

Current Protocols in Bioinformatics

Eukaryotic Linear Motifs on the ELM database

Marc Gouw¹, Hugo Samano¹, Kim Van Roey¹, Francesca Diella¹, Toby Gibson¹, Holger Dinkel^{1,2}

¹ *Structural and Computational Biology, European Molecular Biology Laboratory, Meyerhofstrasse 1, 69117 Heidelberg, Germany*

² *Leibniz-Institute on Aging – Fritz Lipmann Institute (FLI), Beutenbergstrasse 11, 07745 Jena, Germany*

Keywords

Linear motifs, Bioinformatics, Protein-Protein Interaction, Molecular switches, Cell regulation

Significance statement

Abstract

The Eukaryotic Linear Motif (ELM) resource (elm.eu.org) is a manually curated database of short linear motifs (SLiMs). This protocol explains how to best use this resource and explains how to access the database content (both manual and scripted access), how to interpret the output, and how to predict novel putative motifs in any given protein sequence.

Introduction

The activity and function of a protein is tightly regulated by its cellular environment. To interact with their surroundings, proteins use various types of binding modules that each display distinct binding properties Wright and Dyson (1999). One prominent type of binding module consists of short linear motifs (SLiMs) Diella (2008). These compact binding sites are generally located in intrinsically disordered regions (IDR) of the proteome and commonly bind to surface of a globular domain in a protein Davey et al. (2012). SLiMs mediate different types of interactions that regulate protein functionality, and hence are important regulators of the dynamic processes involved in cell signalling Van Roey et al. (2012; 2014) (Figure 1). The number of SLiM instances in the human proteome is currently suggested to be over one million Tompa et al. (2014). Identifying SLiMs and elucidating their functionality is an essential step in understanding cell regulation. The Eukaryotic Linear Motif (ELM) resource contributes to this process by providing the necessary tools to researchers working on motifs. It consists of a database and a prediction tool. The database provides a categorised repository of experimentally validated linear motif classes and instances that were manually annotated from the literature. The ELM prediction tool in turn relies on annotated data, both from the ELM database and other resources, to accurately analyse unknown sequences for candidate motifs and assist researchers in selecting the most plausible ones for experimental validation

and discard likely false positive hits, saving them valuable time and assets Dinkel et al. (2012). The following protocols will guide users through the different ELM applications, explaining how to browse the curated data available in ELM, how to analyse a protein sequence for putative motifs, and how to interpret these data and avoid common pitfalls in SLiM discovery.

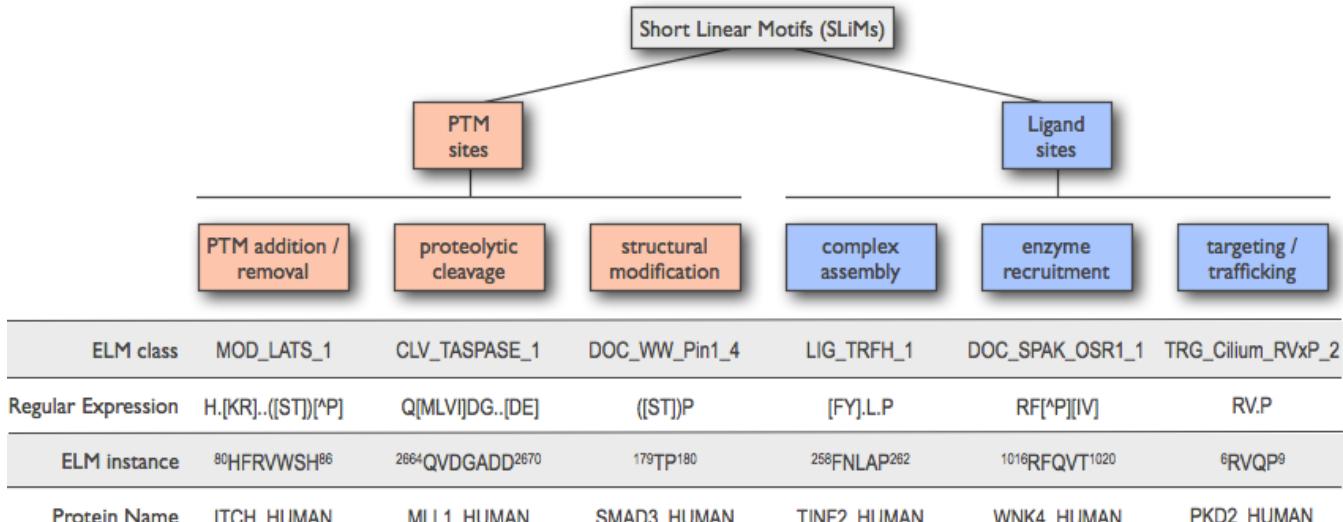


Figure 1: For each ELM class, the functional category to which it belongs is indicated by a three-letter prefix. Each ELM class is defined by a regular expression. Peptide sequences in proteins that match the regular expression of a specific ELM class and that were experimentally validated to be functional motifs are captured as ELM instances of that class. Degrons are a specific subtype of enzyme-recruiting docking motifs (see text for a detailed description).

(Basic): Explore the content of the ELM DB

The core of the ELM database is a repository of manually annotated motifs and instances. As of December 2016, ELM contains over 260 motif classes categorized into 6 different types: DOC (docking), LIG (Ligand binding), DEG (degradation), CLV (cleavage), MOD (post translational modifications), and TRG (targeting/anchoring) motifs (Figure functional_classification_of_SLiMs). These motifs are derived from various types of experiments reported in literature. Each manually annotated motif also has a set of bona fide instances (occurrences) of this motif. Currently, there are over 3000 annotated instances annotated from over 2500 publications. The motif classes and motif instances have been uploaded by a large group of annotators from around the globe. The complete catalogue of manually curated data can be searched, browsed and explored on the ELM website

TODO MARC: explain: elms, annotations, classes, instances, regular expressions. And links to GO, methods PSI. we use DOC CYCLIN etc as example.

Necessary Resources

Software & Hardware

A modern browser such as Firefox, Chrome, or Safari. ELM is best viewed on a laptop or desktop computer, although tablets and smartphones will also work.

Database content overview

The screenshot shows the ELM database homepage. At the top, there is a navigation bar with links to "ELM Home", "ELM Prediction", "ELM DB", "ELM Candidates", "ELM Information", "ELM downloads", and "Help". The main content area features a heading "Welcome to the Eukaryotic Linear Motif (ELM) resource". Below this, a text block explains the purpose of the database, mentioning eukaryotic linear motifs (SLiMs) and their biological roles. To the right of the text is a 3D molecular structure visualization. Further down, there is a "Protein sequence" input field with placeholder text "Enter Uniprot identifier or accession number: (auto-completion) e.g. EPN1_HUMAN, P04637, TAU_HUMAN, [RANDOM]". Below it is a text area for pasting sequences. At the bottom of the main content area, there are two buttons: "Cell compartment (one or several)" and "Taxonomic Context". To the right of the main content area is a vertical sidebar titled "PDB-Structure 1SDZ showing a peptide from ELM class LIG_BIR_III_3". This sidebar contains a list of recent database updates, each with a small red square icon:

- ELM database update
We have added new instances for: **LIG_APCC_ABBA_1**, **LIG_APCC_ABBAvCdc20_2** as well as **DOC_MAPK_HePTP_8**, **DOC_MAPK_MEF2A_6** and **DOC_MAPK_DCC_7**
- ELM Database Update
We have updated several MOD_CDK motifs and added new instances:
MOD_CDK_1 is now: **MOD_CDK_SPxK_1**, and **MOD_CDK_SPK_2**. **MOD_CDK_SPxxK_3** have been added.
- ELM database update
Several new ELM classes and instances have been added:
LIG_BH_BH3_1, **DEG_COP1_1**
- ELM database update
The class **DOC_PP2A_KARD_1** has been replaced by **DOC_PP2A_B56_1**, and new instances have been added.

Figure 2: The homepage of the ELM database (elm.eu.org).

