As illustrations we have chosen images of collection items
of the Museum of Toulouse, the Natural History Museum
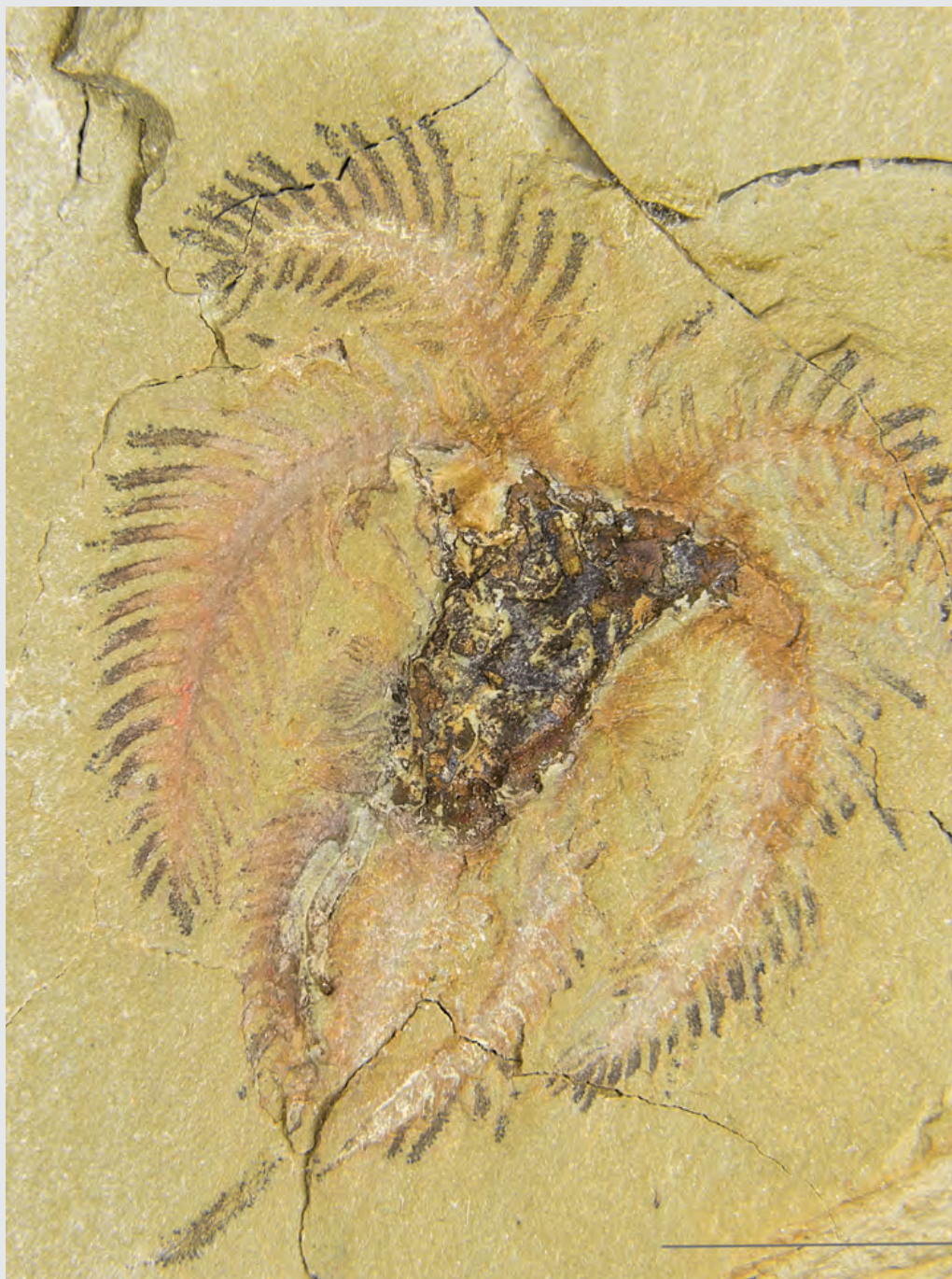of the city of Toulouse (www.museum.toulouse.fr).
They were produced in the Project Phoebus, a collaboration
between the Museum and Wikimedia France.
(Project Phoebus 2013; Berthelot 2013) The project started in 2010
and allows 'Wikimedians' to access the collections, photograph specimens
of their choice, and make them available on Wikimedia Commons.
Already about 2000 high-quality photographs have been uploaded to
Wikimedia Commons, and largely reused throughout Wikimedia projects.
They are provided by the photographers under the Creative Commons
Attribution ShareAlike 3.0 unported license (short: CC BY-SA 3.0).

Furca mauritanica
(Peter Van Roy, 2006),
holotype. Early Ordovician.
Zagora Province, Morocco.
Museum of Toulouse;
photograph: Didier Descouens, CC BY-SA 3.0
<http://commons.wikimedia.org/wiki/File:Furca_mauritanica_MHNT.jpg>

Virtual museums, digital reference collections and e-science environments

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Abstract:

There are three main variants of virtual museums which focus on content, communication or collaboration. An emerging new variant could incorporate them as well as operate in an eco-system of Web-based services that also comprises e-science infrastructures and educational portals. In this eco-system, digitised museum reference collections are important resources for e-science environments of arts & humanities, natural history and other disciplines. But the semantics of digital collections and virtual museums should reflect the richness of cultural heritage content and contexts to allow for intelligent, concepts-based discovery, navigation and access. The CIDOC-CRM and the LIDO specification are key semantic resources in these respects.

1 Introduction: Museums' new tools in the box

The Statutes of the International Council of Museums (ICOM) define a museum as follows:
A museum is a non-profit, permanent institution in the service of society and its development, open to the public, which acquires, conserves, researches, communicates and exhibits the tangible and intangible heritage of humanity and its environment for the purposes of education, study and enjoyment. (ICOM 2007)

The definition does not mention technologies a museum will use, but the application of digital technologies is widely recognized to be helpful in fulfilling its functions in novel and effective ways. Indeed, conceiving a museum that does not avail of some of the technologies that are such a great part of our everyday life would be as anachronistic as thinking of a museum without electricity or heating.

