



In Centro

Collected Papers
Volume III

Time

Editors:

Guy D. Stiebel

Ido Koch

Avner Ecker

Amir Gorzalczany

Yotam Tepper

Amit Shadman

Salome Dan-Goor

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Volume III



Central Region



The Sonia and Marco Nadler Institute of Archaeology
The Jacob M. Alkow Department of Archaeology and Ancient Near Eastern Cultures
The Chaim Rosenberg School of Jewish Studies and Archaeology
The Lester and Sally Entin Faculty of Humanities



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A Computational Model for Absolute Chronology in Archaeology

Eythan Levy

Introduction

This paper summarizes our recent approach to chronological modelling in archaeology. This approach is based on the ChronoLog software (chrono.ulb.be), developed by the author in collaboration with Prof. Gilles Geeraerts (Université libre de Bruxelles) and Dr. Frédéric Pluquet (Haute École Louvain en Hainaut). We first review our model, based on the notion of chronological networks, and then present our software tool, ChronoLog. We end with a few concluding remarks and directions for future research.

The “Chronological Networks” Model

This research started from the observation that chronological data induce a network. Kings, strata, ceramic types and other archaeological *realia* are all connected to each other via a network of synchronisms. Hence, any chronological change to one entity in this network (for example, changing the dates of a given king) might potentially affect the dating of other units along the network. How can such networks be formalized? Can a practical software tool be built to study these networks? Our survey of the literature showed

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that no such tool was available for archaeological researchers. Hence, we developed both a theoretical formalization of chronological networks and an accompanying software. In this paper, we review the main tenets of our model (for full details on chronological networks, see Levy *et al.* 2021).

A chronological network comprises three types of entities: time-periods, sequences and synchronisms.

Time-periods

The time-period is the basic unit of chronological networks. It can represent a stratum, a reign, a ceramic type, a historical period, a cultural phase, or any other chronological unit containing no gap. A time-period contains three variables: its start, end and duration (expressed in years). The start or end of a period can be known (e.g., 1200 BCE), lower bounded (e.g., after 1200 BCE), upper bounded (e.g., before 1300 BCE), in a range (e.g., 1200–1300 BCE), or unknown. The same holds for durations (five years, at least five years, at most five years, between five and ten years, or unknown). For examples, see Fig. 1.

Sequences

Time-periods can be grouped into sequences—i.e., they follow each other directly. More formally, in each sequence, the end of a period equals the start of the next period. Sequences are drawn as time-periods stacked on top of each other, with the earliest period on top and the latest at the bottom. A sequence



Fig. 1: Examples of ChronoLog time-periods: Period A lasts exactly six years, from 1984 to 1990; Period B lasts exactly six years, at an unknown absolute time; Period C starts no earlier than 1300 CE, ends no later than 1400 CE, and lasts 20–40 years (the start date appears in the lower left corner, the end date in the lower right corner and the duration in the center)

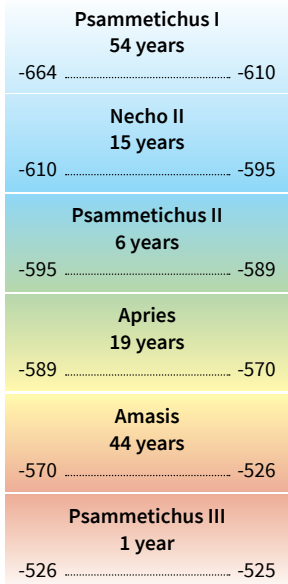


Fig. 2: Example of a sequence: the Twenty-sixth Egyptian Dynasty, with known dates and durations

can represent, for example, a dynasty, a stratigraphic sequence, or a sequence of cultural phases. Fig. 2 provides an example of a sequence.