1. The ELM database is an online web resource. Open a browser and navigate to elm.eu.org to visit the homepage (Fig. 2). This page shows a brief explanation of the ELM resource, and a form to search for SLiMs (which we cover in further detail in [Protocol 3](#) and [Protocol 4](#)). The column to the right is the news column, and is continually updated with the latest news about changes and additions to the database.
2. On the ELM homepage click on the menu link **ELM DB** for an overview of the database statistics (Fig. 3). This page displays the types and amounts of annotations contained in the database and

The ELM relational database stores different types of data about experimentally validated SLIMs that are manually curated from the literature. ELM instances are classified by motif type, functional site and ELM class. A functional site contains one to many ELM classes, which are described by a regular expression and list experimentally validated motif instances matching this sequence pattern. All data curated in ELM DB can be searched on the ELM website according to the following categories:

- 262 annotated ELM classes**
- 3,026** experimentally validated **ELM instances** in **197** taxons
- 113 ELM methods** described in **2,975** articles to experimentally validate ELM instances
- 428 solved PDB structures** for curated ELM instances (from [PDB](#))
- 131 globular ELM binding domains** (from [Pfam](#), [SMART](#), and [InterPro](#))
- 1,425 interactions** mediated by curated ELM instances
- 879 regulatory switches** mediated by curated ELM instances (from [Switches.ELM DB](#))
- 784 pathways** from [KEGG](#) involving linear motifs annotated in **832** Sequences
- 242 viral instances** interfering with host cellular processes
- 11 ELM related diseases** annotated as being caused by aberrant motif function
- 2 examples where pathogens abuse** motifs to deregulate host cells

Search ELM Instances and Classes

Please cite: [ELM 2016-data update and new functionality of the eukaryotic linear motif resource. \(PMID: 26615199\)](#)

ELM data can be downloaded & distributed for non-commercial use according to the [ELM Software License Agreement](#)

feedback@elm.eu.org

Recent database updates:

- ELM database update
We have added new instances for: **LIG_APCC_ABBA_1**, **LIG_APCC_ABBAvCdc20_2** as well as **DOC_MAPK_HePTP_8**, **DOC_MAPK_MEF2A_6** and **DOC_MAPK_DCC_7**
- ELM Database Update
We have updated several MOD_CDK motifs and added new instances:
MOD_CDK_1 is now: **MOD_CDK_SPxK_1**, and **MOD_CDK_SPK_2**. **MOD_CDK_SPxxK_3** have been added.
- ELM database update
Several new ELM classes and instances have been added:
LIG_BH_BH3_1, **DEG_COP1_1**
- ELM database update
The class **DOC_PP2A_KARD_1** has been replaced by **DOC_PP2A_B56_1**, and new instances have been added.
- ELM database update
Several new ELM classes and instances have been added:
LIG_CSK_EPIYA_1, **LIG_Rb_LxCxE_1**, **DOC_MAPK_JIP1_4**, **DOC_MAPK_NFAT4_5**
- ELM database update
Several new ELM classes and instances have been added.

Figure 3: The ELM database statistics overview page shows the most up to date database statistics. As of January 2017 ELM has just over 3000 annotated instances in 262 different motif classes.

a few links to third-part databases. Each line contains at least one link which will take you to the corresponding contents page (for example, clicking on **ELM instances** will take you to the page displaying all of the annotated instances in the database).

Browsing motif classes and annotated instances

- Click on the sub-menu **ELM classes** under **ELM DB** to visit the page listing all of the ELM classes (Fig. 4). For each class, the following information is provided: ELM identifier, short description, regular expression, number of instances annotated for each class, and number of structures available. For details on each class, click on the ELM identifier; to get a list of annotated instances for an individual class, click on the number of instances.

Use the search bar at the top of the page to filter for certain motif classes. For example, typing “MAPK” and hitting submit will perform a full-text search on all motif classes in the ELM database containing the term “MAPK”. The green buttons on the left can also be used to filter

Figure 4: The list of all motif classes annotated in the ELM database.

this table. For example, toggling the “DOC” button will remove all DOC classes from the table (and clicking it again will bring them back). Lastly, the yellow tsv link can be used to export all motif classes as a “tab separated values” file.

4. Search the table for the term DOC_CYCLIN_1 and click on **DOC_CYCLIN_1** in the left column to navigate to the page with details about the DOC_CYCLIN_1 motif class (Fig. 5). This page contains a description of the functional site class (a Cyclin recognition site), and a short description of the ELM and its regular expression, as well as a probability score, the taxonomic distribution of the motif and which domain (if any) is responsible for the interaction.

The probability score is the probability that the regular expression represents a random selection of amino acids (similar to an information content score). A lower score indicates that the motif pattern is more difficult to find by chance in a random sequence.

5. Scroll further down the DOC_CYCLIN_1 page (Fig. 5) to view more details about the manually annotated data and instances in the database (Fig. 6) The “abstract” contains a more detailed de-

The Eukaryotic Linear Motif resource for Functional Sites in Proteins

search ELM Database

ELM Home ELM Prediction ELM DB ELM Candidates ELM Information ELM downloads admin

«DOC_CKS1_1» »DOC_GSK3_Axin_1»

DOC_CYCLIN_1

Accession: ELME000106

Functional site class: Cyclin recognition site

Functional site description: Functional site that interacts with cyclins, and thereby increases the specificity of phosphorylation by cyclin/CDK complexes.

ELM Description: Substrate recognition site that interacts with cyclin and thereby increases phosphorylation by cyclin/cdk complexes. Predicted proteins should have a CDK phosphorylation site ([MOD_CDK_1](#)). Also used by cyclin/cdk inhibitors.

Pattern: [RK].L.{0,1}[FYLIVMP]

Pattern Probability: 0.0053239

Present in taxon: Eukaryota

Interaction Domain: Cyclin_N (PF00134) Cyclin, N-terminal domain (Stoichiometry: 1 : 1)

PDB Structure: [1JSU](#)



■ See 24 Instances for DOC_CYCLIN_1

■ **Abstract**

The cyclin recognition site (alias Cy or RxL motif) is found in a wide range of cyclin/CDK interacting proteins ([Takeda,2001](#)). The presence of this motif in CDK substrates substantially increases the level of phosphorylation at ([ST])Px[KR] motifs ([MOD_CDK_1](#)). Example proteins are the retinoblastoma protein, E2F 1-3 and p53. CDK phosphorylation mainly occurs in the nucleus but there also is some evidence for cytoplasmic function. For example, the cytoplasmic SRC and TAU proteins are known cyclin/CDK targets. The motif is recognised by a conserved region in the cyclin protein and binds in a similar manner as the p21Kip cyclin inhibitor ([1JSU](#)).

■ **4 selected references:** [Show](#)

■ **5 GO-Terms:** [Show](#)

Figure 5: The motif details page for DOC_CYCLIN_1 . This page contains all of the manual annotation details for the DOC_CYCLIN_1 motif, the biological background summarized from the scientific literature including links to the primary literature and to external resources (Pubmed [Coordinators \(2017\)](#), the Gene Ontology [Consortium \(2017\)](#), PDB ([Berman et al. \(2002\)](#)) and more).

scription of the motif annotation. Click on the **show** button next to the “selected references” header for a list of publications relevant to this motif. Click on **show** next to “GO terms” for a complete list of all Gene Ontology (GO) terms annotated for this motif.

6. Scroll further down the DOC_CYCLIN_1 page to view the “Instances” header (Fig. 6) This table contains the list of all annotated DOC_CYCLIN_1 instances in the database of this motif. This includes the protein identifier, the start and end positions of the instance, the specific sequence matching the regular expression representing the motif and the “logic” of the instance. The “# Ev.” indicates the number of experimental evidences associated with the annotation. “Organism” indicates in which species in which the protein is found. Lastly the “Notes” column contains links to any “interactions” or “switches” present in the database, as well as links to PDB if this structure exists in PDB.

Abstract

The cyclin recognition site (alias Cy or RxL motif) is found in a wide range of cyclin/CDK interacting proteins (Takeda, 2001). The presence of this motif in CDK substrates substantially increases the level of phosphorylation at [(ST)Px[KR] motifs (MOD_CDK_1). Example proteins are the retinoblastoma protein, E2F 1-3 and p53. CDK phosphorylation mainly occurs in the nucleus but there also is some evidence for cytoplasmic function. For example, the cytoplasmic SRC and TAU proteins are known cyclin/CDK targets. The motif is recognised by a conserved region in the cyclin protein and binds in a similar manner as the p21kip cyclin inhibitor (1JSU).

