one person. Musicians and Bands must have a name; Tunes and Tracks must have a title; Instruments must have a label (E.7).

3.4. Evaluation (A.6)

Our approach to evaluating the Jazz Ontology is based on testing the ontology in practice through populating (Section 5) and merging (Section 5.4) heterogeneous datasets based on the ontology (G.3), and then releasing online tools that query the datasets for active use by the jazz community [20] (G.5, see Fig. 1 in the Supplement). Additionally, SPARQL queries were implemented (Section S3 of the Supplement) based on the competency questions defined in Section S1 of the Supplement – these can be run when the ontology is modified to ensure consistency (G.1). See Section 6 for more details.

4. Semantic model

This section describes the semantic model developed primarily for the representation live jazz performances and liking jazz related metadata. We begin with the general model that fulfils the formal requirements one to three (Section 3.1). Model extensions for requirement four (segmentation and licks) and for requirement five (provenance and workflow) are also presented below.

4.1. Basic model

Fig. 4 shows the basic model that describes and relates discographic and sessionographic information in jazz. It is based primarily on the FRBR model and a large subset of the Music Ontology. Alignments with the MusicBrainz ontology are also provided for expressing information about discographic entities. These are shown in parenthesis in Fig. 4. This aims to achieve maximum interoperability, retaining the generality of the Music Ontology, at the same time allowing a direct mapping for the jazz-related data crowd-sourced and curated by MusicBrainz. We keep the same colour and shape coding for FRBR concept groups throughout the paper, to illustrate how FRBR layers are implemented in our

²⁶ A dedicated bibliography can be found in the Dig That Lick project deliverable “Licks in the Literature of Jazz Research” <http://dig-that-lick.eecs.qmul.ac.uk/Docs/DTL--Lit%20Review.docx>.

²⁷ <http://motools.sourceforge.net/event/event.html>.

²⁸ <http://motools.sourceforge.net/timeline/timeline.html>.

²⁹ <http://smiy.sourceforge.net/olo/spec/orderedlistontology.html>.

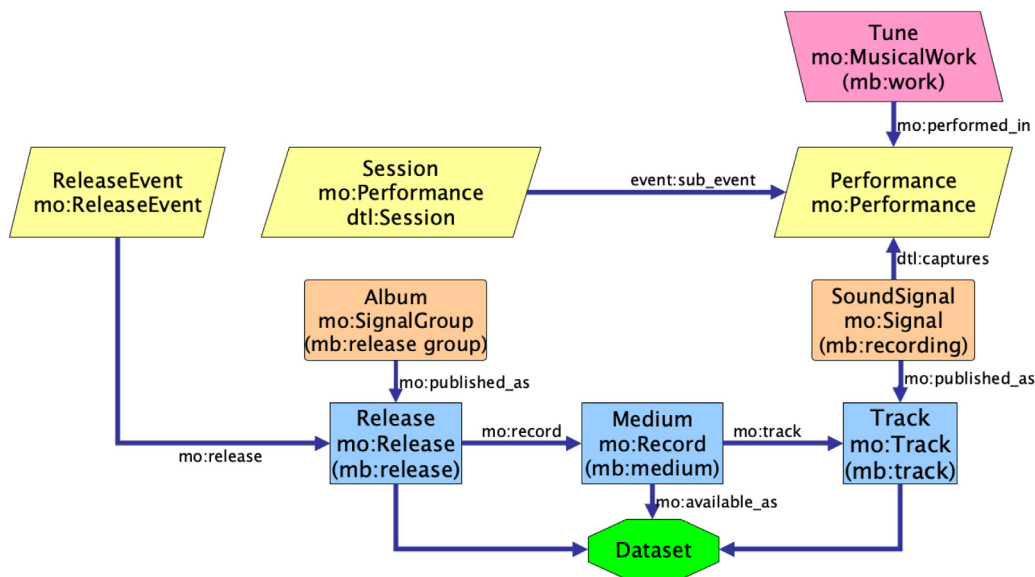


Fig. 4. The basic semantic model for discographic and sessionographic information in jazz. The layered diagram with the form/colour coding shows how the model implements the FRBR semantic model (compare with Fig. 1) and the Music Ontology (compare with Fig. 2). The shapes represent classes with their semantic concept in jazz as well as Music Ontology (mo) and Dig That Lick (dtl) classes they were implemented as. MusicBrainz (mb) semantic concepts are given in brackets where they apply. For the complete diagram see Fig. 1 in Supplement.

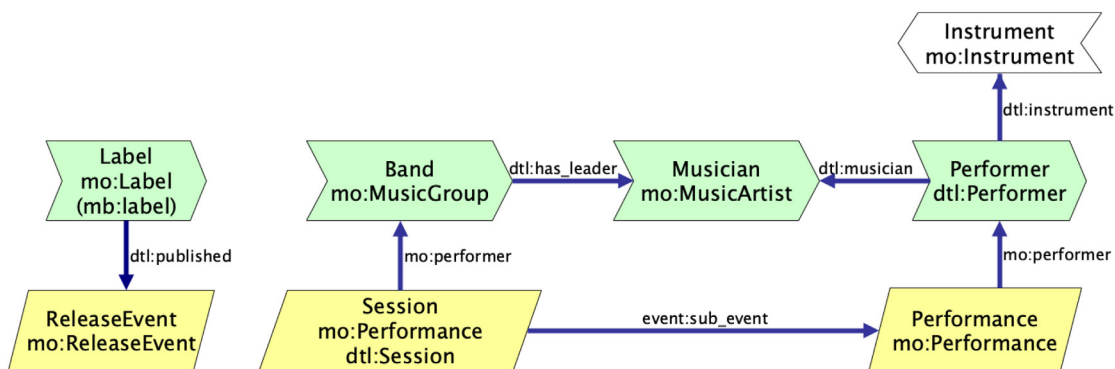


Fig. 5. Relationships between prominent events (yellow), agents (green), and objects (white) in the Jazz Ontology. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

ontology and how our classes inherit from the Music Ontology. See Section 2 for the explanation of FRBR groups, and Fig. 1 for shape and colour coding. For the complete diagram see Fig. 1 in the Supplement.