Synchronisms

Synchronisms express the connections between time-periods and are what makes our models connected into a network-like structure. Clearly, there can be many types of synchronisms between two time-periods, and the chronological networks model features a precise typology of such synchronisms. We represent a synchronism as a simple line connecting two time-periods, with the type of synchronism written above the line (Fig. 3). Table 1 provides a list of the main synchronisms occurring in chronological networks, with precise definitions. For a more detailed list of synchronisms, and a detailed discussion of their chronological significance, see Levy, Piasetzky and Fantalkin 2021.

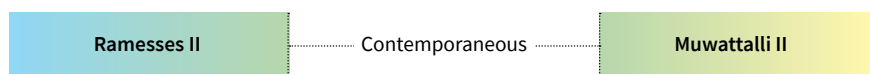


Fig. 3: Example of a synchronism between Egyptian pharaoh Ramesses II and Hittite king Muwattalli II; these kings wrote letters to each other, implying that their reigns intersect at some point; the contemporaneity synchronism used here is one of the simplest types of synchronisms, expressing merely that the two time-periods intersect at some point, but that we have no further knowledge of the relation between the two time-periods

Table 1: Examples of the main types of synchronisms used in the “chronological networks” model (in the figures, time flows from above to below)

Name	Image
Contemporaneity (A contemporary with B)	
Inclusion (A included in B)	
Overlap (A overlaps with next period B)	
Starts during (A starts during B)	
Ends during (A ends during B)	
Synchronized start	
Synchronized end	
Equality	
Ordered boundaries	$A \left\{ \begin{array}{l} \text{starts} \\ \text{ends} \end{array} \right. \left\{ \begin{array}{l} \text{before} \\ \text{after} \end{array} \right. \left\{ \begin{array}{l} \text{start of} \\ \text{end of} \end{array} \right. B$
Delay synchronism	$A \left\{ \begin{array}{l} \text{starts} \\ \text{ends} \end{array} \right. \left\{ \begin{array}{l} \text{exactly} \\ \text{at least} \\ \text{at most} \end{array} \right. \left\{ \begin{array}{l} X \text{ years} \\ \text{before} \\ \text{after} \end{array} \right. \left\{ \begin{array}{l} \text{start of} \\ \text{end of} \end{array} \right. B$

Example

Fig. 4 provides an example of a simple chronological network (dubbed “ChronoLand”), featuring two strata, two kings and two synchronisms. The strata have unknown dates but a supposed duration of between 20 and 100 years. The first king, Albert, has a reign of at least ten years, starting no earlier than 1200 CE. The second king, Baldwin, has a reign of at least 35 years, ending no later than 1300 CE. It is known from historical and archaeological sources that Stratum 2 starts during the reign of Albert and Stratum 1 ends during the reign of Baldwin. Why does this model constitute a network? First, because the periods are connected to each other via synchronisms, and second, because this connection implies that any change to the dates or duration of one time-period has the potential to affect the dating (or duration) of other time-periods.

Computing Chronologies

Clearly, the model outlined above enables us to represent a wide variety of chronological data, including relative and absolute chronological knowledge. Yet as such, it only dealt with the representation of data, not with computational issues. We now illustrate the need of chronological software to not only encode

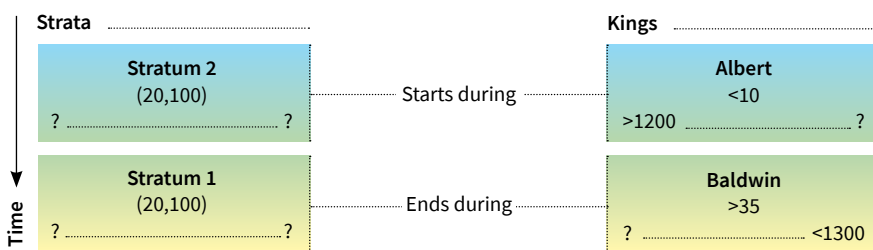


Fig. 4: Example of a small chronological network, featuring two sequences, the first representing a stratigraphic sequence (an earlier stratum [Stratum 2] followed by a later stratum [Stratum 1]) and the second one a dynastic sequence (King Albert followed by King Baldwin); this example illustrates the representation of partial chronological knowledge in the time-periods and shows the use of two different types of synchronisms to represent the relation between Stratum 2 and Albert and between Stratum 1 and Baldwin