4 selected references: Show

5 GO-Terms: Show

24 Instances for DOC_CYCLIN_1
(click table headers for sorting; Notes column: ⚡ =Number of Switches, ⚪ =Number of Interactions)

Acc., Gene-, Name	Start	End	Subsequence	Logic	#Ev.	Organism	Notes
P04637 TP53 P53_HUMAN	381	385	GQSTSRRKKLMFKTEGPDS	TP	4	Homo sapiens (Human)	1H26
P46527 CDKN1B CDN1B_HUMAN	30	33	EHPKPSACRNLFGPVDHEEL	TP	5	Homo sapiens (Human)	1H27 1JSU
P38936 CDKN1A CDN1A_HUMAN	19	22	NPCGSKACRRLFGPVDSEQL	TP	4	Homo sapiens (Human)	1 1
P06789 E1 VE1 HPV18	127	130	NSGQKKAKRRLFTISDSGYG	TP	3	Human papillomavirus type 18	1
Q99741 CDC6 CDC6_HUMAN	94	98	HSHTLKGBRLLVFDNQLTIKS	TP	2	Homo sapiens (Human)	2CCH
Q14207 NPAT NPAT_HUMAN	1062	1066	AAKPCHRRLVCFDSTTAPVA	TP	1	Homo sapiens (Human)	
P39880 CUX1 CUX1_HUMAN	1301	1305	NYRSRIRRLFIEEIQAGSQ	TP	1	Homo sapiens (Human)	
P38826 ORC6 ORC6_YEAST	178	182	ESPSITRKLAFFEEDEDEDE	TP	1	Saccharomyces cerevisiae (Baker's yeast)	
Q9WTQ5 Akap12 AKA12_MOUSE	501	504	IKVQGSPLKKLFSSSGLKKL	TP	1	Mus musculus (House mouse)	1
Q00716 E2F3 E2F3_HUMAN	134	138	GGGPPAKRRLELGESGHQYL	TP	1	Homo sapiens (Human)	
Q14209 E2F2 E2F2_HUMAN	87	91	AGRPAKRKLDEGIGRPVV	TP	1	Homo sapiens (Human)	
Q01094 E2F1 E2F1_HUMAN	90	94	LGRPPVKRRLDILETDHOYLA	TP	3	Homo sapiens (Human)	1H24
P50445 rnx

Figure 6: The second part of the DOC_CYCLIN_1 motif details page shows the motif abstract GO terms, and the list of annotated instances.

The instance “logic” is an annotation of whether this is a bona-fide instance, or whether it is a non-functional instance. TP (True positive) indicates the instance is annotated with experimental evidence showing it is functional. FP (False Positive) instances have experimental evidence suggesting function, but are believed to be non-functional after careful examination by our annotators. TN (True Negative) instances have been experimentally determined to be non-functional, and U (Unknown) instances do not have enough evidence to determine whether it is functional or not. The overwhelming majority of instances in ELM are TPs.

- Click on the sub-menu **ELM instances** in **ELM DB** to visit the page where you can search and browse the instances annotated in ELM. (Fig. 7). Note that only the first 100 instances matching the search criteria are shown. The search form can be used to filter results by a full text search, by instance logic, or organisms.

This table can be filtered by motif class using the green toggle filters on the left hand side. Lastly, the yellow buttons at the top of the page can be used to download the instances in the following

The Eukaryotic Linear Motif resource for Functional Sites in Proteins

search ELM Database

ELM Home ELM Prediction ELM DB ELM Candidates ELM Information ELM downloads admin

Search ELM Instances

Full-Text Search (use "*" to get all instances)

Filter by instance Logic
Filter by organism

submit Reset

export 100 instances as: gff pir fasta tsv

CLV	DEG	DOC	LIG	MOD	TRG	ELM identifier	Acc., Gene-, Name	Start	End	Subsequence	Logic	#Ev.	Organism	Notes
						DOC_MAPK_HePTP_8	P08018 PBS2 PBS2_YEAST	217	234	SLSARRGLKLPPGGMSLKMP	U	1	Saccharomyces cerev... 	1
						DOC_MAPK_HePTP_8	P35236 PTPN7 PTN7_HUMAN	38	50	HVR <u>QERRGSNVALD</u> VRS	TP	6	Homo sapiens (Human) 	1
						DOC_MAPK_HePTP_8	P15822 HIVEP1 ZEP1_HUMAN	1422	1437	P <u>LERRGPLVROISLN</u> IAP	TP	1	Homo sapiens (Human) 	2
						DOC_MAPK_HePTP_8	Q15256 PTPRR PTPRR_HUMAN	333	345	PI <u>GERRGSNVSLTLD</u> MSS	TP	3	Homo sapiens (Human) 	1
						DOC_MAPK_HePTP_8	P54829 PTPN5 PTN5_HUMAN	239	251	S <u>MGLERRGSNVSLTLD</u> MCT	TP	5	Homo sapiens (Human) 	3
						DOC_MAPK_HePTP_8	Q62132 Ptpr PTPRR_MOUSE	332	344	PI <u>GERRGSNVSLTLD</u> MSS	TP	3	Mus musculus (House mouse) 	2
						DOC_MAPK_HePTP_8	P06784 STE7 STE7_YEAST	7	19	RKT <u>QBRNLKGILNLN</u> IHPDV	TP	9	Saccharomyces cerev... (Baker's yeast) 	2B9H 3
						DOC_MAPK_HePTP_8	P38590 MSG5 MSG5_YEAST	26	38	PRS <u>QNRNTKNLSDIAALH</u>	TP	3	Saccharomyces cerev... (Baker's yeast) 	2B9I 1
						DOC_MAPK_HePTP_8	Q6PJF5 RHBDF2 RHDf2_HUMAN	19	31	SSR <u>QSRKPPNLSDITPP</u> E	TP	1	Homo sapiens (Human) 	1
						DOC_MAPK_HePTP_8	Q96CC6 RHBDF1 RHDF1_HUMAN	12	24	TSS <u>QRKPPNLSDITPSA</u> V	TP	3	Homo sapiens (Human) 	1

Figure 7: The “instances” page can be used to search for instances in the ELM database.

formats: *gff*, *pir*, *fasta* or *tsv*.

- Type “p53_human” in the search box to search for ELM Instances in this protein. Find the row for the ELM class DOC_CYCLIN_1 and click on the instance subsequence (highlighted in red) to go to the instance details page of this instance (Fig. 8) The top part of the page contains details about the instance and the protein it was identified in, and link to the Uniprot entry for the protein Consortium (2015).
- Scroll down to the “Instance Evidence” header to view details on the experimental evidence used to annotate this instance. The each experimental method is annotated using the Proteomics Standards Initiative Method Identifier (PSI-MI) Kerrien et al. (2007) as well as the references in which the experiments were published.

The “biosource” indicates whether method is in vivo, in vitro, in siccilo or a combination of these. The “logic” column indicates whether this experiment “supports” or “contradicts” this instance being functional. Each method is also annotated with a “reliability”, which can be any

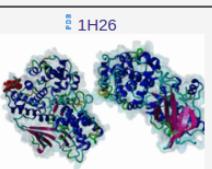
The Eukaryotic Linear Motif resource for Functional Sites in Proteins

search ELM Database

ELM Home ELM Prediction ELM DB ELM Candidates ELM Information ELM downloads admin

DOC CYCLIN_1

■ Instance

Accession	Acc. Gene-, Name	Start	End	Subsequence	Logic	PDB	Organism	Length
ELMI000051	P04637 TP53 P53_HUMAN	381	385	GQSTSRH KKLMF KTEGPDSD	TP		Homo sapiens (Human)	393

■ Instance evidence

Evidence class	PSMI	Method	BioSource	PubMed	Logic	Reliability	Notes
experimental	MI:0405	competition binding	in vitro	Luciani,2000 [PDF]	support	certain	InteractionDetection
experimental	MI:0074	mutation analysis	in vivo/in vitro	Luciani,2000 [PDF]	support	certain	FeatureDetection
experimental	MI:0065	isothermal titration calorimetry	in vitro	Lowe,2002	support	certain	InteractionDetection
experimental	MI:0114	x-ray crystallography	in vitro	Lowe,2002	support	certain	InteractionDetection FeatureDetection

■ Pathways

The sequence P04637 is implicated in the following 35 Pathways: (color codes: This sequence=red, interacting sequence=orange)

- Amyotrophic lateral sclerosis (ALS)
- Apoptosis
- Basal cell carcinoma
- Bladder cancer
- Cell cycle
- Central carbon metabolism in cancer
- Chronic myeloid leukemia
- Colorectal cancer
- Endometrial cancer
- Epstein Barr virus infection
- Gloma
- HTLV I infection
- Hepatitis B
- Hepatitis C
- Human simplex infection

Figure 8: The instance details page for the DOC_CYCLIN_1 instance annotated for protein P53_HUMAN with start/end position “381-385”. This page also contains links to many external databases including Uniprot Consortium (2015), PDB Berman et al. (2002), NCBI taxonomy, Pubmed Coordinators (2017), and KEGG Pathways Kanehisa et al. (2016), as well as the PSI-MI controlled vocabulary Kerrien et al. (2007).

of “certain”, “likely”, “unlikely” or “unspecified”.