We introduced a shortcut between the Music Ontology classes Performance and Signal, bypassing the abstract Sound concept (mo:Sound) and the recording event (mo:Recording). This is useful for simplifying the description of historical recordings where information about recordings can no longer be obtained. The shortcut is justified conceptually for contexts in which the recording process does not require any additional description. In fact, the recording process is more straightforward in jazz, where the focus is on live performance, than in other genres of Western music: whereas for popular music the producer plays an important role and the recording equipment and setup can be captured, for jazz recordings this information is usually not available. If a future ontology user decides to add information about recordings using the Music Ontology, rules can be defined to infer the relation between mo:Signal and mo:Performance, ensuring compatibility with software using our ontology.

In Fig. 4, Session is defined as an event consisting of sub-events which are Performances of a single song/piece/composition. Tune is the basis of a jazz performance, which provides a melodic

theme and/or a chord progression for improvisation. SoundSignal is the sound of a song/composition captured in the audio signal. It is realised as mo:Signal, but it also relates to mo:Sound from a conceptual perspective. See Section S2 in the Supplement for more detailed descriptions of entities in the Jazz ontology.

Fig. 5 illustrates some significant differences between the Music Ontology and our model. In jazz, musicians often play more than one instrument, sometimes during one performance, sometimes between performances. They may also pick up new instruments during their career. To reflect this, we introduced a new Performer class which denotes the relationship between a Performance and a Musician. This fills a gap in the Music Ontology which does not include a generic Performer class reflecting this prominent concept in jazz music. A Performer is best conceptualised as a triple of the form (Performance, Musician, Instrument); there can be more than one Performer relating a Performance to a given Musician, if that Musician plays more than one Instrument in that Performance.

Bands in jazz are a much looser concept than, for example, in Western pop music. Their lineups can change from Session to Session; the constant of the band is usually its leader. Often the band is named after the leader – jazz databases often exploit this notion in their models too (see Section 5.2). In other cases, bands

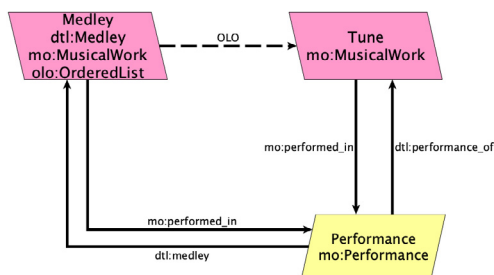


Fig. 6. Medley is represented by means of the Ordered List Ontology (OLO) with Tunes in its slots. Its implementation is shown as a dashed line.

do have names which are distinct from the leader’s name – we therefore decided to model bands explicitly as mo:MusicGroup connected to its leader (a MusicArtist) using the has_leader property. In some circumstances however, particularly in jam sessions, a band may have no leader or may have more than one leader. This is permitted by the ontology as no strong commitments are made at the logical level (e.g. no cardinality constraints or complex class descriptions).

Another important notion in jazz is the relationship between the Band and its lineup. The lineup changes frequently from session to session. This may be observed even between tracks; in free text annotations it is often represented through notes like: “musician A on tracks 2 and 5” or “for this session musician B departed and musicians C and D joined”. The way to disentangle this maze of often inconsistent annotations unambiguously is to relate Performers to single Performances and not to Bands.

It must be noted that jazz performances are not always released or even recorded (therefore the properties captures and published_as are optional). Also many jazz performances are jam sessions, where musicians play together in ad-hoc combinations without a designated band, so a band is not necessarily present for each session. Yet, in recorded and released sessions, a band is usually named, sometimes just as a list of performing musicians, following music industry conventions which require a single name for the performing artist.

4.2. Medleys

Since jazz is based strongly on improvisation, modifying and recombining existing tunes is a widespread practice, and as a result, medleys are frequent in our datasets. Even though performance of medleys can be represented implicitly using the event decomposition model, they are not directly modelled in the Music Ontology.

A Medley is typically a set of tunes strung into one performance, without breaks between them. Often various musical devices are used to justify the transitions from one tune to the next. In the overwhelming majority of cases, the combination of the tunes is linear, e.g., they follow one after another. We therefore turned to the Ordered List Ontology to model the order of the played tunes.³⁰ The complete medley is modelled as an OrderedList and the tunes within it are the objects in its slots. The Performance is then related to both the list (the medley tune) and to each of the tunes (Fig. 6).

Alongside medleys, there are many other ways how existing tunes can be recombined, transformed, or built upon in jazz. We therefore introduced further properties relating Performance and Tune, such as has_intro, changes_of, theme_of, variations_on, citation_of, all of which we encountered in our datasets.

"ca. September 1924"	"between 27. 2. and 17. 3. 1941"	"end 1946"
"17.- 22.1.1924"	"(first half of) June 1952"	"poss. October 1950"
"early December 1924"	"08. or 12.03.1946"	"spring & summer 1953"
"July 28/August 1, 1924"	"January-February 1946"	"January 29-31 & February 1, 1992"
"about mid November, 1928"	"late summer 1950"	"March 13, 2003-October 25, 2004"
"ca. February 9-14, 1925"	"prob. June 1946"	"late 1960s - early 1970s"

Fig. 7. Examples of date annotations from our datasets.

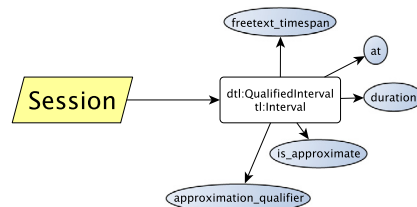


Fig. 8. Approximate date spans are implemented as QualifiedInstant and QualifiedInterval inheriting from TimeInterval and TimeInterval from the Timeline ontology.

4.3. Dates

For a systematic study of jazz, session dates are crucial, yet they are not always known. In many cases only approximate dates are given. Dates are often annotated as text, in a variety of formats which are not always consistent (see Fig. 7). For example, a date string *ca. mid to late summer 56* implies that the event took place around the second and last thirds of summer 1956. The century in case of jazz is unambiguous since jazz is around 100 years old. The approximation qualifier *ca.* can be interpreted as *around*, meaning that the event might have happened slightly before or after the given time constraints. Yet quantitatively *ca.* is much less clear cut than, e.g., *late* or *beginning*. *Ca.* is also different from *probably*, which indicates general uncertainty, without affecting the given time constraints.