and visualize the data, but also to automate chronology building based on these data. Indeed, when looking at the example of Fig. 4 above, we are still in want of a chronology. How can all the displayed data be combined into a chronology? In other words, what are the tightest possible ranges one can obtain for the start and end date (and duration) of each time-period? Clearly, the presence of synchronisms must help us deduce at least some information regarding the absolute dates of the strata and kings. Hence, we need a tool to compute such a chronology, and to ensure that the computed chronology is the tightest (i.e., most precise) one that can be deduced from the available data.

Tightening

The tightest possible chronology one can deduce from the network of Fig. 4 is shown in Fig. 5: the strata are now assigned a duration of at most 80 years, Albert starts reigning no later than 1260, dies between 1200 and 1265, and Baldwin dies no earlier than 1240. In the same way, earliest and latest start/end dates have been computed for each stratum. These new dates derive from a phenomenon we have called “chronological propagation”: dates of a given time-period propagate to neighboring time-periods following the available synchronisms, and affect their neighbors in different ways, depending on the precise types of synchronisms involved (for a precise characterization of the propagation behaviour of each type of synchronism, see Levy, Piasetzky and Fantalkin 2021). In this case, the 1300 CE latest end of Baldwin propagates to

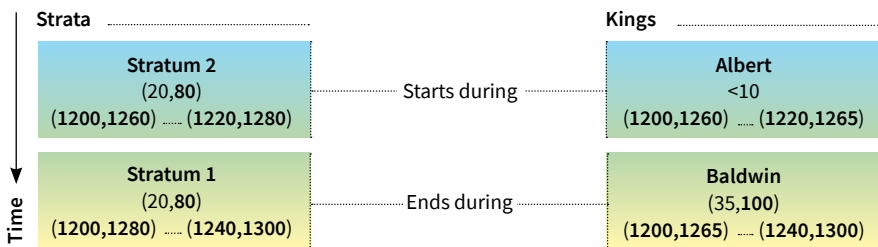


Fig. 5: The tight chronology deduced from the network of Fig. 4; updated results have been computed for the start, end and durations of each time-period (tightened results are shown in bold)

the latest end of Stratum 1 via the “ends during” synchronism. It then combines with the 20-year minimum stratum duration to provide Stratum 1’s earliest start of 1280 CE. This date then propagates to the end of Stratum 2, where it combines again with the minimum duration to provide Stratum 2’s earliest start of 1260 CE, which in turn propagates to King Albert via the “starts during” synchronism, providing Albert’s earliest start of 1260 CE. In short, a date coming from Baldwin (1300 CE) propagated all the way to Albert, via Strata 1 and 2, incorporating minimum durations along the way. Clearly, spotting such propagation paths with the naked eye is a challenging task. A computational approach is therefore required. Furthermore, each period is affected by many different propagation paths, thus necessitating a clever approach to find the path yielding the most precise chronological results. We call the search of such precise chronological bounds (i.e., the tightest possible results for the start dates, end dates and durations) the “tightening operation” (see Levy *et al.* 2021: 6–7 for a full discussion).

Consistency Check

Clearly, chronological data can at times be inconsistent. Hence, even before computing the tight chronology of a chronological network, we must check its consistency. The chronological network of Fig. 6 shows a modified version of the previous network, in which Baldwin is awarded at most 25 years of reign (instead of at least 35). Such a model is not consistent—i.e., its data are contradictory. Detecting the inconsistency with the naked eye is a challenging task. The problem is the following: with the new data, the whole dynasty lasts at most 35 years (10+25), but the stratigraphic sequence lasts at least 40 years (20+20). Yet the two synchronisms imply that the stratigraphic sequence starts and end within the lifetime of the dynasty. In other words, we must make (at least) 40 years fit within (at most) 35 years, which is impossible.