There is no shortage in theoretical reflection about this fact and its impact as exemplified, for example, by a reader such as *Museums in a Digital Age* (Parry 2009), comprising over forty chapters, and other publications that investigate how new technologies transform institutional cultures, methods and relationships with audiences (e.g. Cameron & Kenderdine 2007; Kalay, Kvan & Affleck 2007). Hence, in our contribution we hardly need to go into much theoretical discussion of what we see as new tools in the box of modern museums.

In Chapter 2 we address different variants of virtual museums with focus on content, communication or collaboration. There could be, and in some of the addressed examples actually is, a tighter integration of these variants. However, what we emphasise particularly is that virtual museums could increase their capabilities and utility much more within an eco-system of services, comprising also e-science infrastructures, educational portals and related other services.

In Chapter 3 we note that many already hard pressed museum collections are challenged to make these costly to maintain and seemingly underused cultural assets more accessible. Porting them to the Web and helping people to find what they are looking for appears to be a good solution. Often

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this is implemented in a way that resembles a "visible storage" approach. However, there is not much benefit in gazing at a lot of images online, just as there is little acquisition of cultural knowledge when reading some attached descriptive metadata.

In order to go beyond a simple "put it on the Web" solution, a semantic layer provided by rich metadata and ontologies specifically developed for cultural heritage content must be implemented. Chapter 4 briefly describes some options for this that have become available recently.

Furthermore, Chapter 5 draws attention to the development of e-science environments for researchers in disciplines such as arts & humanities and highlights digital reference collections of museums as particularly relevant e-research resources.

2 Variants of virtual museums

The concept of the virtual museum is still *"under construction"* (Schweibenz 2004), though not as a concept in search of one overarching definition but as an evolution of different variants involving different actors and different digital technologies. For example, the EU-funded V-MUST project (FP7, Network of Excellence, 2011-2015), defines virtual museums as *personalized, immersive, interactive experiences that enhance our understanding of the world around us* (V-MUST 2013). The project has collected information about over 40 such museums, mainly 3D and virtual reality museums, but admits that *a proper definition does not exist* and more systematic analysis is necessary.

We understand virtual museums more generally as services that support some or all museum functions (i.e., acquire, conserve, research, communicate and exhibit). Such services can be extensions of *bricks and mortar* museums into the digital environment or be provided by other organisations or even individuals (some websites of course use the designation "museum" inappropriately; cf. Karp 2004). A useful categorisation is to distinguish between variants of virtual museums that have their primary focus on content, communication, or collaboration.

2.1 Content-centric variants

Content-centric variants of virtual museums invite the visitor to access and explore a large number of digitised or "born-digital" collection items and authoritative information of one or multiple museums.

The *single-museum variant* evolved from the first static websites that presented in a brochure-like style information about the museum such as mission, history, collections, exhibitions, educational programmes, opening hours, contact details, etc. Next such websites also presented online exhibitions of collection highlights or a digital extension and teaser for a temporary exhibition. More recently they aim to "democratize" the museum holdings by providing access to fully digitised collections. Sometimes such collections also include 3D representations of artefacts. There is slow growth in 3D content of museums because mass digitisation methods

Marocaster coronatus (Black & Reboul, 2011),
holotype. Barremian Stage. Taba, Taourirt province, Morocco. Museum of
Toulouse; photograph: Didier Descouens, CC BY-SA 3.0
<http://commons.wikimedia.org/wiki/File:Marocaster_coronatus_MHNT.PAL.2010.2.2_%28Close_up%29.jpg>

such as those used by libraries for printed material cannot be applied, e.g. due to the more complicated handling of museum objects.

Under the category of content-centric variants of virtual museums we also subsume most current Web-based Virtual Reality (VR) applications such as "virtual tours" that reproduce mimetically visiting galleries and inspecting the displayed paintings, statues and other museum objects (examples of such virtual museums and exhibitions are presented in Pis Marcos 2009a) One major advantage of this approach is the opportunity to see artefacts clearly with online zooming mechanisms rather than viewing them behind a showcase.

In the case of the *multiple-museum variant* a common portal or gateway to the distributed databases of the participating institutions is developed by a dedicated national or regional organisation (for example, the Virtual Museum of Canada). Often such organisations also support the digitisation work of the museums and take care for adherence to agreed standards in order to ensure proper aggregation and interoperability. The latter is mainly based on the Open Archive Initiative (OAI) Protocol for Metadata Harvesting and Dublin Core metadata.

Yet this approach is not confined to museums; rather a major goal of most such digital cultural heritage networks is cross-domain federated search and presentation of content, i.e. from libraries, archives and museums. Some examples in Europe are BAM - Bibliotheken, Archive, Museen in Germany <www.bam-portal.de>, CultureGrid in the UK <www.culturegrid.org.uk>, Kulturpool in Austria <www.kulturpool.at> and Kringla in Sweden <www.kringla.nu>.

It has been observed that museums have not been among the institutions that are most eager to participate in such initiatives. A good part of this reluctance is that in such initiatives they miss the curatorial and educative element of contextualisation and interpretation. Indeed, it is widely felt that for stimulating user interest and engagement more is needed than providing metadata and access to collection items. Automatic solutions for creating timelines, trails or exhibitions on the fly have not really been convincing as yet, because the historic narrative or at least some meaningful relations between artefacts and events are missing.

2.2 Communication-centric variants

Communication-centric virtual museums are about promoting cultural learning, knowledge and enjoyment through providing context rather than just access to collection objects. Hence such

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Fagus sylvatica pliocenica (Sap.).
Piacenzian Stage. Niac, Ayrens, Cantal, France. Museum of Toulouse;
photograph: Didier Descouens, CC BY-SA 3.0
<http://commons.wikimedia.org/wiki/File:Fagus_sylvatica_pliocenica_MHNT.PAL.VEG.2002.31.jpg>

virtual museums are *environments for storytelling* that deploy a variety of media to narrate what is known about historic events and artefacts, their meaning and relevance. Such didactically organised media include narrative texts, images, timelines, maps, animations and videos. Videos, for example, are used for including historical documentaries, oral history interviews, demonstrations and explanations by subject experts and historians.