To account for these ambiguities we introduce two new classes building upon Instant and Interval from the Timeline Ontology: QualifiedDateInstant and QualifiedDateInterval. They inherit the original attributes from Instant (at) and Interval (at and duration); additionally the date is classified as approximate or exact, and the original string is supplied for later processing (Fig. 8). The above example can be represented as follows:

```
event:time [ a tl:Interval,
              dtl:QualifiedDateInterval ;
              tl:at "1956-07-02"~xsd:date ;
              tl:duration "61 days, 0:00:00" ;
              dtl:approximation_qualifier "ca" ;
              tl:timeline tl:universaltimeline ;
              dtl:freetext_timespan "ca. \ mid to late summer
              56" ;
              dtl:is_approximate "1" ] .
```

4.4. Solos and licks

Fig. 9 lays out the model for music segmentation in audio and symbolic representations. The left column corresponds to the complete performance, the middle column to the solo and the right column to the lick segment. Other types of segments can be represented analogously. SoloPerformance and LickPerformance are placed on the Performance Timeline, with timestamps for the beginning and the end of the segment or its duration (see Section S2 in Supplement for class definitions).

The upper row represents the events, extending the basic model diagram to the right (see Fig. 4, Performance is a sub_event

³⁰ <http://smiy.sourceforge.net/olo/spec/orderedListontology.html>.

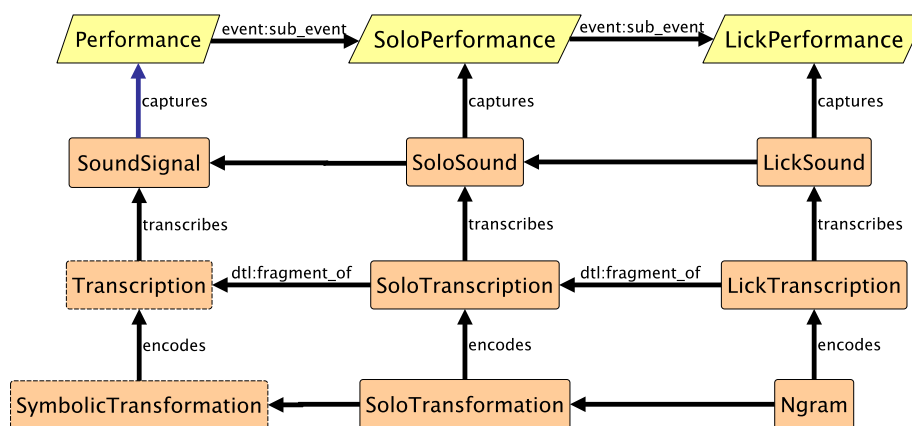


Fig. 9. Solos, licks, their transcriptions, and symbolic representations.

of Session). The second row represents our concept of SoundSignal. The third row is the transcription of the SoundSignal, i.e. a symbolic representation of the signal such a musical score. Transcription can be either manual or automatic. There may be more than one transcription, in fact, in case of automatic processes, there will probably be a large number of transcriptions. The transcription will be in any format produced by the transcriber. Finally, the lower row represents a symbolic transformation of the transcription to the desired format: it can be a score; a pitch or a scale degree representation; an interval representation like “2,1,2,-3,-4,2”, indicating the number of semitones between played pitches; onset time list, or any other form of symbolic representation. These representations are often generated with the view of further processing, such as pattern matching. There can be symbolic transformations of various types for a given transcription. It should be noted that the lowest layer corresponds to technical tasks in the musicological analysis of jazz, rather than representing entities that are important in the domain of jazz specifically.

4.5. Provenance and workflow in jazz analysis

This section describes the modelling of musicological analysis of jazz, in particular using automated metadata generation. This part of the model is less specific to jazz and can be applied in a similar way to modelling analysis tasks in other musical genres and traditions.

Automatic metadata generation leads to a multiplicity of metadata versions of varying quality. For instance, when an algorithm for automatic melody extraction is tested, evaluated, and improved, followed by further testing and evaluation, a melodic transcription is generated at every iteration. To keep track of the versions and their origins, provenance and workflow capturing are essential.

The Provenance Ontology (PROV-O)³¹ lays out a general framework for describing provenance. Its three main classes are Entity, Activity, and Agent. In the case of metadata generation, a workflow is an Activity which generates entities such as a Transcription for a Sound or a Match for a pair of Licks. In the case of manual transcription, the transcriber is the Agent associated with the TranscriptionWorkflow; for automatically generated transcriptions, the workflow is associated with the algorithm, code, or application which was executed.

Our datasets in the context of automatic metadata creation can be understood as a layered digital library [43] that comprises an audio collections layer, a metadata layer, and a computational

analysis layer which is described by workflows. The outcomes produced by workflows constitute the feature metadata layer – the input for the exploratory analysis, which can be carried out by other workflows or by human researchers. An example of the application of this concept to a digital library of music is described by [78].

Fig. 10 outlines the workflow capturing model for Dig That Lick. Transcriptions are generated by the TranscriptionWorkflow, which typically include a reference to the algorithm used, the version of the code, a link to the code, and all the parameters used to run the code. After a transcription has been generated, transformed to the required format and n-grams representing sequences of musical symbols or entities are collected, the PatternSimilarityWorkflow is employed to find matching patterns in other performances. A PatternSimilarityWorkflow documents the similarity measure (e.g., similarity function and threshold) as well as the code implementing the matching with its version and parameter settings. Examples of further automatic metadata generation agents that may be represented by the ontology include SoloFinder for automatic solo detection, and InstrumentRecogniser for the solo and lick segments. Any automatic content analysis process can be represented similarly.

Finally, the whole process of symbolic representation generation, from transcriptions to n-grams, together with the generated data and the pattern matching could be summed up as Lick-SimilarityWorkflow and managed as a single object. This is of particular use for jazz data researchers who are less interested in the technical details of lick matching and prefer to focus on further analysis tasks for which lick matching is just one of the steps. Such an object may provide an API enabling the researcher to set important parameters such as similarity threshold, and using default values for all other parameters, without having to set up each workflow separately. At the same time, when inconsistencies arise, e.g., the SPARQL query does not find that one important result it found yesterday or a year ago, the documentation of the workflow allows full accountability about the changes undertaken on the automatic algorithms' side, and, if necessary, reproducibility of previous results. For a more detailed modelling of automatic audio analysis workflows see [43].