The two examples given here are meant to convey the message that checking and computing chronologies is a difficult task to perform with the naked eye, even on a small model with only four time-periods, let alone on real-life case

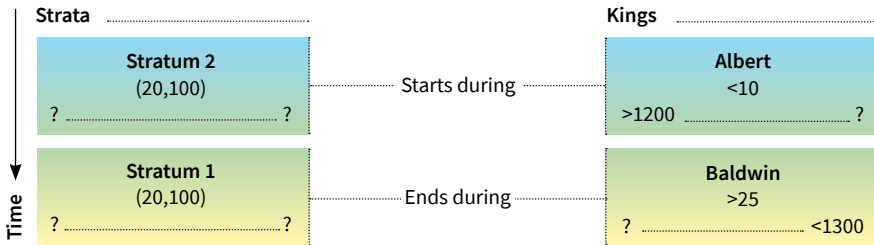


Fig. 6: Example of an inconsistent model; Baldwin is now awarded at most 25 years of reign (instead of at least 35); the model is inconsistent because the minimum 40 years of the two strata cannot be made to fit within the timespan of the dynasty, restricted to at most 35 years

studies involving dozens (or hundreds) of time-periods. We conclude that one cannot achieve this task without recourse to specialized software. The next section presents the ChronoLog software, which we have developed precisely for such purposes.

ChronoLog

ChronoLog is a software tool designed for archaeologists and historians to encode their chronological data in the shape of a chronological network, to check the consistency of the data, and to automate the building of chronologies (tightening). The main idea of the software is to offer a user-friendly tool which requires no mathematical knowledge on the part of the users, and which enables them to test several different chronological scenarios, and immediately see the outcome of different chronological hypotheses. The software is fast, enabling users to work with very large networks, and it also provides a detailed report (called a “trace”) of each computed result. ChronoLog is available for free at chrono.ulb.be, and consists of a Java executable file (JAR file). ChronoLog runs on any operating system (Windows, MacOS, Linux, a.o.) with a recent Java installation (note that JAVA can be downloaded free of charge at java.com/en/download/).

Encoding the Network

ChronoLog enables users to encode their chronological network by point-and-click (see the online user manual for more details, though the software’s interface is quite self-explanatory). Fig. 7 illustrates the model presented above (Fig. 4), as encoded in ChronoLog. The graphical syntax is similar to that used in the theoretical chronological networks exposed above: duration at the center of the time-period, start date at the bottom left, end date at the bottom right. Clicking on a time-period enables the changing of its start date, end date or duration, and clicking on a synchronism enables the changing of the type of synchronism. New synchronisms are created simply by joining two periods with the mouse. New sequences and periods can be created directly by the user by clicking the “Add period” button, or by inserting a predefined sequence from ChronoLog’s library of standard sequences, including Egyptian, Mesopotamian, Greek and Hittite sequences (among others).

Testing Hypotheses

ChronoLog automatically launches a consistency check whenever new data is added to the model and, if the model is consistent, it launches the tightening procedure to update the chronology. Any updated value (start date, end date, or duration) is shown in red, in order to ease visualization of the impact of the new data.