The communication-centric museum may also use *virtual reality* applications. Actually such environments are often seen as the prime variant of virtual museums. Among the first publications that introduced the term "virtual museum" is a paper of the International Conference on Hypermedia & Interactivity in Museums 1991, suggesting that such a museum *will deal with virtual artifacts, in a virtual setting accessible from a telecommunication network in a participatory manner* (Tsichritzis & Gibbs 1991). Some authors even promoted immersive online 3D environments, equipped with a variety of information and study tools, as the ultimate future of virtual museums (Jones & Christal 2004).

Yet we do not think that the VR museum is the most important virtual museum variant. Certainly 3D virtual reality can allow a better understanding of cultural heritage in some cases, in particular, virtual reconstructions of archaeological sites and historic monuments. But the misconception should be avoided that in order to promote learning and enjoyment a 3D environment is required *that places the patron in the museum space or the actual space of a current or past exhibit* (ibid.). This misconception has often guided the development of 3D museums and galleries on the Second Life platform (examples of such 3D environments are presented in Pis Marcos 2009b and Urban, Marty & Twidale 2007).

A virtual reproduction of the museum exhibition space may even be detrimental to the understanding of history and heritage because it conflates the historic context and meaning of artefacts (that should be communicated) with the museum (the communicator). In other words, paraphrasing Marshall McLuhan's famous formula *the medium is the message* (1964), the virtual museum should not be the message. Nevertheless there are many examples where VR representation of buildings and rooms as an environment for narration has been put to good use (for example, The Secret Annex Online of the Anne Frank House and The Virtual Museum of Iraq, cf. the links in the references).

The primary paradigm of the communication-centric variant is the virtual museum as learning space. As described by Werner Schweibenz (2004) such a space *offers different points of access to its*

virtual visitors, according to their age, background and knowledge. The information is presented in a context-oriented way instead of being object-oriented. Moreover, the site is didactically enhanced and linked to additional information that motivates virtual visitors to learn more about a subject they are interested in and to revisit the site. The goal of the learning museum is to make the virtual visitor come back and establish a personal relationship with the online-collection. Ideally, the virtual visitor will come to the museum to see the real objects.

Such virtual museums typically are websites where context is provided in a *thematic approach*, with images of selected collection objects and the opportunity to access similar or related artefacts. Some institutions and networks also provide teaching and learning resources that are tied in with national curricula or allow teachers to create and share projects, lesson plans and assignments that draw on available digital content. For example, the Scottish Cultural Resources Access Network (SCRAN), The National Archives' Education Service, and the Virtual Museum of Canada's Teacher Centre (cf. the links in the references).

Finally, it may be worthwhile to note that museums could engage more thoroughly in the communication of *how the institution works*, its professional practices and criteria, exhibit development and other behind-the-scenes activities. Exemplary in this regard is the Powerhouse Museum (Sydney, Australia) with its weblogs *Inside the collection* and *Photo of the Day* that introduce curators, present current work on collections objects, and the stories behind historical photographs (cf. the links in the references).

2.3 Collaboration-centric variants

Communication-centric virtual museums communicate, but in most cases this is one-way communication from the museum to its audiences. Two-way communication and collaboration with "non-experts" in museum activities such as curating an exhibition is still rare. Yet the Web 2.0 environment, which builds on an *architecture of participation* (O'Reilly 2005), is stimulating the emergence of a new variant of virtual museums, the Web 2.0 museum.

As a matter of fact there is a massive and growing use worldwide of Web 2.0 or *social software* applications such as Weblogs, Wikis (e.g., Wikipedia), bookmark and content sharing platforms (e.g., del.icio.us, Flickr, YouTube), and social networking services (e.g., Facebook, MySpace, LinkedIn). The buzz around the Web 2.0, in particular, social networking platforms, has also motivated some museums to think about how they might *open up*, involve user communities and explore forms of collaboration.

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Parastagmatoptera flavoguttata (Serville, 1839),
male specimen. Montsinéry, French Guiana. Museum of
Toulouse; photograph: Didier Descouens, CC BY-SA 3.0
<http://commons.wikimedia.org/wiki/File:Parastagmatoptera_flavoguttata_MHNT.jpg>

The two main experimental forms of Web 2.0 based collaboration focus on tagging of content on top of museum public access catalogues and participation through activities on content sharing platforms.

Examples of museums that invited users *to tag and annotate resources* (i.e. add user created keywords) include the Powerhouse Museum (Australia) and the Steve.Museum (Trant 2009), that involves several American art museums. The Powerhouse Museum's "OPAC2.0" made accessible 62 000 object records with high quality zoomable images and promoted user engagement and input. The user-contributed descriptive terms (so called "folksonomies") were also used for leveraging content discovery mechanisms. None of the most tagged objects were on public display in the museum. (Chan 2007)

The second main form of Web 2.0 collaboration uses *content sharing platforms*, either popular ones such as Flickr or those provided as a service by the museum or other cultural institution. Both aim to promote user engagement but the activity is usually set apart from the museum's own website. Among the most active museums in this area is the Brooklyn Museum (New York), which since 2006 has utilized a variety of Web 2.0 sites and services, firstly off-site and now integrated in their own website to link museum and Web-based visits (Bernstein 2008).

Examples of museums and galleries that support users in organising, sharing and exploring *their own online collections* are Collection X <www.collectionx.museum> (McIntyre et al. 2008), which is managed by the Art Gallery of Ontario (Canada), and Collectish <http://collectish.com>, a facility provided by the Melbourne Museum (Australia).

While there are many other examples of museums experimenting with social software applications, overall the spill-over of the tremendous growth of the Web 2.0 into the cultural heritage sector is still rather limited. This is because such applications, if used in an open way, put users and user-generated content and not the institution and its authoritatively curated content at the centre of the equation. They respond to people's interest to take part, express themselves, share ideas and own content.