Finding Switches and molecular interactions

10. Repeat the previous search by clicking on the sub-menu **ELM instances** under **ELM DB** and type “p53_human” in the search box. This time, find the ELM instance DOC_WW_PIN1_4 motif with the start/end position “30-35”. (You can sort the table by clicking on the header lines: click on “Start” to sort by start position). Click on the start/end position or the subsequence which will take you to the details page (Fig. 9). This page is similar to that described for the P53 instance DOC_CYCLIN_1 (Fig. 8). Additionally, for this instance there is information available about its interaction partner and a molecular switch which is mediated by this motif instance.

The Eukaryotic Linear Motif resource for Functional Sites in Proteins

search ELM Database

ELM Home ELM Prediction ELM DB ELM Candidates ELM Information ELM downloads admin

DOC WW Pin1 4

■ Instance

Accession	Acc. Gene-, Name	Start	End	Subsequence	Logic	PDB	Organism	Length
ELMI001957	P04637 TP53 P53_HUMAN	30	35	WKLLPEN N VLSP L PSQAMDD	TP	---	Homo sapiens (Human)	393

■ Instance evidence

Evidence class	PSMI	Method	BioSource	PubMed	Logic	Reliability	Notes
experimental	MI:0059	gst pull down	in vivo/in vitro	Wulf,2002 [PDF]	support	certain	InteractionDetection
experimental	MI:0074	mutation analysis	in vivo/in vitro	Wulf,2002 [PDF]	support	certain	FeatureDetection

■ Interactions

Uniprot Id	Domain family	Domain Start	Domain End	Affinity Min/Max (μ Mol)	Notes
(Q13526) PIN1_HUMAN	PF00397 (WW) WW domain	7	37		[mitab] [xml]

■ Switches

This ELM instance is part of the following 1 switching mechanism annotated at the [switches.ELM](#) resource:

- SWTI000037:

Phosphorylation of S33 in the Pin1-binding motif of Cellular tumor antigen p53 (TP53) induces binding to the Peptidyl-prolyl cis-trans isomerase NIMA-interacting 1 (PIN1) protein.

Figure 9: The instance details page for the DOC_WW_PIN1_4 instance found in Human P53 (P53_HUMAN) with start/end position “30-35”.

11. Scroll down to the “Interactions” header to view information about this instance’s interactions (Fig. 9). This instance interacts with PIN1_HUMAN via the “WW” domain (Pfam identifier PF00397; found on position 7-37 in PIN1_HUMAN). If available, binding affinities are also shown here. Interaction data is made available in *mitab* and *xml* format (Kerrien et al. (2007)), and can be downloaded by clicking on the yellow buttons in the right column.
12. Scroll further down to the “Switches” section for a brief overview of the switches details of this instance obtained form switches.ELM (Van Roey et al. (2013)) (Fig. 9). This particular instance is involved in the switch phosphorylating P53. Clicking on the diagram will open an external link to the switches.ELM website.

Exploring Links External Protein Resources

13. Click on the sub-menu **ELM methods** in **ELM DB** to see a list of all experimental methods which have been used to identify motifs and instances (Fig 10). This table shows the internal method

The screenshot shows the ELM (Eukaryotic Linear Motif) database interface. At the top, there is a navigation bar with links to "ELM Home", "ELM Prediction", "ELM DB", "ELM Candidates", "ELM Information", "ELM downloads", and "admin". The main content area has a title "112 different methods used in ELM annotation". Below this, a table lists various experimental methods with their PSI-MI identifiers, names, biosources, interaction types, and instance counts. A filter bar at the top of the table allows users to search by term and export the data as a tab-separated file (tsv).

ID	PSIMI ID	Method	Biosource	Interaction	#Instances	Notes
98	MI:0004	Affinity Chromatography Technology	in vivo/in vitro	association	36	InteractionDetection
9	MI:0005	Alanine Scanning	in vivo/in vitro/in silico		327	FeatureDetection
37	MI:0257	Antisense RNA	in vivo		3	InteractionDetection
67	MI:0007	Anti Tag Coimmunoprecipitation	in vivo	association	114	InteractionDetection
277	MI:0010	Beta Galactosidase Complementation			2	InteractionDetection
309	MI:0809	Bimolecular Fluorescence Complementation			8	InteractionDetection
156	MI:0969	Biolayer Interferometry			1	InteractionDetection
327	MI:0968	Biosensor			1	InteractionDetection
458	MI:2163	By Homology	in silico	association	10	ParticipantIdentification
203	MI:0225	Chromatin Immunoprecipitation Array			2	InteractionDetection
104	MI:0402	Chromatin Immunoprecipitation Assay	in vivo	association	2	InteractionDetection
137	MI:0091	Chromatography Technology	in vitro	physical association	16	InteractionDetection
18	MI:0016	Circular Dichroism	in vitro	association	19	InteractionDetection
65	MI:0017	Classical Fluorescence Spectroscopy	in vitro	association	119	InteractionDetection
405	MI:0990	Cleavage Assay			10	InteractionDetection
129	MI:0194	Cleavage Reaction	in vivo/in vitro		50	InteractionDetection
23	MI:0019	Coimmunoprecipitation	in vivo/in vitro	association	563	InteractionDetection
16	MI:0403	Colocalization	in vitro		152	
146	MI:0807	Comigration In Gel Electrophoresis	in vitro		7	InteractionDetection
123	MI:0404	Comigration In Non Denaturing Gel Electrophoresis	in vivo	association	4	InteractionDetection
132	MI:0808	Comigration In Sds Page	in vitro		5	InteractionDetection

Figure 10: The list of all experimental methods used in the ELM database, along with their PSI-MI identifiers.

identifier in the first column, a link to the corresponding entry in the PSI-MI database (Kerrien et al. (2007)), and the method name as annotated by the PSI-MI controlled vocabulary, as well as the type of experiment (in vitro/in vivo). Clicking on the link in the “instances” column will list all instances annotated using that method.

The filter bar on the top page can be used to filter the list of methods. The tsv link creates a downloadable file in “tab separated values” format.

14. Click on the sub-menu **ELM pdb structures** in **ELM DB** to see a list of all macromolecular structures in the ELM database (Fig. 11). Structures annotated in ELM ideally (but not always) show both interaction partners, motif and domain. This page also contains links to RCSB/PDB (Berman et al. (2002)), the individual instance and the motif class of that instance.

The filter bar on the top page can be used to filter the list of structures shown. The yellow tsv link creates a downloadable file in “tab separated values” format.

The screenshot shows the ELM (Eukaryotic Linear Motif) website interface. At the top, there is a logo and the title "The Eukaryotic Linear Motif resource for Functional Sites in Proteins". Below the title is a search bar labeled "search ELM Database". A navigation menu at the top includes links for "ELM Home", "ELM Prediction", "ELM DB", "ELM Candidates", "ELM Information", "ELM downloads", and "admin".

A main heading "428 PDBs found:" is displayed above a table. The table has four columns: "PDB_ID", "Title", "ELM instance", and "ELM class". Each row in the table represents a specific PDB entry with its details. For example, entry 2FOP is described as "The crystal structure of the n-terminal domain of hausp/usp7 complexed with mdm2 peptide 147-150" and is associated with ELM instance MDM2_HUMAN and class DOC_USP7_MATH_1.