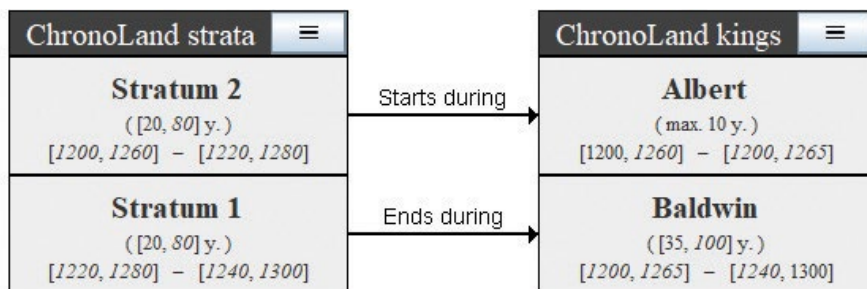


Fig. 7: The model of Fig. 4, encoded in ChronoLog; the straight numbers represent the inputs, while the italicized ones represent the updated dates and durations obtained via the tightening procedure

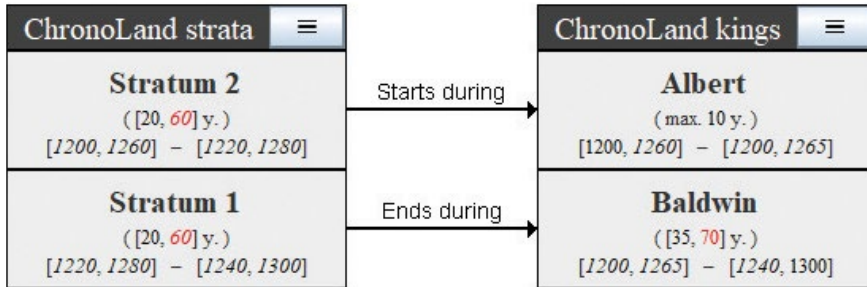


Fig. 8: Updating the network: setting a 70-year maximum duration for Baldwin yields a 60-year maximum duration for each stratum (changes shown in red)

Fig. 8 provides an example in which the user changes the maximum duration of Baldwin to 70 years (recall from Fig. 4 that Baldwin was not awarded any maximum duration before) and wishes to see if that change will impact the chronology. One sees in red that this change modified the maximum duration of both strata from 80 to 60 years. Performing such trials lies at the core of the ChronoLog philosophy: we see chronology as something fluid, where different hypotheses should be envisioned and their outcomes assessed, rather than as a monolithic field where dates are considered “frozen” and not subject to alternative interpretations.

Trace Reporting

When ChronoLog detects an inconsistency in a model, it provides a detailed report explaining why the model is inconsistent. Such reports are called traces. In the same way, for each computed date (or duration), the user can ask for a trace explaining the full propagation path that led to that result. Fig. 9 provides an example showing the trace for the 1280 latest start of Stratum 1. ChronoLog produces both a trace in textual form (featuring mathematical inequalities and the chain of involved time-periods) and a visual trace by coloring in pink all the time-periods and synchronisms involved in the propagation path. In this example, one sees that the 1280 CE result for Stratum 1 derives from the 1300 CE latest end of Baldwin, which propagates to the end of Stratum 1 via the “ends