5. Ontology population: RDF dataset content, integration and enrichment

In this section we describe how we collected audio datasets (Jazz Encyclopedia, Illinois, Porkpie); how they were associated with sessionographic information; how they were recombined for the purposes of coverage and representation (100 Years of Jazz,

³¹ <https://www.w3.org/TR/prov-o/>.

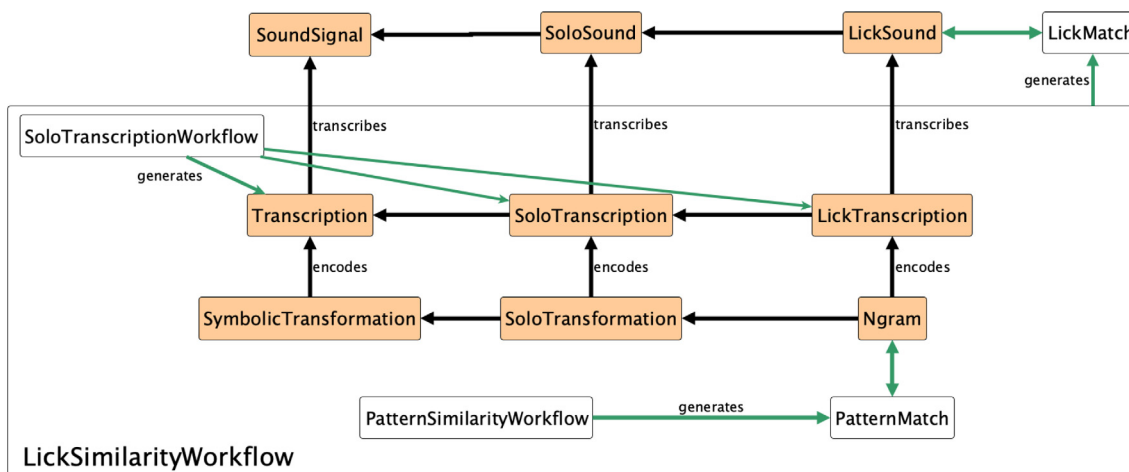


Fig. 10. Workflows for automatic metadata generation and analysis.

DTL1000); and how our RDF datasets (JE, ILL, 100 Years of Jazz, DTL1000) were constructed.

In order to test the ontology and its support for semantic integration and interoperability, we assembled a large corpus of jazz recordings. The data comprises over 50K tracks, aiming to ensure that the collection was broadly representative, without obvious gaps or omissions. The collections that contributed to our audio corpus were:

- the Jazz Encyclopedia – a collection of 500 CDs documenting jazz from its beginnings to the 1950s.
- the Illinois collection – jazz CDs from the library of the University of Illinois Urbana-Champaign.
- the Porkpie collection – a set of audio CDs used in the JDISC project (but not directly related to the metadata collected in the JDISC project).

The Illinois and Porkpie collections contained only basic discographic information attached to the CDs: album title, (album) artist name, track titles, track numbers, and (for Illinois) label and release number. For sessionography we turned to the most authoritative jazz metadata database used by jazz researchers – the Jazz Discography (see Section 5.2). The metadata we collected and created can be found on the ‘Dig That Lick’³² ‘Metadata’ subproject³³ on the Open Science framework.

5.1. The Jazz Encyclopedia

“The Encyclopedia of Jazz: The World’s Greatest Jazz Collection”,³⁴ accompanied by extensive annotations, was released by Membran, a German music label group that specialises in releasing large CD sets. The collection is probably among the largest ever commercially released compilations. It consists of five parts: classic jazz, swing time, big bands, bebop and modern jazz, each comprising 100 compact discs. Altogether the dataset consists of 9,065 tracks, recordings of 6,255 distinct tunes performed by 898 bands between 1917 and 1958. A CD usually presents one band, or in some rare cases several bands from the same time, area or style. Some bands have more than one CD dedicated to them.

The collection is accompanied by a metadata file in CSV format. It lists CDs with their order number and title, and for each

track it contains the following information: title(s), composer(s), band name, date string, area string, and a list of musicians with their corresponding instruments. Although the data shows evidence of considerable effort and careful curation, within the fields of the top-level structure there is a often unstructured text which is non-trivial to parse. In addition, the file required cleaning: in some cases data appeared in wrong fields, and a significant number of musician and instrument lists were truncated. We cleaned the data and reconstructed the truncated strings with the help of the printed booklets.³⁵

Parsing track titles presented an interesting problem. Normally, a track title contains the name(s) of the tune(s) played in a performance. In some cases, e.g., when the track is a medley, more than one tune title is provided. These cases were mostly structured consistently in the CSV fields. Yet there were more complex cases, such as where a performance had an introduction, or was based on a theme from a different tune, and that title was given in brackets. Other information was also given in brackets: an alternative title of the same tune, a composer of a classical piece, additional information such as take or part number. Finally, in some cases brackets were part of the original tune title. Our parser attempts to disambiguate these cases, when sufficient information is provided.

Instrument abbreviations provided in the CSV file, although largely consistent, did not match those commonly used in jazz documentation. We provide a mapping to standard instrument names where possible – they are also included as an attribute to the instruments in the RDF repository alongside the original description. There are many exotic instruments in this dataset, from washboard to piccolo flute. Additionally descriptions of other sound events are included (e.g., ‘not audible’ or ‘occasional shouting’) which makes it difficult to parse the instrument data. Performers or their instrument metadata may include a question mark. To capture this type of uncertainty, we implemented a confidence attribute for the performer class. We stopped short of devising a thesaurus of musical instruments, given the time constraints of the project. See [37,79] for knowledge representation issues in musical instrument ontology design and automatic instrument classification methods.

Of all metadata, dates required the most effort to clean and process (see Section 4.3 for examples of provided date strings). We developed a parser for approximate datespans capable of processing the dates in our datasets. Altogether we have been

³² <https://osf.io/buxvr/>.

³³ <https://osf.io/rqk7z/>.