This presents a great challenge for many institutions and their current practices of communicating, contextualising and interpreting cultural heritage. For example, museums will ask: *What about dumbing down? Who is going to moderate? What if they don't like our exhibition?* (Ellis & Kelly 2007) Indeed, the issues implied in open approaches of museum interaction are profound

Diactor bilineatus (Fabricius, 1803),
male specimen. Piste St-Elie, PK19, French Guiana. Museum of Toulouse;
photograph: Didier Descouens, CC BY-SA 3.0
<http://commons.wikimedia.org/wiki/File:Diactor_bilineatus_MHNT.jpg>

and concern ownership of content, loss of authority, security and reliability of external services, and fears about unfavourable public and sponsor perceptions of the institution. Coming to terms with these issues will require research on, and careful experimentation with, appropriate approaches that work for cultural heritage institutions. (cf. Ellis & Kelly 2007; Simon 2010)

2.4 Towards the recombinant virtual museum

The overview above illustrates that the current development phase of virtual museums is characterised by a coexistence of very different variants. In an evolutionary perspective these variants are different in terms of genotype, technology, habitat and services. The content-centric variants stem from the genotype *library* (focus: access, i.e. content discovery and delivery), the communication-centric variants from the core genotype *museum* (focus: context, i.e. learning about history and heritage), and the collaboration-centric variants from *community centre* (focus: participation, i.e. sharing ideas and resources).
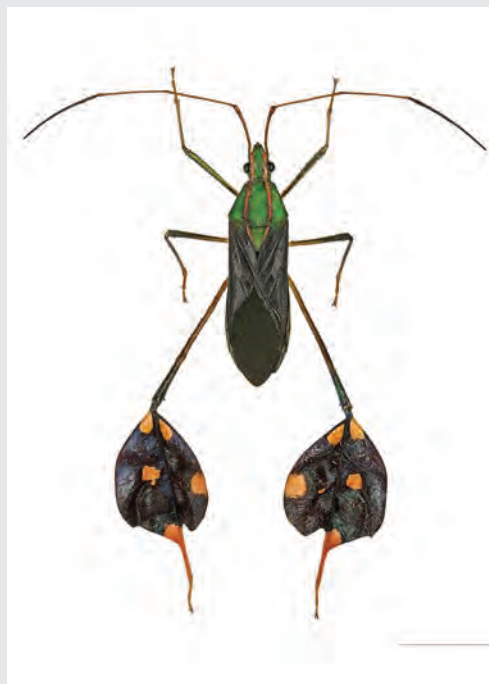
Hence the question arises what could be integrating principles and standards that might allow for leveraging the investment in virtual museums and their different services. This requires looking for a different, encompassing genotype, which may be called the *recombinant virtual museum*, a concept that is inspired by articles of Lorcan Dempsey that focused on novel digital library environments (Dempsey 2003, 2005 and 2006).

Such a virtual museum will operate as a node in an *eco-system of services* that are characterised by recombinant ability, the ability to share, reuse and combine metadata, semantics, content, applications and processes. Within this eco-system the virtual museum will make available its own services as well as drawing on different services of other providers. The services can be located at different "DNA sequences" of the recombinant virtual museum, i.e. sequences for acquiring, curating, studying, communicating and exhibiting.

This can be services for controlled vocabulary that are accessed at various points in the metadata lifecycle, e.g. creation, indexing, sharing, use for content discovery, browsing, access, re-use, etc.; for example, the Online Computer Library Center (OCLC) provides several such controlled vocabulary or terminology services, including services for metadata cross walking. Basically also

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Tropidacris collaris (Stoll, 1813), male specimen. Route de Kaw, PK40,
French Guiana. Photograph: Didier Descouens, 01/02/2012, CC BY-SA 3.0
<http://commons.wikimedia.org/wiki/File:Tropidacris_collaris_MHNTdos_vol.jpg>

Open Archive Initiative (OAI) <www.openarchives.org> services, the mainstay of current content-centric cultural networks, are recombinant in the sense that aggregated metadata can be filtered and relevant items fed into, re-used and combined by different thematic channels. A familiar example also are RSS (Rich Site Summary) services that allow for continually updating websites and end-users with information and links to content (e.g. articles, recordings, videos), delivered according to topics of interest.

Obviously a modular and service-oriented approach based on *Web Services* will play a central role in the recombinant virtual museum scenario. Web Services can provide functionality across different platforms for almost any purpose (e.g. controlled vocabulary, data exchange, search & retrieval, presentation and so forth), called on-demand or built into a variety of applications from portals to mobile devices. A major element in this approach is availability of open Application Programming Interfaces (APIs) and ability to re-use services as well as information resources. Many such resources may in the future be accessible as Linked Data <http://linkeddata.org>, i.e. data that is semantically linked based on the W3C Semantic Web standard RDF (Resource Description Framework).

The most important point about the recombinant virtual museum, however, is that it interoperates in an eco-system that comprises, for example, services of e-science infrastructures or educational repositories or portals. To illustrate the concept, within the eco-system the virtual museum would provide services related to reference collections to e-science environments for arts & humanities or biodiversity researchers and, in turn, enrich the presentation of collections or thematic exhibitions with results of research projects (e.g. documentation and analysis of archaeological excavations or environmental studies). In the case of educational repositories the museum would, for example, feed content such as historical images into educational material and, in turn, extend its learning resources with links to the educational material in which the content is used for illustration or further study. Similarly the museum could provide content to popular thematic websites of public service broadcasters (e.g. history channels) or of NGOs engaged in species conservation and benefit from the additional visibility of their collections.

Thus the recombinant virtual museum fully adopts the network logic of the Internet and operates as a node in information flows that create, both externally and internally, added value related to different purposes such as research, education or leisure activities.

Nemoptera sp. (Latreille, 1802), male specimen.
Randina, Greece. Museum of Toulouse;
photograph: Didier Descouens, CC BY-SA 3.0
<http://commons.wikimedia.org/wiki/File:Nemoptera_sp._MHNT.ZOO.2004.0.736.jpg>

3 Making museum collections more accessible

Virtual museums are building on their own and/or distributed content, i.e. digitised collections that are accessible on the Web. However, we should not over-look the situation of the phy-sical collections. As a matter of fact, most museum collections large and small are under pres-sure. They often lack funds and staff while, at the same time, patrons would like these costly-to-maintain and seemingly underused cultural assets to become more accessible.

This is a major topic in the museum world which has become virulent in recent years. There have been inquiries and surveys on the actual access and use of museum collections (in the UK, for example, Museums Association 2005 and Keene 2008), and many publications that explain why collections are important, for example, specimen collections of natural history museums, which are among the most hard pressed (cf. the excellent account by Suarez & Tsutui 2004).

3.1 Visible storage

As a matter of fact, large museums have only a fraction of their collection holdings on display at any given time, estimated at 2% at natural history museums or 5% at art museums (cf. Lord 2012). But would presenting more objects make sense when an average museum visit is somewhere between one and two hours and even carefully displayed objects in an exhibition are only recognised for a few seconds?