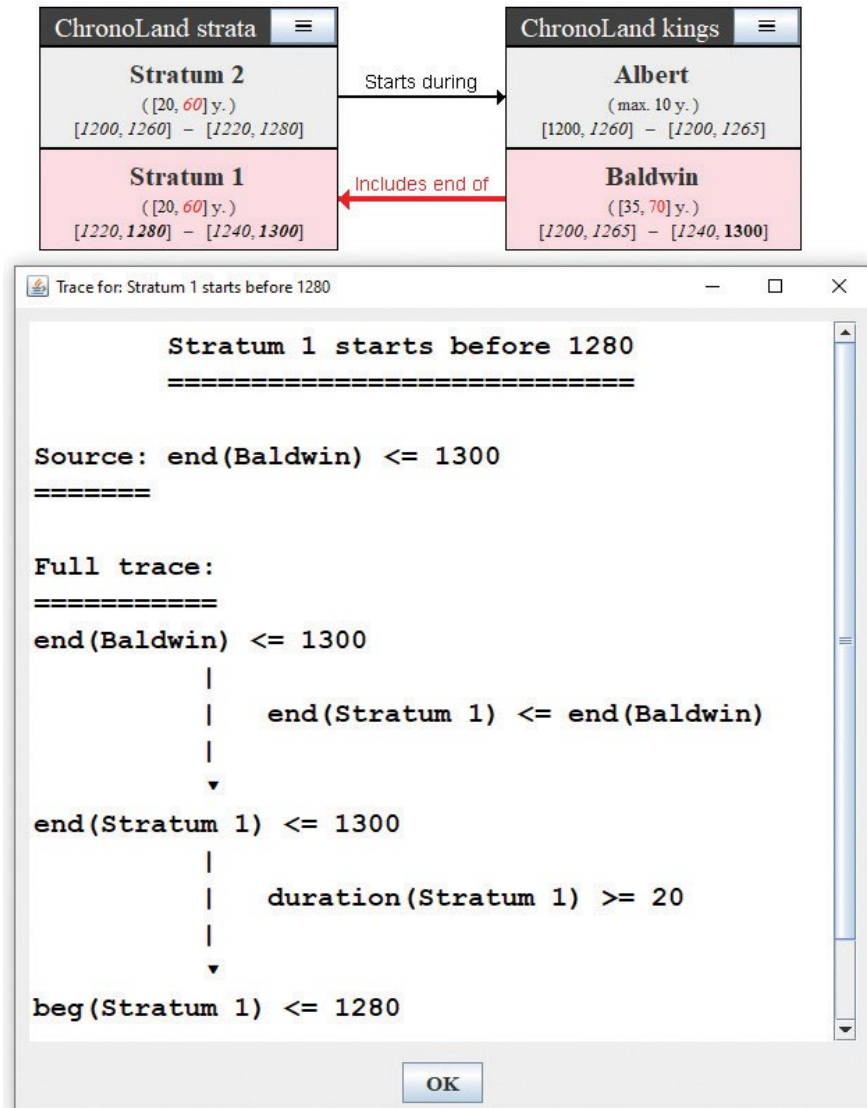


Fig. 9: Example of trace reporting; the trace, shown graphically in pink and also textually, shows that the 1280 CE latest start of Stratum 1 derives from the 1300 CE latest end of Baldwin, then propagates to the end of Stratum 1 via the “ends during” synchronism, then propagates to the start of Stratum 1 via that stratum’s 20-year minimum duration

during” synchronism, then propagates to the start of Stratum 1 via the 20-year minimum duration. For large models, identifying long propagation paths with the naked eye is a complex task; hence the need for a computational tool to find the traces. Furthermore, trace reporting (coupled with an explicit encoding of all the ground hypotheses of a given chronological discourse) is indispensable for chronological results to be falsifiable, that is, for enabling researchers to check the accuracy of a claimed chronology. In other words, each chronological result claimed by ChronoLog is purely deductive, based on the encoded data, and verifiable by the user through the reported trace.

Tagging

An additional feature of ChronoLog is that it allows users to tag their sequences with (free-text) keywords such as “stratigraphic,” “epigraphic,” or “radiocarbon” (among others), in order to identify the type of information involved in a given sequence. This enables users to obtain selective chronologies with just a click of the mouse. For example, one might wish to check how the removal of all stratigraphic data would affect the chronology of a region. This allows the production of not only one given chronology for a given chronological network, but several different chronologies, depending on the type of information taken as ground data. As an example, Fig. 10 shows our same basic model, with the list of tags displayed under the main panel. We have unchecked the “Stratigraphy” checkbox, which automatically excludes the two strata from the model and recomputes the chronology. We can see (in red) how the latest start and earliest end of Baldwin have been affected by the removal of the strata.