PDB_ID	Title	ELM instance	ELM class
2FOP	The crystal structure of the n-terminal domain of hausp/usp7 complexed with mdm2 peptide 147-150	MDM2_HUMAN	DOC_USP7_MATH_1
2FOO	The crystal structure of the n-terminal domain of hausp/usp7 complexed with p53 peptide 359-362	P53_HUMAN	DOC_USP7_MATH_1
2G2L	Crystal structure of the second pdz domain of sap97 in complex with a glut-a c-terminal peptide	GRIA1_RAT	LIG_PDZ_Class_1
2G30	Beta appendage of ap2 complexed with arh peptide	ARH_HUMAN	TRG_AP2beta_CARGO_1
2GBQ	Solution nmr structure of the grb2 n-terminal sh3 domain complexed with a ten-residue peptide derived from sos direct refinement against noes, j-couplings, and 1h and 13c chemical shifts, 15 structures	SOS1_MOUSE	LIG_SH3_3
2GPH	Docking motif interactions in the map kinase erk2	PTN7_HUMAN	DOC_MAPK_HePTP_8
2GPO	Estrogen related receptor-gamma ligand binding domain complexed with a synthetic peptide from rip140	NRIP1_HUMAN	LIG_NRBOX
2GTH	Crystal structure of the wildtype mhv coronavirus non-structural protein nsp15	R1AB_CVMA5	LIG_Rb_LxCxE_1
2HE2	Crystal structure of the 3rd pdz domain of human discs large homologue 2, dlg2	AT2B4_HUMAN	LIG_PDZ_Class_1
2HE4	The crystal structure of the second pdz domain of human nherf-2 (slc9a3r2) interacting with a mode 1 pdz binding motif	DHRS2_HUMAN	LIG_PDZ_Class_1
2HGO	Structure of the west nile virus envelope glycoprotein	Q3I0Y8_WNV	MOD_N-GLC_1
2HKQ	Crystal structure of the c-terminal domain of human eb1 in complex with the cap-gly domain of human dynactin-1 (p150-glued)	MARE1_HUMAN	LIG_CAP-Gly_1
2I04	X-ray crystal structure of magi-1 pdz1 bound to the c-terminal peptide of hpv18 e6	VE6 HPV18	LIG_PDZ_Class_1
2I01	X-ray crystal structure of sap97 pdz3 bound to the c-terminal peptide of hpv18 e6	VE6 HPV18	LIG_PDZ_Class_1
2IOL	X-ray crystal structure of sap97 pdz2 bound to the c-terminal peptide of hpv18 e6.	VE6 HPV18	LIG_PDZ_Class_1
2I1N	Crystal structure of the 1st pdz domain of human dig3	AT2B4_HUMAN	LIG_PDZ_Class_1
2I3S	Bub3 complex with bub1 glebs motif	BUB1_YEAST	LIG_GLEBS_BUB3_1
2I3T	Bub3 complex with mad3 (burbr1) glebs motif	MAD3_YEAST	LIG_GLEBS_BUB3_1
2IHS	Crystal structure of the b30.2/spry domain of gustavus in complex with a 20-residue vasa peptide	VASA1_DROME	LIG_SPRY_1
2IVR	Beta aipoendae in complex with b-arrestin neotide	ARRB1_HUMAN	TRG_AP2beta_CARGO_1

Figure 11: The list of all known structures in PDB which are also in ELM.

- Click on the sub-menu **ELM binding domains** under **ELM DB** to see a complete list of all the interaction domains in ELM (Fig. 12). This table shows the ELM classes which have been annotated with a corresponding interaction domain. This table shows the ELM class, a link to the Pfam [Finn et al. \(2016\)](#), SMART [Letunic et al. \(2015\)](#) or InterPro ([Finn et al. \(2017\)](#)) domain, as well as the name of the interacting domain followed by a brief description.

The filter bar on the top page can be used to filter the list of interactions shown. The tsv link creates a downloadable file in “tab separated values” format.

- Click on the sub-menu **ELM switches** in **ELM DB** to see a complete list of all the switches in ELM (Fig. 13). This table shows the motif class, contains a link to Uniprot, and the start and stop positions of the motif mediating the switch. The last two columns have links to switches.ELM, and a brief description of the switch also taken from switches.ELM [Van Roey et al. \(2013\)](#).

The filter bar on the top page can be used to quickly filter the list of interactions shown.

The Eukaryotic Linear Motif resource for Functional Sites in Proteins

search ELM Database

ELM Home ELM Prediction ELM DB ELM Candidates ELM Information ELM downloads admin

290 interaction domains annotated in ELM

Filter this table

export as: [tsv](#)

ELM identifier	Interaction Domain Id	Interaction Domain Name	Interaction Domain Description
CLV_NRD_NRD_1	PF00675	Peptidase_M16	Insulinase (Peptidase family M16)
CLV_PCSK_FUR_1	PF00082	Peptidase_S8	Subtilase family
CLV_PCSK_PC1ET2_1	PF00082	Peptidase_S8	Subtilase family
CLV_PCSK_PCT7_1	PF00082	Peptidase_S8	Subtilase family
CLV_PCSK_SKI1_1	PF00082	Peptidase_S8	Subtilase family
CLV_TASPASE1	PF01112	Asparaginase_2	Asparaginase
old_LIG_14-3-3_1	PF00244	14-3-3	14-3-3 protein
old_LIG_14-3-3_2	PF00244	14-3-3	14-3-3 protein
old_LIG_14-3-3_3	PF00244	14-3-3	14-3-3 protein
LIG_AP_GAE_1	PF02883	Alpha_adaptinC2	Adaptin C-terminal domain
LIG_AP2alpha_1	PF02296	Alpha_adaptin_C	Alpha adaptin AP2, C-terminal domain
LIG_AP2alpha_2	PF02296	Alpha_adaptin_C	Alpha adaptin AP2, C-terminal domain
DEG_APCC_DBOX_1	PF00400	WD40	WD domain, G-beta repeat
DEG_APCC_KENBOX_2	PF00400	WD40	WD domain, G-beta repeat
LIG_BIR_II_1	PF00653	BIR	Inhibitor of Apoptosis domain
LIG_BIR_III_1	PF00653	BIR	Inhibitor of Apoptosis domain
LIG_BIR_III_2	PF00653	BIR	Inhibitor of Apoptosis domain
LIG_BIR_III_3	PF00653	BIR	Inhibitor of Apoptosis domain
LIG_BIR_III_4	PF00653	BIR	Inhibitor of Apoptosis domain
LIG_BRCT_BRCA1_1	PF00533	BRCT	BRCA1 C Terminus (BRCT) domain
LIG_BRCT_BRCA1_2	PF00533	BRCT	BRCA1 C Terminus (BRCT) domain
LIG_BRCT_MDC1_1	PF00533	BRCT	BRCA1 C Terminus (BRCT) domain
LIG_CAP-Gly_1	PF01302	CAP_GLY	CAP-Gly domain
LIG_Clathr_ClatBox_1	PF01394	Clathrin_propel	Clathrin propeller repeat
LIG_Clathr_ClatBox_2	PF01394	Clathrin_propel	Clathrin propeller repeat
DEG_COP1	PF00400	WD40	WD domain, G-beta repeat
LIG_CORNRBOX	PF00104	Hormone_recep	Ligand-binding domain of nuclear hormone receptor
LIG_CtBP_PxDLS_1	PF00389	2-Hacid_dh	D-isomer specific 2-hydroxyacid dehydrogenase, catalytic domain
DOC_CYCLIN_1	PF00134	Cyclin_N	Cyclin, N-terminal domain
LIG_Dynamin_DLG_1	PF00000	Dynamin_light	Dynamin light chain-type 1

Figure 12: A list of all interactions annotated in the database.

Visualizing KEGG pathways from ELM

- Click on the sub-menu **ELM pathways** in **ELM DB** to see a list of all KEGG pathways contained in ELM (Fig. 14). Pathways are from the “Kyoto Encyclopedia of Genes and Genomes” (KEGG Kanehisa et al. (2016)) database mapped to ELM instances.
- On the “ELM pathways” page (Fig. 15) click on the link **gallus gallus** to navigate to the page containing all pathways annotated for chicken.
- One the page with chicken pathways (Fig. 15) click on **Adherens junction** to the KEGG entry for this pathway, with each protein’s color corresponding to ELM classes (see the color legend right side of figure 16).

The screenshot shows the ELM (Eukaryotic Linear Motif) website interface. At the top, there is a logo and the title "The Eukaryotic Linear Motif resource for Functional Sites in Proteins". Below the title is a search bar labeled "search ELM Database". The main content area is titled "ELM Switches". A table lists various switches, each with a unique ID, sequence ID, start/stop positions, switch ID, and a detailed description of its function and context.