Since the 1980's, many museums have made more of their collection items accessible by offering an open study centre or "visible storage" as it is called nowadays. In such museum areas masses of artefacts are put in rows or clusters of glass cases, or paintings, mounted two or three high on partition walls. Visitors can roam freely through the rooms, decide to devote some more time to one of the thematic sections, take a closer look at some artefacts, read the label information and, even, note down the catalogue number and access details on one of the computers that are also often available in such areas (cf. Hilberry 2002; for a brief introduction Collections Conversations 2012).

Clearly visible storage is not feasible for the huge specimen collections of natural history and archaeological museums, whereas art museums may find it somewhat easier to apply. However, it is always an option to present, maybe annually, an exhibition that highlights one of the collections

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Congiopodus torvus (Gronow, 1772),
Cape of Good Hope. Museum of Toulouse; photograph: Pierre Selim, CC BY-SA 3.0
<http://commons.wikimedia.org/wiki/File:Agriopus_torvus_-_MHNT_-_ICHT.1995.111.jpg>

that tend to be overlooked or are seen as difficult to communicate. For example, the Uffizi in Florence has an annual *I mai visti (Never seen before)* exhibition that presents art works from their depot that are selected and combined to illustrate a particular theme (on the 2012/2013 exhibition see Polo Museale Firenze 2012). Similarly a natural history exhibition could highlight exemplars of a bird or butterfly collection together with results of recent laboratory or field studies, thereby highlighting the curatorial and research work of the museum.

Overall the experience with large visible storage spaces is that for most visitors it is simply over-whelming, while there are others who welcome the opportunity to see many more artefacts and look up information about objects that attracted their interest. But the most important influence of the approach may be that it is inviting people *to think about museums*, how they arrange exhibitions, and why some artefacts are presented prominently while others have to stay in the stored collection.

3.2 More effective use of museums' stored collections

One particularly threatening argument in the request for more accessible museum collections is that they are underused. Concerning visitors of stored collections, a survey of museums in England and Wales with 181 respondents showed that the numbers indeed are low overall (Keene 2008). 50 or fewer collection visitors per year were reported by 55% of the museums and only 20% welcome over 400 visitors. The primary purpose was research, but also other uses were reported by museums that promote special educational or creative use programmes. 74% of the survey respondents thought that stored collections are used insufficiently.

Another inquiry into museum collections and their use has been conducted by the UK Museums Association. Jane Glaister, who chaired the inquiry, emphasises:

Too many museum collections are underused not displayed, published, used for research or even understood by the institutions that care for them. Many museum staff find the notion that collections can be underused problematic. It conflicts with their sense that museums have a duty to preserve material for future generations. But if an object sits in a store for ten years, without anyone looking at it, and if it is not published or made available on the Internet, can

Lepisosteus osseus (Linnaeus, 1758), Amazone. Museum of Toulouse;
photograph: Pierre Selim, CC BY-SA 3.0
<http://commons.wikimedia.org/wiki/File:Lepisosteus_osseus_-_MHNT_-_ICHT.1995.22.jpg>

that museum be realising its responsibilities towards the object and towards the public? If we, as a profession, are merely acting as caretakers and not as collection activists then we are not fulfilling our obligations.
I believe that we must be more honest about this issue. (…) It is easy to become frustrated with politicians and funders who may have a simplistic approach to stored collections, and who may make unreasonable demands to 'display it or get rid of it'. But this attitude stems from a real problem too much unused stuff, draining resources. And unless museums start actively addressing this problem, they are going to have unwelcome solutions imposed on them they must seize the initiative. (Glaister 2005)

The key challenge for museums according to Glaister is *to realise more of the fantastic potential of their collections* by giving more people more opportunities to engage with them, increasing virtual access to collections, and releasing available information and promoting knowledge generation (e.g. more collection-focused research work of students).

3.3 Porting collections to the Web

For about twenty years many museums across Europe have participated in initiatives for content digitisation and online access within EU and national programmes. In part driven by the urge to make collections more accessible, they took the opportunity, applied for funding and, if successful, digitised some collections and made them searchable on their website and/or portals for domain or cross-domain federated search.

In a way this resembles replicating the visible storage approach on the Web, though of course with some important differences. More interested people (indeed, worldwide) can mine a museum's digital collections for artefacts of certain types, styles, genres, etc. Federated search portals allow for extending the volume of potentially relevant items by drawing on databases of more museums and, in the case of cross-domain portals, also of libraries and archives.

There are some advantages in this, not least serendipity, for example, when the search results for particular museum artefacts include thematically or otherwise related content from libraries and archives. Yet, on most users the effect is similar to the experience of the museum visitor who

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Triodon macropterus. Gift of Eugène Trutat, 1867.
Museum of Toulouse; photograph: Pierre Selim, CC BY-SA 3.0
<http://commons.wikimedia.org/wiki/File:Triodon_macropterus_-_MHNT_ICHT.1995.332.jpg>

leaves a visible storage space overwhelmed and in search of a firmer foothold as provided by thematic exhibitions.

As noted in the section on content-centric variants of virtual museums, there is a clear need to go beyond providing metadata and access to collection items. Some relatively simple options such as showing objects in relation to historic periods and maps may be a good starting point. But for promoting, within content browsing and access processes, cultural understanding a rich semantic layer is required that makes it possible to contextualise museum artefacts based on higher-level conceptual relations of domain ontologies.

4 Museum semantics

4.1 Ontologies

Enhancing virtual museums of history and heritage requires the implementation of complex conceptual models, because the semantics of such museums should reflect the richness of cultural content and contexts. There have been a number of efforts to organize cultural heritage concepts in an ontology, i.e. a formal representation of those concepts and the relations between them. A metadata schema is instead the description of the way in which data are stored in digital repositories and concerns the search and retrieval of the stored digital content.

Although they are not the same thing, there are important relationships between the two concepts. Indeed, some metadata schemas derive from an ontology, while others do not but may be mapped to it; i.e. the individual metadata correspond to a combination of concepts described in the ontology. Such a combination will then translate into a set of Resource Description Framework (RDF) "triples" (i.e. subject-predicate-object), expressing the relations between entities which identify the same concept. The advantage of expressing information in the W3C standard RDF is that it can be machine-processed and enable Linked Data based discovery and access to content.