Radiocarbon

Radiocarbon dates, expressed as ranges (e.g., 900–800 BCE), can be directly included into ChronoLog. Yet ChronoLog does not use probabilities; hence, the probabilistic confidence level (e.g., 68% or 95%) associated to the radiocarbon result is not taken into account by ChronoLog. The inclusion of a radiocarbon result into ChronoLog is treated just like any other piece of data: it is considered

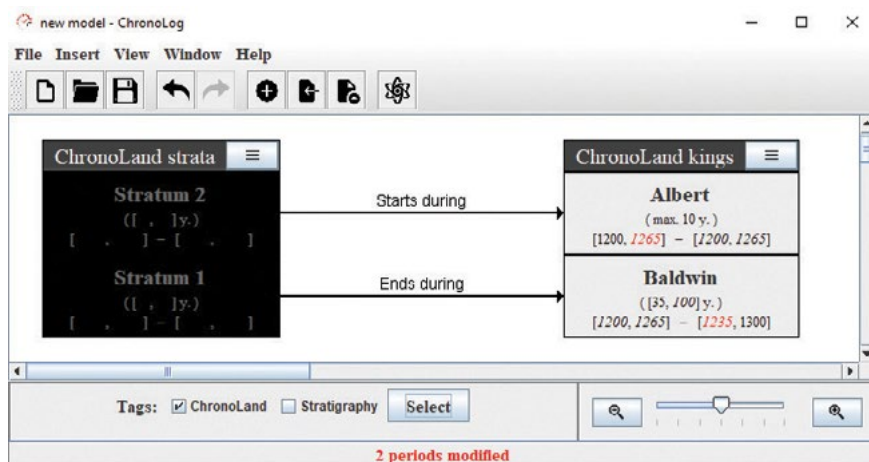


Fig. 10: Example of tagging; the strata have been removed from the model by unchecking the “Stratigraphic” tag at the bottom of the window; as a result, Albert now has a latest start of 1265 CE instead of 1260 CE and Baldwin an earliest end of 1235 CE instead of 1240 CE (the image also displays the full ChronoLog window, including its menu, toolbar and status bar)

true (unless an inconsistency is detected) and used for constructing the chronology. An example of a large ChronoLog model including radiocarbon dates has been presented in Levy *et al.* 2022a. This model evaluates the date of appearance of Philistine pottery at Megiddo under a variety of hypotheses regarding strata durations, Egyptian synchronisms, and inclusion/exclusion of radiocarbon results. Using the mechanism of tags described above, it allowed us to propose several computer-generated chronologies for the event under discussion and to better assess the respective contribution of historical data vs. radiocarbon results in the obtaining of the final chronology.

A totally different approach is possible, consisting of using ChronoLog as a graphical user interface for building Bayesian radiocarbon models for the OxCal software (c14.arch.ox.ac.uk/oxcal/OxCal.html). OxCal is the most widely used tool for building Bayesian radiocarbon models. The goals of such models is to incorporate prior chronological knowledge (dates, durations, synchronisms) into the radiocarbon calibration process in order to obtain more precise

radiocarbon dating results. However, building an OxCal model is a technical task, for which many archaeologists have to rely on the help of a radiocarbon specialist. ChronoLog enables archaeologists to build complex OxCal models by themselves, with just a few clicks of the mouse. They first build a regular chronological model using ChronoLog, representing the prior chronological data, then encode all their radiocarbon (uncalibrated) determinations directly into ChronoLog, and finally click on a button which automatically generates the OxCal model. This approach was described in detail in Levy *et al.* 2022b. Fig. 11 shows the ChronoLog interface for encoding radiocarbon determinations. Once encoded, the user chooses between either saving the generated OxCal script directly on his own computer, or having ChronoLog directly connect to the OxCal website and open the model there.