ELM class	Sequence Id	Start/Stop	Switch Id	Description
LIG_SH2_STAT5	O43561	161-164	SWTI000001	Phosphorylation of Y161 in the SH2-binding motif of Linker for activation of T-cells family member 1 (LAT) induces binding to the 1-phosphatidylinositol-4,5-bisphosphate phosphodiesterase gamma-1 (PLCG1) protein.
DOC_AGCK_PIF_1	P31749	469-474	SWTI000002	Phosphorylation of S473 in the PIF motif of RAC-alpha serine/threonine-protein kinase (AKT1) by Serine/threonine-protein kinase mTOR (MTOR) (as part of mTORC2 complex) induces intramolecular interaction with the PIF-binding pocket, resulting in crosactivation of RAC-alpha serine/threonine-protein kinase (AKT1) . Dephosphorylation of the PIF motif by PHLPP1/J2 (PHLPP1 for Akt2/3 and PHLPP2 for Akt1/3) results in reduced Akt activity, probably by disrupting the interaction with the Akt PIF pocket and thus crosactivation.
DOC_AGCK_PIF_1	P05771-2	656-661	SWTI000003	Dephosphorylation of the PIF motif by PHLPP1/J2 results in reduced stability and increased degradation of PKC. This is countered by autophosphorylation of the PIF motif, but mTORC2 might also contribute.
DOC_WW_Pin1_4	Q12800	326-331	SWTI000004	Phosphorylation of T329 in the Pin1-binding motif of Alpha-globin transcription factor CP2 (TFCP2) induces binding to Peptidyl-prolyl cis-trans isomerase NIMA-interacting 1 (PIN1) , which isomerizes the peptide bonds at the nearby-phosphorylated SP motifs (S291 and S309) to the trans configuration, thereby facilitating their dephosphorylation, which is required for the transcriptional activity of Alpha-globin transcription factor CP2 (TFCP2) .
LIG_PLK	P30307	129-131	SWTI000005	Phosphorylation of T130 in the PLK-docking motif of M-phase inducer phosphatase 3 (CDC25C) by Cyclin-dependent kinase 1 (CDK1)-Cyclin AB subfamily generates a recruitment site for Serine/threonine-protein kinase PLK1 (PLK1) , which then phosphorylates M-phase inducer phosphatase 3 (CDC25C) . This results in inactivation of the NES of M-phase inducer phosphatase 3 (CDC25C) , thereby promoting its nuclear localization.
LIG_PLK	P30305	49-51	SWTI000006	Phosphorylation of S50 in the PLK-docking motif of M-phase inducer phosphatase 2 (CDC25B) by Cyclin-dependent kinase 1 (CDK1)-Cyclin AB subfamily generates a recruitment site for Serine/threonine-protein kinase PLK1 (PLK1) , which then phosphorylates and activates M-phase inducer phosphatase 2 (CDC25B) .
LIG_FHA_1	P64897	19-25	SWTI000007	Phosphorylation of T21 in the FHA-binding motif of Uncharacterized protein Rv1827/MT1875 (Rv1827) by Probable serine/threonine-protein kinase pknG (pknG) results in auto-inhibition due to an intramolecular interaction with the FHA domain. As a result, phosphorylation-independent interactions of the FHA domain with metabolic enzymes, which regulate the catalytic activity of these enzymes, are blocked (See also switch details).
LIG_14-3-3_3	P30307	213-218	SWTI000008	Phosphorylation of S216 in a 14-3-3-binding motif of M-phase inducer phosphatase 3 (CDC25C) by Serine/threonine-protein kinase Chk1 (CHEK1) induces binding to 14-3-3 protein beta/alpha (YWHAB) , which negatively regulates M-phase inducer .

Figure 13: A list of all switches annotated switches. ELM also contained in ELM.

Browsing Infections and Diseases

- Click on the sub-menu **ELM virus instances** under **ELM DB** to see a list of all instances in ELM that have been annotated as being abused by viruses (Fig. 19). The columns are identical to those listed in Step 7 (Fig. 7).

The green buttons on the left can be used to filter this table by motif class. Click on the yellow links on the top right of the page to download the (complete) table in gff, pir, fasta or tsv format.
- Click on the sub-menu **ELM diseases** under **ELM DB** to see a list of all motif classes that have been annotated with a disease (Fig. 18). Disease information is taken from the Online Mendelian Inheritance in Man (OMIM) database McKusick (2007).

The screenshot shows the ELM (Eukaryotic Linear Motif) website. At the top, there is a navigation bar with links to "ELM Home", "ELM Prediction", "ELM DB", "ELM Candidates", "ELM Information", "ELM downloads", and "admin". The main content area has a title "Pathways linked from ELM instances". Below the title, a message states: "The following list contains taxons for which sequences at ELM have been mapped to pathways annotated at the 'Kyoto Encyclopedia of Genes and Genomes' (KEGG) database." There is a search bar with placeholder text "Please select a taxon or enter any search term:" and a "submit" button. A list of taxons follows:

- [Arabidopsis thaliana](#) (4)
- [Ashbya gossypii ATCC 10895](#) (1)
- [Bos taurus](#) (65)
- [Caenorhabditis elegans](#) (5)
- [Candida albicans SC5314](#) (1)
- [Canis lupus familiaris](#) (3)
- [Danio rerio](#) (6)
- [Drosophila melanogaster](#) (12)
- [Equus caballus](#) (2)
- [Gallus gallus](#) (16)
- [Homo sapiens](#) (231)
- [Mus musculus](#) (167)
- [Oryctolagus cuniculus](#) (29)
- [Plasmodium falciparum](#) 3D7 (1)
- [Rattus norvegicus](#) (139)
- [Saccharomyces cerevisiae](#) (26)
- [Saccharomyces cerevisiae S288c](#) (10)
- [Schizosaccharomyces pombe](#) (11)
- [Schizosaccharomyces pombe](#) 972h- (6)
- [Solanum lycopersicum](#) (1)
- [Strongylocentrotus purpuratus](#) (1)
- [Sus scrofa](#) (30)
- [Vibrio cholerae](#) (2)
- [Xenopus laevis](#) (23)
- [ALL](#) (792)

Please cite: [ELM 2016-data update and new functionality of the eukaryotic linear motif resource. \(PMID: 26615199\)](#)
ELM data can be downloaded & distributed for non-commercial use according to the [ELM Software License Agreement](#)

feedback@elm.eu.org

Figure 14: A list of all Pathways from KEGG with proteins in ELM.

Finding Help and Frequently Asked Questions

22. Click on the **Help** button on the right of the top navigation menu to visit the ELM Help page. This page has answers to the most Frequently asked questions, which you can see by clicking on a particular question. For example: Click on “Regular expressions” for a detailed description of the symbols used to build regular expressions to define motif classes.

(Alternate) General Search Box

A general search text box is available to query the entire collection of manually curated information in ELM DB. This search field can be found at the top of almost all pages on the ELM website (for example in Fig. 22). This search is a full-text search across multiple selected data sources in the database, including protein and ELM class.

The screenshot shows the ELM (Eukaryotic Linear Motif) website interface. At the top, there is a navigation bar with links to "elm Home", "elm Prediction", "elm DB", "elm Candidates", "elm Information", "elm downloads", and "admin". The main content area has a title "Pathways linked from ELM instances". Below this, a table lists various KEGG pathways and their associated ELM instances and sequences. To the right of the table, there is a sidebar with information about KEGG database redirects and a color scheme legend for ELM classes.

TAXON	Pathway entry	Pathway name	# Instances	# Sequences
	gga04520	Adherens junction	2	2
	gga04144	Endocytosis	2	2
	gga04012	ErbB signaling pathway	4	2
	gga04510	Focal adhesion	9	6
	gga04540	Gap junction	1	1
	gga04912	GnRH signaling pathway	4	2
	gga05168	Herpes simplex infection	3	1
	gga05164	Influenza A	3	1
	gga04010	MAPK signaling pathway	3	1
	gga04810	Regulation of actin cytoskeleton	5	4
	gga05132	Salmonella infection	3	1
	gga04530	Tight junction	1	1
	gga04620	Toll like receptor signaling pathway	3	1
	gga04270	Vascular smooth muscle contraction	2	1
	gga04370	VEGF signaling pathway	2	2
	gga04310	Wnt signaling pathway	4	2

Please cite: ELM 2016-data update and new functionality of the eukaryotic linear motif resource. (PMID: [26615199](#))
 ELM data can be downloaded & distributed for non-commercial use according to the [ELM Software License Agreement](#)

feedback@elm.eu.org

Figure 15: A list of all KEGG pathways in *Gallus gallus* involving proteins annotated in ELM.

Necessary Resources

Software & Hardware

Using the General Search

A modern browser such as Firefox, Chrome, or Safari. ELM is best viewed on a laptop or desktop computer, although tablets and smartphones will also work.

1. Use the general search field (on the top of the page) to do a general search for P53 using its Uniprot identifier by typing “P04637” in the search field and hitting “Enter”. This will search across instances, motif classes and switches to find any matches to the search query “P04637”. The results are grouped into matching instances (Fig. 20) candidate classes and switches (Fig. 21). As there are no classes with “P04637” in the name, no classes are returned with this query.