The best-known cultural heritage ontology is CIDOC-CRM <www.cidoc-crm.org>, the Conceptual Reference Model for concepts and relations in cultural heritage documentation which is an official ISO standard (ISO 21127:2006). CIDOC-CRM is used by major content integration projects, for example, the Classical Art Research Online Services (CLAROS) <www.clarosnet.org> and Arachne <http://arachne.uni-koeln.de>, the central object database

Dactylopterus volitans. Museum of Toulouse;
photograph: Pierre Selim, CC BY-SA 3.0
<http://commons.wikimedia.org/wiki/File:Dactylopterus_volitans_-_MHNT_-_ICHT.1995.88.jpg>

of the German Archaeological Institute (DAI) and the Archaeological Institute of the University of Cologne. It also is the reference system for applications of 3D-COFORM (EU FP7 project, 2008-2012, <http://www.3d-coform.eu>) that developed 3D documentation as an affordable, practical and effective mechanism for long-term docu-mentation of tangible cultural heritage.

Moreover, CIDOC-CRM has inspired, among others, the metadata schema Lightweight Information Describing Objects (LIDO), adopted by Athena for museum content, and has deeply influenced the Europeana Data Model (EDM), which are addressed below.

Another ontology-based approach has been implemented by CultureSampo <www.kulttuurisampo.fi>, a Finnish cultural heritage portal that is based on a set of domain ontologies within the FinnONTO national system. (Hyvönen, Mäkelä & Kauppinen 2009) These are described as lightweight domain ontologies created semi-automatically by transforming thesauri already in use. The process of deriving a simple ontology from a thesaurus is not uncommon, basically abstracting from a terms list to a concept list, which produces a rather simple conceptual model.

4.2 Metadata schemas

There are still many proprietary metadata schemas used by museums, though the situation is much better than that of the documentation systems used by archaeologists, where there are as many systems as archaeologists. This situation caused quite some disputes until the concepts of aggregation and mapping were introduced.

Mapping enables the integration of different repositories by establishing correspondence between the respective metadata schemas. However, because of the necessary richness and complexity of such schemas as required by the museum mission, simple metadata models such as Dublin Core do not appear satisfactory.

The same problem arose with the first version of the metadata schema Europeana Semantic Elements (ESE). Museums fostered the adoption of much richer ones, with the CIDOC Conceptual Reference Model perspective. These requests eventually led to the acknowledgement of such needs by Europeana in the EDM data model (cf. Doerr et al. 2010; Europeana professional 2012) and to the creation of LIDO that has been released by the ICOM-CIDOC Working Group Data Harvesting and Interchange in November 2010. LIDO is understood as

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Double-edged scraper; Aurignacian, 37,000-28,000 BP.
Aurignac cave, Haute-Garonne, France. Former collection of Édouard Lartet, 1861.
Museum of Toulouse; photograph: Didier Descouens, CC BY-SA 3.0
<http://commons.wikimedia.org/wiki/File:Lame_Aurignac_Lartet_global_N%C2%B0II.jpg>

a tool suitable to address most of, if not all, the museum needs, to ease mapping from existing local data models, and to enable data harvesting.

As it is well known to Athena partners, LIDO is the result of a joint effort of the CDWA Lite (J. Paul Getty Trust 2006), museumdat (2007), SPECTRUM (most recent edition 4.0, March 2011) and CIDOC-CRM communities. The schema combines the CDWA Lite and museumdat schemas and is informed by SPECTRUM. Being CIDOC-CRM compliant, it aims at contributing information of all kinds of museum objects for resource discovery. The mapping of other metadata schemas to CIDOC-CRM, for example the work in archaeological research documentation inspired by the CRM, may lead as well to crosswalks to LIDO.

The question now is if any of the above mentioned data models has provisions for all the information that is necessary for the virtual museum as outlined above, in particular for the recombinant virtual museum. The answer is of course "no", simply because the latter is still an abstraction. But, these data models can potentially provide for such information: CIDOC-CRM and rich metadata schemas compliant with it have the flexibility and extensibility to allow for novel applications.

5   Virtual museums and e-science environments

As noted above in the section on the recombinant virtual museum, we envisage a strengthening of the research function of museums through interaction with e-science environments for researchers from different related disciplines. Depending on the focus of the museum, for example, this will be e-science environments for archaeologists, historians of art and architecture or, in the case of natural history, taxonomists and bio-diversity researchers.

E-science refers to ICT-enabled forms of research that are data-intensive, distributed and collaborative. The terms e-science or science cyberinfrastructure are commonly used as synonyms; the former is used in Europe and the latter is commoner in the USA (cf. ACLS 2006; NSF 2007). E-science networks and environments support a variety of research methods with tools and services for data capture and management, processing, analysis, visualisation and so forth. In the context of cultural heritage artefacts and collections, this includes methods such as physical and chemical analysis of artefacts, finding patterns in large data sets, visual and other comparative analysis of collection artefacts, etc.

We expect that (recombinant) virtual museums within a few years will interoperate with e-research environments of natural sciences, humanities computing (or digital humanities) environments or any other discipline that works with museum resources or supports genuine research and professional work of museums. With regards to museum resources below we primarily highlight reference collections.

5.1 E-science environments

In recent years ICT-supported research has seen a tremendous expansion for many reasons such as advanced capability of technologies for a variety of research purposes, the prospect that new scientific questions can be addressed through processing and analysis of "big data", and the achievements of showcase disciplines such as bio-informatics.

There are also high expectations for other "data driven" disciplines (cf. European High-level Expert Group on Scientific Data 2010) and much funding is made available through the EU Framework Programme as well as national research funding agencies. On the roadmap of the European Strategy Forum on Research Infrastructures (ESFRI) <http://ec.europa.eu/research/esfri/>, funded through the Infrastructures strand of the EU Framework Programme, there are the large-scale development projects, including infrastructures for the social sciences and humanities: Digital Research Infrastructure for the Arts and Humanities (DARIAH) <www.dariah.eu>, Council of European Social Science Data Archives (CESSDA) <www.cessda.org>, and Common Language Resources and Technology Initiative (CLARIN) <www.clarin.eu>.