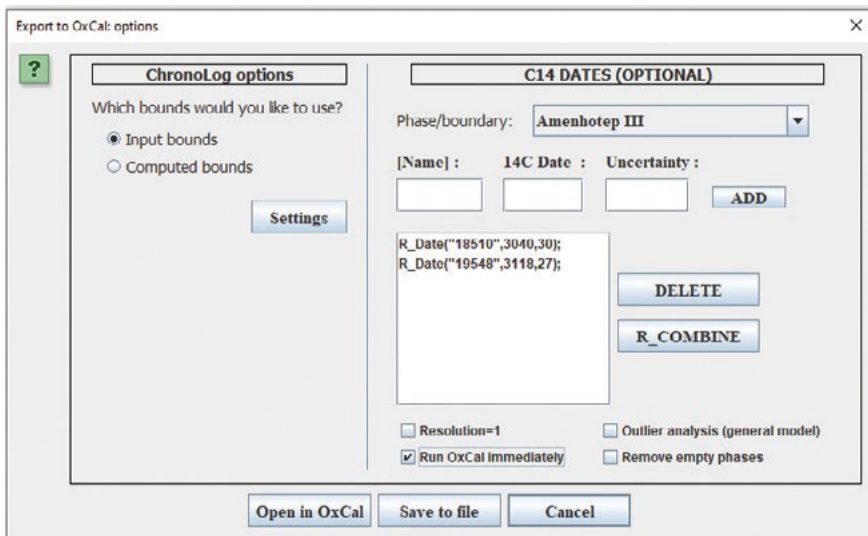


Fig. 11: The ChronoLog radiocarbon encoding dialogue

Conclusion

This paper briefly summarizes our approach to chronological modelling in archaeology. We presented our concept of chronological networks—formalizing the concept of interconnected chronological data (see Levy *et al.* 2021)—and our concept of chronological propagation—formalizing the classical notion of archaeological cross-dating (see Levy, Piasezky and Fantalkin 2021). We then presented the ChronoLog software (chrono.ulb.be), which implements these two notions, allowing users to build chronological networks by themselves, to check their consistency, to obtain a computer-generated chronology based on their data, to test chronological hypotheses, and also to automatically generate radiocarbon Bayesian models for OxCal. To the best of our knowledge, no other tool currently provides an equivalent range of chronological features. ChronoLog is still under active development, with new versions being posted online every six months, approximately.

The advantages of the ChronoLog for engaging chronological debates in archaeology are manifold: 1) all the chronological ground hypotheses of the debate are clearly laid on the table, in the ChronoLog model, with no hidden assumptions or “rules of thumb”; 2) every claimed result (computed date or duration) is fully traceable, hence verifiable by human users; 3) any inconsistency in the data is automatically detected and reported by the software; and 4) users can generate several different chronologies for a given case study, depending on the type of data one wishes to include in the model. Case studies published so far have applied this methodology to the Twenty-sixth Egyptian Dynasty (Levy *et al.* 2021: 20–26), to Aegean Late Bronze Age chronology (Levy, Piasezky and Fantalkin 2021: 16–29), to Philistine chronology (Levy *et al.* 2022a) and to several case studies related to Bayesian modelling (Levy *et al.* 2022b).

This brief summary does not permit us to touch on the technical details behind ChronoLog. The chronological computations performed by ChronoLog require complex algorithmic techniques which have been described in full mathematical detail in Geeraerts, Levy and Pluquet 2017, and in a more succinct way in Levy *et al.* 2021. In a nutshell, the set of chronological

constraints encoded in a chronological network is translated into a directed graph (a mathematical model representing a network), on which shortest-path algorithms are applied in order to compute the chronology. In a way, finding the tightest possible chronology is similar to finding the shortest path from one point to the other using a car navigation system, but with chronological events instead of geographical locations and time delays instead of geographical distances. To the best of our knowledge, such algorithmic techniques have not been previously applied to archaeological chronology. For future versions of ChronoLog, we plan to continue exploiting a wide array of algorithmic techniques in order to automatically detect new synchronisms, to provide a quantitative assessment of the strength of given chronological results, expressed in terms of the number of different propagation paths supporting these results (see Levy, Piasezky and Finkelstein 2020 for preliminary steps in that direction), and to automatically detect chronological data that do not contribute to the final computed chronology.

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