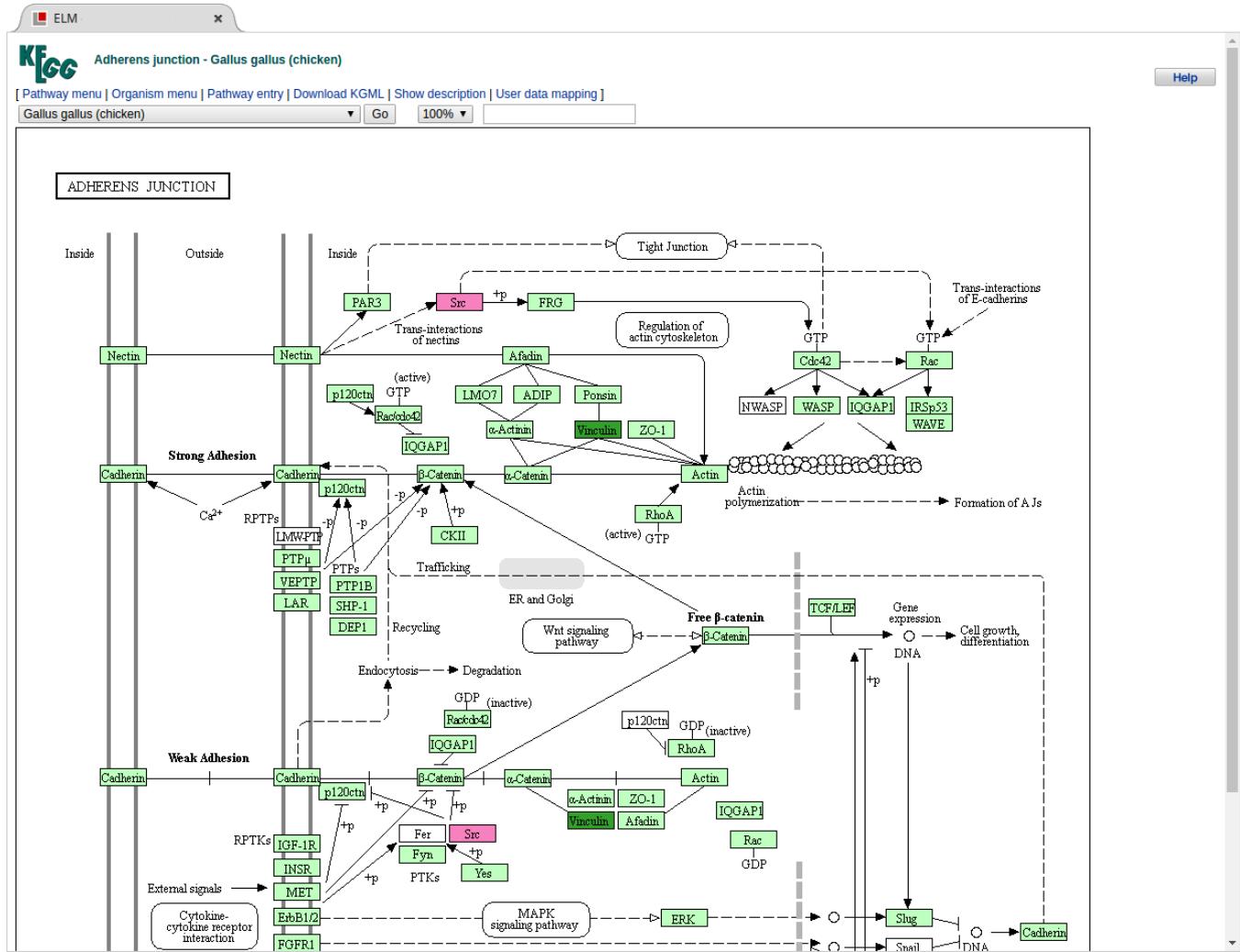


Figure 16: A list of all annotated pathways for taxon *Gallus gallus*

The “candidate classes” are a separate part of ELM, where users can propose novel classes to be annotated. Although these are returned by the general search, we would advise users not to use this data, as it is still pending curation.

2. Perform a search using the keyword “p53” in the general search field instead of its Uniprot identifier “P04637”. The set of results retrieved using this term as search query (Fig. 22) in this case are different, returning 31 instances and 44 switches (instead of 14 and 11). The reason for this is that the phrase “P53” also matches the Uniprot identifier of CDH1_YEAST (P53197). This is important to keep in mind when using the general search field.

(Basic) Predicting ELMs in proteins

One of the most useful (and used) features in ELM is the ability to detect motifs in proteins and sequences. Given a protein’s amino acid sequence, the “ELM Predictions” pipeline searches for occurrences of each

The screenshot shows the ELM (Eukaryotic Linear Motif) web interface. At the top, there's a logo and the title "The Eukaryotic Linear Motif resource for Functional Sites in Proteins". Below the title is a search bar labeled "search ELM Database". The main navigation menu includes "ELM Home", "ELM Prediction", "ELM DB", "ELM Candidates", "ELM Information", "ELM downloads", and "admin". On the left side, there's a vertical sidebar with colored boxes for each motif class: CLV (green), DEG (blue), DOC (orange), LIG (red), MOD (purple), and TRG (yellow). The main content area is titled "Browse Viral ELM Instances". It contains a table with the following data:

ELM identifier	Acc., Gene-, Name	Start	End	Subsequence	Logic	#Ev.	Organism	Notes
CLV_PCSK_FUR_1	P056861 env ENV_FFV	124	128	GNTSSSSRRRDQYHKLPV	TP	4	Feline foamy virus	1 1
CLV_PCSK_FUR_1	P03383 env ENV_HTLV2	305	309	PVPPPATRRRAVPIAVNLV	TP	3	Human T-lymphotro...	1 1
CLV_PCSK_FUR_1	P03375 env ENV_HV1B1	508	512	AKRRVVVERKRAVGIGALFL	TP	3	Human immunodefici...	1 1
CLV_PCSK_FUR_1	P03420 F FUS_HRSVA	133	137	IVTLSKAKKKRFLGFLGVG	TP	3	Human respiratory...	1 1
CLV_PCSK_FUR_1	P03188 gB GB_EBVB9	429	433	TPAAVLRRRDRAGNATTPV	TP	1	Human herpesvirus... (Epstein-Barr virus (strain B95-8))	
CLV_PCSK_FUR_1	P27909 POLG_DEN1B	202	206	SQTGEHRDKRSVALAPHVG	TP	3	Dengue virus 1 Br...	1 1
CLV_PCSK_FUR_1	P11223 S SPIKE_IBVB	534	538	KITNGTRFRRRSITENVANC	TP	2	Avian infectious ...	
CLV_PCSK_FUR_1	P11223 S SPIKE_IBVB	687	691	LLTNPSSRRKRSLIEDLLFT	TP	2	Avian infectious ...	
CLV_PCSK_FUR_1	Q05320 GP VGP_EBOZM	498	502	GLITGGRRTREAEVNQPK	TP	4	Ebola virus - May...	1 1
CLV_PCSK_FUR_1	P03107 L2 VL2 HPV16	9	13	RHKRSAKRTKRSATQLYKT	TP	1	Human papillomavi...	1 1
CLV_PCSK_FUR_1	P60170 GP VSGP_EBOZM	321	325	EPKTSVVRRELLPTQGPT	TP	3	Ebola virus - May...	
DEG_APCC_KENBOX_2	P03116 E1 VE1_BPV1	27	31	TEAECESDKENEPEPGAGVEL	TP	1	Bovine papillomav...	
DEG_SCF_FBW7_2	P03070 Large T antig LT_SV40	699	705	ICRGFTCFKKPPTPPEPET	TP	3	Simian virus 40	1 1

Figure 17: A table of the ELM instances abused by viruses.

motif class using regular expressions, applies a set of filters to remove false positives and creates a diagram to visualize resulting set of putative motifs.

In this protocol we will be viewing the manually annotated data of a typical protein, using p53 (Uniprot ID: P53_HUMAN /P04637) as an example. We will cover how to find the manually annotated motifs and instances, and how to find the motif instances, the references used to annotate each instance, the experimental protocols used, and additional information including relationships to biological pathways (KEGG), diseases (OMIM) and molecular switches (switches.ELM).

Necessary Resources

Software & Hardware

A modern browser such as Firefox, Chrome, or Safari. ELM is best viewed on a laptop or desktop computer, although tablets and smartphones will also work.

Figure 18: A list of all diseases in ELM.

Predicting ELM instances: Input form

1. Open a browser, and navigate to the ELM homepage: <http://elm.eu.org>. Enter the Uniprot ID P53_HUMAN in the search field labelled “Enter a uniprot identifier or accession number”. The page should autocomplete/suggest the protein “P53_HUMAN / P04637 (Homo sapiens)” (Fig. 23). Click on this entry to confirm that we want to search for motifs in this protein. Click on **Submit** to submit the query to the server.

The autocompletion mechanism queries Uniprot for protein identifier; if it succeeds, then additional information from Uniprot will be used to pre-populate the filter boxes. In this example, P53_HUMAN is recognized as a Human protein, and so “Homo sapiens” is automatically filled in the “Taxonomic Context” field. Also, P53 has been annotated (by Uniprot) to be localized to nucleus, cytosol, endoplasmic reticulum and mitochondrion, so these are also automatically applied as search criteria. The motif cutoff of “100” is a sufficiently high (lenient) threshold to allow all other detected motifs to be shown.