³⁴ MusicBrainz entry: <https://musicbrainz.org/series/de056225-6766-4e7d-95e9-7b032b8b2b79>.

³⁵ The cleaned version of the file can be downloaded from the Open Science Framework project: <https://osf.io/6jes7/>.

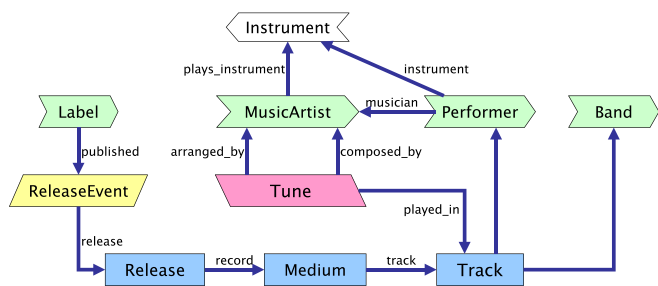


Fig. 11. Semantic model of the metadata provided with the Jazz Encyclopedia.

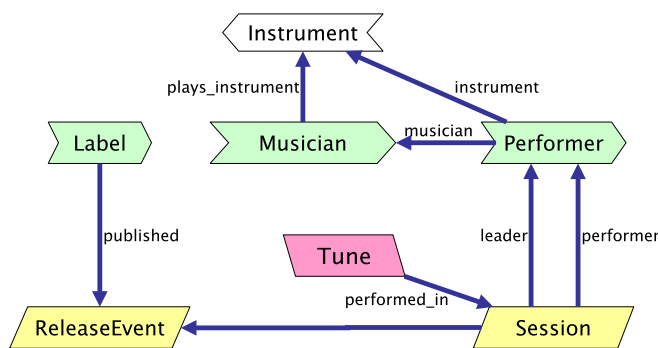


Fig. 12. Semantic model of sessionographies in the Jazz Discography.

able to process about 20,000 approximate dates with our parser. The code is available on GitHub.³⁶ Approximate dates are a frequent feature in a number of domains outside music, e. g., history, archaeology and cultural heritage more generally. Also, in many cases, user generated metadata results in approximate or ambiguous dates. We anticipate that our tool will be useful in those domains.

Overall, our Jazz Encyclopedia RDF repository³⁷ contains high quality, detailed data and is one of the very few machine-readable jazz metadata repositories of this size and quality.

5.2. The Jazz Discography

The Jazz Discography³⁸ (JD) is the largest resource of information on jazz sessionography. It is available as a printed book and a CD-Rom, yet the most recent version is accessible as an online subscription. This resource is considered by jazz researchers and libraries to be the most complete and reliable source of sessionographic data. It covers all styles and epochs of jazz. As of October 2019 the online database included over 49K leaders, over 242K recording sessions, over 1.3M musician entries, over 1.5M tune entries and over 420K record releases.³⁹

The Jazz Discography is organised by Leaders and the concept of Band is otherwise absent (Fig. 12). Where a band name does not contain the leader's name, it is stored in the leader's 'first name' field. Otherwise band names are omitted. We introduced both concepts, bands (as a class) and leaders (as a property). Information about sessions for each leader is presented as human-readable semi-structured text. For example, a list of musicians is given for the first session, and for the following sessions remarks indicate which musicians departed and which

new musicians joined. There are further remarks for single tune performances within sessions, indicating, e. g., that a given musician only plays on track one. The necessity of such remarks clearly shows that the model adapted by the Jazz Discography is not ideal and needs refinement. We therefore introduced a concept of Performance which captures what would become a track on a CD. Each Performance has its own list of performers, thus avoiding the need for comments and adjustments of lineup lists (see Section 4.1). Performance also allowed us to link sessionographies to discographies, connecting Performances and Tracks via SoundSignal.

Dates, places and venues of sessions in the Jazz Discography are given in one string. It was not always possible to parse these strings properly due to inconsistencies of syntax. Where separation of place and date was possible, we used our dateParser to process dates, which successfully parsed a large majority of dates.

5.3. The 100 years of Jazz dataset

The Jazz Encyclopedia (Section 5.1) offered excellent and reliable metadata and good coverage of jazz styles and epochs from the beginnings of jazz up to the 1950s. To complement this audio dataset to cover the whole history of jazz, we chose audio tracks from our Illinois audio collection which we could match with sessionographic metadata from the Jazz Discography (Section 5.2). The coverage of matching metadata between the Jazz Discography metadata and our audio CD corpus was surprisingly low (matching via label names resulted in 34% coverage). 3,368 tracks from the Illinois audio were chosen covering later decades of jazz starting from 1960. These tracks comprised the ILL dataset. The union of the two collections, the JE and the ILL datasets, consists of 12,433 tracks with audio recordings and corresponding bibliographic and sessionographic metadata, representing the 100 years of jazz history – we called this corpus the “100 Years of Jazz” dataset.

For this audio dataset, we built two RDF repositories, one for Jazz Encyclopedia tracks and one for Illinois tracks, resulting in JE and ILL RDF datasets respectively. While both sources provided different sets of metadata (compare Figs. 11 and 12), each with its own inconsistencies, we were able to express the metadata and their relationships in terms of our semantic model in both cases, thus demonstrating the generality of our model. The two RDF datasets were then merged based on name equivalence (see Section 5.4), resulting in the 100 Years of Jazz RDF dataset.

5.4. Merging and reconciliation

We performed the merging of two of our repositories: the Jazz Encyclopedia (JE) and the Illinois subset with the Jazz Discography metadata (ILL). This process is a proof of concept for further merges of jazz metadata repositories using our ontology.

Because the two datasets did not overlap in time, no disambiguation of event objects (Sessions, Performances) was required. The decision was taken by jazz researchers in the consortium that in the case of Musicians and Bands equivalence by name is a good approximation at this stage (this approach to disambiguation of musicians and bands had been adopted previously within the datasets). Additionally, for Tunes and Instruments, equivalence by title has been assumed. A straightforward implementation enabled a merged dataset out of the box which successfully drives pattern and similarity search interfaces.

In a more general case where event objects have to be disambiguated and where equivalence by name and by label cannot be assumed, the process will be more complex, involving several iterative stages. If audio is available, audio fingerprints provide a

³⁶ <https://github.com/ppquadrat/DigThatLick/blob/master/dateParser.py>.