Moreover, there is the Advanced Research Infrastructure for Archaeological Dataset Networking in Europe (ARIADNE) project <www.ariadne-infrastructure.eu>, a recently started large-scale EU FP7 Integrating Activity that brings together 24 partners from 16 European countries to develop integrated services for archaeological research.

In the natural sciences the importance of technology-support and, even, technology-drive in research are fully acknowledged, whereas in the humanities this is still not a normal part of the *epistemic culture* (Knorr Cetina 1999). There is ongoing debate on this issue as well as on how to ensure the development of e-research infrastructures, tools and data models that are appropriate to humanities research (cf. Wouters & Beaulieu 2006; Wouters 2007; Anderson, Blake & Dunn 2010).

Careful analysis of current research practices and new possibilities is required in order to ensure that limited resources are invested on the most appropriate approaches. And of course, the researchers of scientific disciplines need to be involved or, rather, take the lead in the development of e-science environments that best fit their requirements (Borgman 2009).

While evangelism may still be necessary in some quarters of the Arts & Humanities, the digital humanities are striving, based on home-grown e-research tools as well systems that are developed

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Painted pebble; Azilian, 12,000-9,500 BP. Le Mas-d'Azil, Ariège department,
France. Former collection of French naturalist Jean Miquel (1859-1940). Museum of Toulouse;
photograph: Didier Descouens, CC BY-SA 3.0
<http://commons.wikimedia.org/wiki/File:Galet_peint_MHNT.PRE.2006.0.93.jpg>

together with technologists. For example, <www.arts-humanities.net/project> documents several hundred digital arts and humanities projects (with emphasis given to projects in the UK), including information on the digital resources created and the methods and tools used in the research; or see the papers and posters presented at the Digital Humanities 2012 conference of the Alliance of Digital Humanities Organizations (ADHO) <http://adho.org>. In short, this is the time to investigate where and how virtual museums fit into the emerging landscape of e-science infrastructures and environments.

E-science infrastructures have been built in the first place in response to the need of some natural and engineering sciences for massive networking and processing of data (e.g. European EGEE - Enabling Grids for E-sciencE and many national Grids). Such e-infrastructures typically are not built to support one specialized application environment but rather so called "middleware" that supports a variety of purposes.

Thus dedicated e-science environments that need massive networking and computing are built on top of the basic Grid functionality. If such a need does not exist, e-science environments are more likely to be built on a robust and flexible Web-based platform for content management, collaboration and other functionality for which add-on modules are provided (for example, the open source system Drupal). Moreover, there is a multitude of other research environments that are set up for bringing together tools and resources for particular projects.

Such environments use, and sometimes considerably extend, the functionality of platforms such as Wikis or Web GIS. For example, the WissKi - Scientific Communication Infrastructure project <http://wiss-ki.eu> developed a semantic Wiki application, implementing the CIDOC Conceptual Reference Model, to work on use cases in art history (e.g. Goldsmith's Art in Nuremberg, 16th-19th century) as well as natural history (e.g. the research diaries of a famous 19th century entomologist, Wilhelm Aerts).

Many projects in the fields of archaeology, history, and other social sciences and humanities disciplines use Web GIS (Gregory & Ell 2008); for example a large-scale project is the Great Britain Historical Geographical Information System (GBHGIS)

Flint ax. Venerque, Haute-Garonne, France.
Former collection of Jean Baptiste Noulet (1802-1890),
specimen described and drawn on a Noulet autograph,
dated 1868. Museum of Toulouse; photograph: Didier Descouens, CC BY-SA 3.0
<http://commons.wikimedia.org/wiki/File:Hachet_Noulet_MHNT.PRE.2011.0.429.jpg>

<www.port.ac.uk/research/gbhgis/>, which integrates a huge amount of information on localities as they have changed over time (e.g. historic maps, historical gazetteers, travellers' tales, census reports).

A different view on e-science environments is their *development pattern*. At least three different patterns can be distinguished:

The first, most common pattern is a chain of projects through which a rich ICT-supported research environment is developed. A good example is the Scratchpads project <http://scratchpads.eu> that is being developed by researchers and IT specialists of the Natural History Museum in London. The project managed to receive continuous co-funding from different sources such as the UK Natural Environment Research Council, the Global Biodiversity Information Facility (GBIF) <www.gbif.org>, the European Distributed Institute of Taxonomy (EDIT) <www.e-taxonomy.eu>, and the Virtual Biodiversity Research and Access Network for Taxonomy (ViBRANT) project <http://vbrant.eu>.

Scratchpads are built on Drupal and allow for creation, management, sharing, and publishing of taxonomic and other biodiversity information. They provide an integrated workbench and collaborative, open access space for the research community. A number of modules and services allow for working on taxonomic classifications, importing or linking to specimen records, images, maps, literature, etc. Among the Web services Scratchpads can use are services provided by GBIF, NCBI Genbank and Biodiversity Heritage Library (BHL).

The second pattern is represented by "laboratories", i.e. research centers that experiment with and support novel forms of ICT-supported collaborative research. Such a laboratory may be situated within a university or other major institution or implemented in a distributed mode, bringing together scholars and IT specialists from different research organizations. An outstanding example is the e-Humanities Group <http://ehumanities.nl> that involves several institutes of the Royal Netherlands Academy of Arts and Sciences (KNAW). The Group runs a five-year programme (2011-2015) on computational humanities and cultures of e-humanities. The latter strand of research focuses on the impact of innovative digital approaches on research questions and methods, interdisciplinary and international collaboration, and novel forms of

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Neolithic arrowhead. Dolmen de la Glène, Saint-Léons, France.
Former collection of Émile Cartailhac (18451921).
Museum of Toulouse; photograph: Didier Descouens, CC BY-SA 3.0
<http://commons.wikimedia.org/wiki/File:Fleche_Cartailhac_MHNT_PRE_2009.0.232.2.jpg>

output and dissemination. A previous project was the AlfaLab, a joint initiative of five KNAW institutes that developed e-humanities tools and resources <http://alfalab.ehumanities.nl>.