³⁷ <https://osf.io/8su3a/>.

³⁸ <https://www.lordisco.com>.

³⁹ <https://www.lordisco.com/tjdonline.html>, last accessed 6/6/2020.

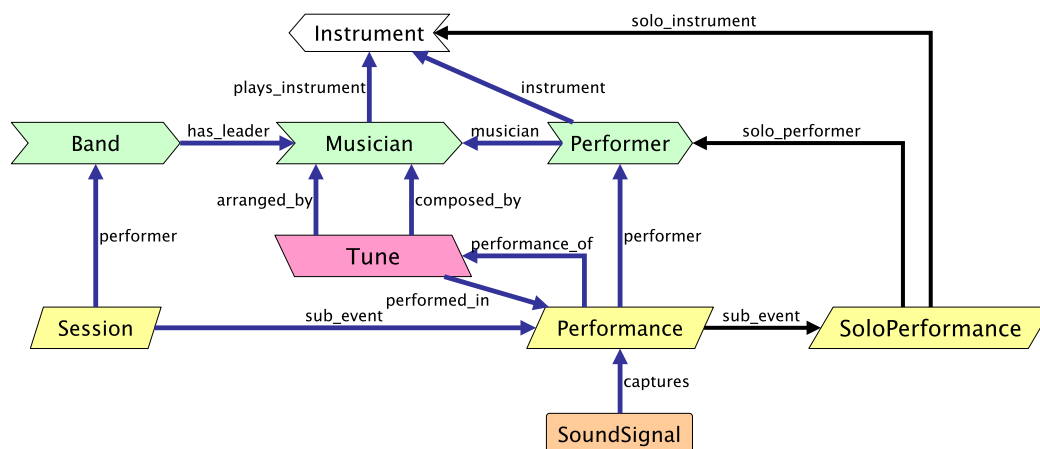


Fig. 13. This part of the ontology is used for the Dig That Lick online applications that query the DTL1000 dataset.

good starting point for finding duplicate Signals, which in turn point to equivalent Performances (one-to-one relationship). An other starting point for finding equivalent objects could be attribute comparison for Sessions: if two Session objects share the date, the place and the Band, they are referring to the same session. Further, objects related to merged entities could be examined: if two Sessions contain the same Performance, they should be representing the same session; if two Bands play the same Session, they are in fact the same band.

5.5. DTL1000 dataset

The DTL1000 audio dataset is a 1,060-track subset of the 100 Years of Jazz dataset, which is balanced in regard to the number of tracks per decade of jazz history and covers a range of different jazz styles. Like the 100 Years of Jazz dataset, it includes audio tracks connected to the respective discographic and sessionographic metadata. Additionally, all tracks were segmented and their style was annotated.

The 1,060 tracks were manually segmented into parts such as ‘theme’, ‘solo’, ‘intro’ and ‘fours’. Solo parts were further annotated with the solo instrument. The segmentation was conducted by one expert (OV). Additionally, two experts (MP and KF) annotated the jazz style of the track using an extension of the style classification system used for the Weimar Jazz Database (TRADITIONAL, SWING, BEBOP, COOL, HARDBOP, POSTBOP, FREE, FUSION plus CONTEMPORARY, LATIN and OTHER) [14, 34–37]. For efficiency reasons, each annotator annotated only one half of the tracks, while reaching agreement for some occasional borderline cases.

Further, melodic lines were automatically extracted for all 1,705 monophonic solos using the novel deep learning approach developed by a Dig That Lick project partner [18]. These included instruments such as trumpet, trombone, saxophones, clarinet, violin, cornet, flute. Melody extraction and pattern matching for polyphonic solos, such as by piano or guitar, are much harder tasks and were not addressed. For transcribed solos, note patterns reflecting licks were collected, and lick matches documented.

We updated our RDF datasets with these manual annotations (Fig. 13). Style labels were attached as an attribute to the SoundSignal class. SoloPerformances and their Instruments were added in accordance with our semantic model (see Section 4.4). Solo Performers were automatically inferred. Transcriptions and licks were processed in a separate PostgreSQL database which provided a very efficient implementation of pattern matching; therefore, there was no need to represent them in RDF, particularly given that the number of n-grams was three orders of magnitude larger than the number of solos.

Instrument could always be assigned to the SoloPerformance object, based on manual annotations supplied with the solo segmentation. Yet, linking the solo to the performer was only possible if just one performer played the annotated instrument in the given performance. For example, if the solo instrument was annotated as trumpet, but there are five trumpeters in the lineup, we cannot infer unambiguously who of them played the given solo. For such cases, we introduced a property `possible_solo_performer`. Disambiguating these links requires detailed domain knowledge. Sometimes jazz aficionados can recognise a performer’s style; alternatively information on soloists and the order of solos on a track might be available in jazz literature or other sources. The Jazz Encyclopedia’s printed booklets provide this information for a subset of the tracks (not in electronic form); similarly, the Jazz Discography database sometimes provides this information. For other tracks, from the past and from less known soloists, this knowledge has been lost. Potentially, automatic methods of soloist recognition could help to close this gap in the future. In particular, information on the performer’s lick preferences could be a good indicator of their unique style.

In a different type of problem case, the annotated solo instrument was not found in the lineup. This was either due to errors of manual annotation (e.g., where instruments are very similar, such as cornet annotated as trumpet) or due to errors in metadata parsing and processing particularly for the Illinois/JD part. Most of these cases have been resolved manually based on the consortium’s jazz expertise.

The resulting repository is used for the “Pattern Search” and “Similarity Search” applications⁴⁰ created in our project, which allow to specify a lick and to search the DTL1000 dataset for the same or similar licks. Metadata is used as prefilter and also displayed with the search results. Fig. 13 shows the subset of the ontology used for our interface.

5.6. Enrichment

While most of the metadata in our RDF datasets has been collected from other sources, we have also enriched these data with new information during our project. DTL1000 was enriched with manual annotations, in particular, with segmentation information, solo instruments, and style annotations (see Section 5.5). Based on manual annotations, solo performers were inferred. For larger datasets, manual annotation is not sustainable. We have introduced two additional ways to enrich data automatically.

⁴⁰ https://dig-that-lick.hfm-weimar.de/similarity_search/.

Table 1

Statistics for our repositories: Jazz Encyclopedia (JE), the subset of the Illinois dataset that we could link to the Jazz Discography metadata (ILL), 100 Years of Jazz dataset (merging of JE and ILL), manually annotated DTL1000 dataset.

	JE	ILL	100 Years	DTL1000
Triples	1,039,091	165,549	1,203,928	429,693
Performances	9,065	3,359	12,424	1060
Sessions	2,718	687	3,405	745
Releases	5	549	554	343
Tunes	6,225	3,060	9,220	1,028
Bands	897	377	1,263	492
Musicians	3,690	2,121	5,645	2,666
Instruments	196	240	393	234

First, we linked our Musicians to existing Linked Open Data entries for them. We relied on the collection created by the LinkedJazz project⁴¹ (see Section 2) which scraped the most informative parts of the Web in search of entries for jazz musicians, in particular, DBpedia,⁴² the Library of Congress authority files⁴³ and the Virtual International Authority File.⁴⁴ Authority files provide variants of the person's name spellings and variants across languages, alongside further curated information; therefore, linking to authority files facilitates disambiguation as well as further identification of entities referring to the same person. A link to DBpedia adds a human usability aspect, allowing to display free text information such as a Wikipedia article as well as photos of the musician and further links, each time a given musician is retrieved.

Second, we used inference to add relationships between jazz musicians which did not exist in the original data. For each Session we collected all the musicians who played in it, alongside the band name and the leader. Based on the experience of the LinkedJazz project, we introduced the following relationships inferred from the existing Session and Performance information:

- `lj:bandMember` for each musician
- `lj:bandLeaderOf` between the leader and each musician

and further between each two musicians:

- `rel:knowsOf`
- `rel:hasMet`
- `mo:collaborated_with`
- `lj:inBandTogether`
- `lj:playedTogether`

These properties facilitate advanced reasoning about musicians' careers, relationships, and influence.

5.7. RDF dataset statistics

This section presents some descriptive statistics about our repositories. Table 1 outlines the overall number of entities in each dataset. Table 2 shows entities which possess important attributes, allowing for more informative queries. Finally, Table 3 provides the numbers specifically related to Solos – these were transcribed and are used for lick matching in our online application.

Table 2

Further statistics for our repositories.

	JE	ILL	100 Years	DTL1000
Sessions with date	2,716	671	3,387	744
Sessions with leader	2,148	554	2,709	628
Performances with musicians	9,064	3,359	12,423	1,034
Bands with leader	645	298	936	401

Table 3

Annotated solos in our RDF datasets. DTL1000 is a balanced subset of the 100 Years of Jazz dataset containing all the solos with the corresponding performances, therefore the numbers for the two datasets are the same. Manual segmentation was performed for all structural parts of the tracks in DTL1000. Yet only monophonic solos were transcribed and added to our datasets.

	JE	ILL	100 Years/DTL1000
Performances with at least one annotated solo	242	389	631
Sessions from which these performances originate	221	243	464
Bands that played these performances	175	159	332
Solos	783	943	1,726
Solos with solo performer	541	696	1,369
Solos with possible solo performers	212	132	341

6. Model evaluation

In the previous section, we have shown that the Jazz Ontology could be used to model different, heterogeneous metadata resources, making them interoperable, enabling dataset merging and enrichment. Next we turn to formal requirements (Section 3.1) to verify that they are fulfilled; and to competency questions (see Section S1 of the Supplement) to ensure that these can be answered successfully based on our datasets.

6.1. Formal requirements

Formal requirements describe what entities and relationships have to be represented by the ontology. The Jazz ontology incorporates discographic concepts such as Track, Release, Album, and Label (FR1), see Fig. 4 for details. All Jazz Ontology class definitions are listed in Section S2 of the Supplement. It also includes Sessions (FR2) which have attributes Date, including approximate dates (see Section 4.3), Area and Venue, and are connected to the Band that played in the given Session (Fig. 5). A Session is related to the Band lineup and musical instrument information via two further concepts: a Performance and a Performer, allowing for unambiguous representation of varying band lineups during one Session (FR2). A Performance is also linked to the Tune or a series of Tunes (Section 4.2) played in it (FR2). Relationships between Musicians `playedTogether` and `bandLeaderOf` have been precalculated for our public datasets⁴⁵ (FR3). Our ontology represents segmentation entities such as Solos and Licks (Fig. 9, FR4) as well as the workflow for automatically created metadata (Fig. 10, FR5), though licks and workflows were not implemented in our datasets.

For the competency questions formulated in Section S1 of the Supplement, we list SPARQL queries and their results on our datasets in Section S3 of the Supplement.

⁴¹ <https://linkedjazz.org>.

⁴² <https://wiki.dbpedia.org>.

⁴³ <http://id.loc.gov/authorities/names.html>.

⁴⁴ <https://viaf.org>.

⁴⁵ The code is available on GitHub: <https://github.com/ppquadrat/DigThatLick/blob/master/JEaddLJrelationships.py>.

Table 4
Ontology metrics.

Metric	Value
Class count	26
Object property count	29
Data property count	24
Individuals count	0
Axioms	197
Logical axiom count	117
Declaration axioms count	80
Subclass axiom count	17
Inverse object properties	1
Object property domain	26
Object property range	26
Data property domain	26
Data property range	21
Direct popularity	0
Inverse popularity:	
– Ontology direct imports	5
– Ontology indirect imports	5
– Classes imports	19
– DataType Properties imports	11
– Object Properties imports	11

6.2. Ontology metrics and formal validation

To formally assess the quality of the Jazz Ontology we follow the approach of [80], presenting domain coverage and popularity measures (Table 4). We also report further metrics calculated by the Protege ontology editor [81].

Based on the populated RDF repositories which cover a large and varied set of jazz performances (see Section 5.7), an average number of triples that describes a well-documented jazz performance is around 140.

The ontology editor Protégé (version 5.5.0) was used to check the syntax of the ontology. The logical consistency has been verified by running (through Protégé) three reasoners, HermiT (version 1.4.3.456) [82], Pellet (version 2.2.0) [83], and FaCT++ (version 1.6.5) [84]. No inconsistencies were found.