Finally, the third pattern is the research environment of a large-scale e-science infrastructure, i.e. the integrated set of tools that is provided on top of the data and service infrastructure. Such e-science environments need to cater for the requirements and workflows of specific domains of study. For example, one infrastructure on the ESFRI Roadmap that is of interest to museums is DARIAH <www.dariah.eu>, the Digital Research Infrastructure for the Arts and Humanities. DARIAH is developing a three-tier research infrastructure that comprises: core services that enable interoperability across heterogeneous distributed data resources (e.g. museum and archival content); reference services (e.g. classification systems, thesauri, gazetteers, biographical data, etc.); and the actual research tools (e.g. for text or image analysis) which are sourced from related projects of the participating institutions and an open DARIAH developer community.

5.2 Digital reference collections

Reference collections are a major component of the research function of museums. Such collections are organized sets of objects that are used for purposes of identification and comparative research. Hence reference here has a different meaning than in the library context where reference works such as dictionaries, encyclopaedias, almanacs, chronologies, maps, etc. are consulted for verifying factual information on a topic.

Museum reference collections comprise objects, man-made artefacts such as pottery or coins as well as natural ones such as geological or prepared biological samples. Reference collections are kept within museums because they need curation and specific conservation methods to ensure their longevity. The best known examples probably are the reference collections for species of major natural history museums, where multiple specimens also show the variation within a species, and one actually may be the type specimen (i.e. the scientific name-bearing representative of that species).

The tremendous value of online accessible reference collections and related terminology is recognized in all areas of research that draw on or support the curatorial work of museums,

archives and other heritage centres. This includes archaeological research (Lange 2004), classical studies (Babeu 2011) or, to give a more specific example, terminological and laboratory-based research (e.g. microscopy and spectrometry) on pigments for art historical studies and conservation (Walsh & Eastaugh 2006; Eastaugh, Walsh & Chaplin 2008).

Digitisation and online accessibility of reference collections allows for using computer-supported methods to tackle new or unsolved research questions or challenge established answers. Of course this requires advanced technologies and standards from data capture and sharing to analysis, interpretation and publishing of results.

This is a vast field, so we will focus on the core of the matter: Digitised and virtually combined reference collections allow for using data-based methods for identifying and measuring different features of artefacts or natural specimens, comparing and classifying them, in particular, also according to different classification systems. On the importance of such different views in archaeological typology see Thorsten Madsen (2004); concerning natural history research, for example, the uBio system <www.ubio.org> allows multiple classifications of the same taxons to be stored; i.e. different experts' views on groups of organisms can coexist in one system (cf. Geser 2009).

Moreover, detection of significant patterns in the data may allow for confirming or questioning hypotheses about aspects of cultural or natural history. Some supportive advanced technical applications for such purposes include image and 3D analysis tools that allow for identification, clustering and comparison of object shapes, structural components or decorative elements.

Of course data on the instrumentation, procedures and parameters used in the digitisation of the artefacts and any computer-supported research based on the digital data must be captured and included in the metadata of the research results. Concerning digitisation modalities and digital objects, researchers of the Institute of Computer Science of the Foundation for Research and Technology - Hellas (FORTH-ICS) have developed the digital provenance model CRMdig, which extends the CIDOC-CRM. (Doerr & Theodoridou 2011) This extension also has been mapped to LIDO; a case study on how CRMdig and LIDO handle the digital information of an object is presented in Pitzalis, Niccolucci and Cord (2011).

The CRMdig model has been verified by various test cases including digitisation of museum artefacts. Within the 3D-COFORM project, the model has been applied to document all stages of the production and reuse of 3D models from cultural heritage objects, including all kinds of digitisation processes and the digitised objects themselves.

In summary, it has become possible to create, in a highly controlled way, digital reference collections and to use the digital data for exploring new or unsolved research questions on cultural history and heritage by applying innovative, flexible and effective methods. Thus digital reference collections can become one major pillar of Arts & Humanities, Natural History and other e-science environments.

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Scorpion - Akan weight for weighing gold dust and merchandise.
Museum of Toulouse; photograph: Didier Descouens, CC BY-SA 3.0
<http://commons.wikimedia.org/wiki/File:Akan_MHNT.ETH.2010.25.013.jpg> (On the Akan measuring system
see <http://en.wikipedia.org/wiki/Akan_goldweights>)

While major collections of museums and other institutions will provide the basis of digital reference collections in terms of volume and scope, it should also be feasible that e-science environments can draw on specific smaller collections or aggregate selected items from many institutions. Indeed, in principle any aggregation of digital objects or, more precisely, data that represent certain features of artefacts or natural specimens may be a temporary reference collection for addressing the research questions under consideration.

6 Summary - Onto the next phase of virtual museums

Building on and exploiting the capabilities of digital technologies will allow museums to curate, research, communicate and exhibit heritage more effectively and in new ways, involving new forms of collaboration. The current variants of virtual museums are already valuable attempts to make museum content and knowledge more readily available, provide learning opportunities, and experiment with collaborative forms of user engagement.

However, with regard to the content-centric variant we noted the issue of replicating on the Web a *visible storage* approach, overwhelming most users rather than promoting engagement and learning. Such an approach certainly does not realize what André Malraux (1947) envisioned as a *musée imaginaire*, a virtual space in which cultural heritage can be experienced, appreciated and understood in unprecedented ways.

Yet implementation of a rich semantic layer can enable intelligent, concepts-based navigation and access by revealing meaningful relations among topics and available content of interest. The routes by which the user discovers the content are as important as the content itself, because, they allow gaining an understanding of essential conceptual relations, how disciplines classify entities, and what terms are used in a field of study.

A major question is how to leverage further the considerable investments in the digitisation of museum collections and creation of virtual museums. Here it will be important to think beyond the museum sector and enable virtual museums to interoperate in an eco-system of Web-based services that also comprises, for example, e-science infrastructures and educational portals.

Bird and its chicks - Akan weight for weighing gold dust and merchandise.
Museum of Toulouse; photograph: Didier Descouens, CC BY-SA 3.0
<http://commons.wikimedia.org/wiki/File:Akan_MHNT.ETH.2010.25.041.jpg>

We particularly highlighted the added value, indeed tremendous new opportunities digital reference collections can offer researchers that are equipped with advanced computer-supported methods and tools. Such collections will become a major pillar of e-science environments for arts & humanities, natural history and other disciplines and can allow for tackling new or unsolved research questions or challenging established answers.

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Stylized bovid head - Akan weight for
weighing gold dust and merchandise. Museum of Toulouse;
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