6.3. In-use validation

During the Dig That Lick project two online applications for investigating licks in jazz were created and released to the jazz community [85]. The Pattern Search⁴⁶ and the Similarity Search⁴⁷ interfaces (see Fig. 1 in the Supplement) utilise the SPARQL queries created to address competency questions, to allow pre-filtering of searches (e.g. limiting them to a particular period) and to display the metadata about the lick query results (e.g. who played the matching licks and when). The Timeline and Network views of the retrieval results give further insights into the presence and distribution of licks [20]. The interfaces were first evaluated by the jazz expert members of the consortium and then released to the public. In the first month after their release in November 2019 hundreds of searches were performed by users from around the world. Moreover, novel research was conducted by means of these applications [76,86–88]. This active and productive use of the interfaces by the jazz community demonstrates the need for and the value of the Jazz Ontology.

7. Conclusion

In this paper, we have presented an ontology that provides a semantic model of jazz, and assessed the ontology in its capacity to facilitate metadata integration in the Dig That Lick project. The main contributions include a semantic data model describing the jazz domain in a way applicable to large, automatically collected and processed datasets. The model is based on detailed domain knowledge, such as band lineup fluidity and importance of band leaders. The integration of discographic and sessionographic information was crucial to relate audio recordings to informative metadata. This experience might be valuable in other musical genres and traditions where digital discographies do not deliver essential information needed by users, such as perhaps world music or ethnomusicological recordings.

Also, with a view to large datasets and automatic metadata creation, we introduced provenance and workflow modelling for documenting these situations, as the basis of reproducibility and explainability, as well as algorithmic optimisation. We created four RDF repositories of different sizes with different aims, populating our ontology and therefore demonstrating its practical applicability. Further, we have demonstrated that repositories based on our ontology can be merged if mechanisms for entity resolution are available. These repositories are being used in online applications for investigating patterns in jazz performances. Moreover, they open many avenues for further systematic studies in jazz history and musician relationships.

8. Future work

Given the complexity of jazz and the richness of information collected by researchers, journalists, and music fans over the years, our work has been a start of what we hope will be an ongoing effort. Below we list some directions in which this work can be taken further.

While we processed the dates from structured but not always consistent strings into machine-readable data, we have not done the same for places. Geographic information is important for jazz studies as well as for automatic processing of, e.g., relationships. Ideally, the place strings should be parsed to extract the area information (e.g., New York) as well as venue where it is given.

A musical instrument thesaurus would be a valuable addition. This could extend the Hornbostel–Sachs classification [89], adding modern instruments and providing an OWL or SKOS representation. A thesaurus would not only improve search and retrieval, it could also help to improve the matching mechanism for both instruments and musicians. A comprehensive thesaurus would allow for instrument label parsing even where comments have been added into that string. Moreover, cases where instruments have been mislabelled due to difficulty in recognising them (e.g., tenor saxophone vs. alto saxophone) would be uncovered and attributed more easily. Also, musicians often play related instruments and more rarely play unrelated ones: if two players with the same name play various saxophones, there is a higher chance they are the same person than if one of them would play trumpet and the other drums.

Following on from that, better mechanisms for disambiguating musicians' names and band names would improve the quality of the repositories. New strategies for matching musicians and bands could be developed, e.g., based on existing Linked Open Data. We envision that a better resolution of musicians and bands would result in particular from more overlapping data, since each new match (e.g., fingerprint match between signals or date match between sessions) would lead to further matches between related entities in the iterative process. Integrating further datasets would therefore allow for musician and band disambiguation that is less reliant on string matching of the names.

⁴⁶ https://dig-that-lick.hfm-weimar.de/pattern_search/.

⁴⁷ https://dig-that-lick.hfm-weimar.de/similarity_search/.

Another problem we encountered was the identification of the soloist, particularly in situations where several musicians in the performance lineup play the annotated instrument. Firstly, information about the order of solos and soloists is sometimes available, though in less digitally accessible form: the Jazz Encyclopedia's printed booklets sometimes have it as a comment, as do the Jazz Discography web pages. Additionally, automatic performer recognition could be used as a tool to disambiguate the soloist. It could be based on lick preferences – using the outcomes from the Dig That Lick project. Alternatively, acoustic properties of the instruments could give further clues about the performer's identity.

In general, automatic audio content analysis is a wide playing field for further enrichment of the metadata. In our project, we automatically extracted note events and licks. Music information retrieval tools exist for identifying chords and harmonic content, key, onsets, tempo, and rhythm, etc. Jazz has been of particular interest to the field of Music Information Retrieval, since it presents the community with a number of challenges, some of which have been explored in this article. In regards to audio, jazz recordings are usually polyphonic, with a rich harmonic content, with little repetition and differing segmentation rules compared to pop music. We hope that researchers in Music Information Retrieval⁴⁸ will take on some of these challenges and produce additional metadata for our corpus.

Most importantly, we hope that our data will be used to study jazz: either to produce hypotheses based on data, which can then be investigated by jazz researchers; or to evaluate hypotheses based on knowledge and intuition about jazz with the help of data. Feeding the findings into our repositories as data would further improve their quality and reach, and would help music researchers in the future.

CRediT authorship contribution statement

Polina Proutskova: Methodology, Software, Investigation, Validation Formal analysis, Writing – original draft. **Daniel Wolff:** Software, Resources. **György Fazekas:** Supervision, Methodology, Validation, Writing – review & editing. **Klaus Frieler:** Conceptualisation, Validation, Data curation, Writing – review & editing. **Frank Höger:** Software, Validation, Data curation. **Olga Velichkina:** Resources. **Gabriel Solis:** Investigation, Resources, Data curation, Writing – review & editing, Funding acquisition. **Tillman Weyde:** Writing – review & editing, Project administration, Funding acquisition. **Martin Pfeleiderer:** Writing – review & editing, Project administration, Funding acquisition. **Hélène Camille Crayencour:** Writing – review & editing, Project Administration, Funding acquisition. **Geoffroy Peeters:** Data curation, Funding acquisition. **Simon Dixon:** Conceptualisation, Resources, Data curation, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.websem.2022.100735>.

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⁴⁸ <https://www.ismir.net>.

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