The Eukaryotic Linear Motif resource for
Functional Sites in Proteins

search ELM Database

ELM Home ELM Prediction ELM DB ELM Candidates ELM Information ELM downloads admin

ELM Help page

Questions and answers

- What methods are used for detecting functional sites?
- Why are the ELM predictions not scored?
- What does the ELM instance mapper do?
- Why is the context of a functional site important?
- What are the currently implemented context filters?
- Is there a nomenclature for representing functional site motifs?
- How can the ELM DB be accessed programmatically?
- Regular expressions
- Why use Regular Expressions in ELM?

Please cite: ELM 2016-data update and new functionality of the eukaryotic linear motif resource. (PMID: [26615199](#))

ELM data can be downloaded & distributed for non-commercial use according to the [ELM Software License Agreement](#)

feedback@elm.eu.org

Dictionary

Definitions and explanations to terms used in the ELM resource.

Biochemical context
For [functional sites](#), the biochemical context has several components: the sequence motif, its relation to the local structure and other domains in the protein as well as the protein complex it may reside in.

Cellular context
Where and when in the cell a site is functional.

Context
The space and time where a [molecular function](#) takes place.

ELM
1. Eukaryotic Linear Motif,
2. The common pattern of a set of linear (sub)sequences that can be related to a [molecular function](#).

ELM instance
An experimentally verified instance of an [ELM](#) in a particular polypeptide.

ELM instance sequence
A protein sequence carrying one or more experimentally verified [ELM instances](#)

Filter
Method for discriminating between likely positive and negative ELM predictions; based on context information.

Functional site
A set of short linear (sub)sequences that can be

Figure 19: The ELM help and Questions & Answers page.

2. Select the search criteria (optional). It is possible to limit the results by “cell compartment”, “taxonomic context” or by changing the “motif probability cutoff”. To restrict the search to include motifs that are active in certain cellular compartments, select one or more from the list (use the “control” key to select more than one option). It is also possible to select a “taxonomic context” to restrict the search to motifs from certain species. Start typing a species name in the “taxonomic context” input field to get an auto-completed list of species to select from. Additionally, a “Motif probability cutoff” can be used to only retain ELM classes whose pattern probability is below the given value. For the current protocol, leave all of these at their default values: “not specified”, “100” and no “taxonomic context”

TODO: Repeat search using stringent filters (homo sapiens, nucleus, 0.01) Do we want to do this? - Marc

The Eukaryotic Linear Motif resource for Functional Sites in Proteins

Search ELM Database

admin

Your search for P04637 resulted in 0 ELM classes, 14 ELM Instances, 0 ELM candidate classes, and 11 ELM Switches:

ELM instances

Identifier	Sequence	Start	Stop	Logic	Taxon	Info
DEG_MDM2_SWIB_1	P04637 TP53 P53_HUMAN	19	26	TP	Homo sapiens (Human)	1YCR
DOC_CYCLIN_1	P04637 TP53 P53_HUMAN	381	385	TP	Homo sapiens (Human)	1H26
DOC_USP7_MATH_1	P04637 TP53 P53_HUMAN	359	363	TP	Homo sapiens (Human)	2F1X 2FOO
DOC_USP7_MATH_1	P04637 TP53 P53_HUMAN	364	368	TP	Homo sapiens (Human)	2FOJ
DOC_WW_Pin1_4	P04637 TP53 P53_HUMAN	78	83	TP	Homo sapiens (Human)	1
DOC_WW_Pin1_4	P04637 TP53 P53_HUMAN	312	317	TP	Homo sapiens (Human)	1
DOC_WW_Pin1_4	P04637 TP53 P53_HUMAN	30	35	TP	Homo sapiens (Human)	1
MOD_CDK_SPxxK_3	P04637 TP53 P53_HUMAN	315	319	TP	Homo sapiens (Human)	
MOD_CK1_1	P04637 TP53 P53_HUMAN	15	21	TP	Homo sapiens (Human)	
MOD_GSK3_1	P04637 TP53 P53_HUMAN	30	37	TP	Homo sapiens (Human)	1
MOD_PIKK_1	P04637 TP53 P53_HUMAN	12	18	TP	Homo sapiens (Human)	
MOD_SUMO_for_1	P04637 TP53 P53_HUMAN	385	388	TP	Homo sapiens (Human)	
TRG_NES_CRM1_1	P04637 TP53 P53_HUMAN	339	352	TP	Homo sapiens (Human)	1
TRG_NLS_Bipartite_1	P04637 TP53 P53_HUMAN	305	323	TP	Homo sapiens (Human)	

Figure 20: The instances retrieved when performing a general search for P53_HUMAN using its Uniprot identifier “P04637”.

Interpreting the prediction results: Graphical Summary

- Click **submit** to start searching for motifs. You will be brought to an intermediate page indicating that your results are being processed, and should be redirected to the final results page within a minute. You can bookmark this page: The results are stored for a week.

The Results are summarized in the first figure on the results page (see figure 24). The graphical summary shows the results generated by the ELM prediction pipeline, combined with additional filters and information from external resources. The visualization should help you interpreting the results and to assess whether or not a motif is present in a sequence, as well as how likely it is to be functional based on its structural context and evolutionary conservation. Motif instances which are manually annotated in the database appear as red (TP) or yellow (FP) ovals in the graphic. Blue/sgray squares represent predicted motif occurrences.

- The first row contains phosphorylation sites as retrieved from phospho.ELM Dinkel et al. (2011),

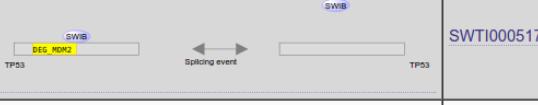
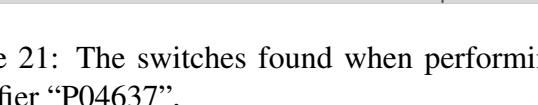
Diagram	Switch	Description
	SWTI000456	Phosphorylation of Cellular tumor antigen p53 (TP53) on T18 (in vitro by Casein kinase I subfamily , requiring prior phosphorylation of S15) inhibits its binding to E3 ubiquitin-protein ligase Mdm2 (MDM2) . In vivo, T18 is phosphorylated in response to DNA damage.
	SWTI000517	Alternative promoter usage and alternative splicing removes the E3 ubiquitin ligase MDM2-binding motif of Cellular tumor antigen p53 (TP53) , abrogating binding to E3 ubiquitin-protein ligase Mdm2 (MDM2) . The splice variant without this motif is resistant to MDM2-mediated degradation, leading to a longer half-life.
	SWTI000519	Alternative splicing removes the deubiquitinating enzyme USP7-binding motif of Cellular tumor antigen p53 (TP53) , abrogating binding to Ubiquitin carboxyl-terminal hydrolase 7 (USP7) .
	SWTI000520	Alternative splicing removes the deubiquitinating enzyme USP7-binding motif of Cellular tumor antigen p53 (TP53) , abrogating binding to Ubiquitin carboxyl-terminal hydrolase 7 (USP7) .
	SWTI000037	Phosphorylation of S33 in the Pin1-binding motif of Cellular tumor antigen p53 (TP53) induces binding to the Peptidyl-prolyl cis-trans isomerase NIMA-interacting 1 (PIN1) protein.
	SWTI000038	Phosphorylation of S315 in the Pin1-binding motif of Cellular tumor antigen p53 (TP53) induces binding to the Peptidyl-prolyl cis-trans isomerase NIMA-interacting 1 (PIN1) protein.
	SWTI000039	Phosphorylation of T81 in the Pin1-binding motif of Cellular tumor antigen p53 (TP53) induces binding to the Peptidyl-prolyl cis-trans isomerase NIMA-interacting 1 (PIN1) protein.

Figure 21: The switches found when performing a general search for P53_HUMAN using its Uniprot identifier “P04637”,

and whether the phosphorylated amino acid is a serine, threonine or tyrosine. Phospho.ELM is a database of manually annotated phosphorylation sites obtained from scientific publications from low and high-throughput experiments. You can follow the link to phospho.ELM by clicking on the phosphorylation site in the image to get more information on individual phosphorylation sites.

Phosphorylation sites are only available when the search is performed with a protein accession (eg. not with a FASTA sequence alone) in step 1 and there is relevant information annotated in the phospho.ELM database. Phosphorylation sites are relevant to interpret ELM motif predictions when the predicted motif requires to be phosphorylated (as in several docking and ligand binding motifs) and for predicting phosphorylation motifs.

5. The second row shows SMART and Pfam domains detected by the SMART database [Schultz et al. \(1998\); Letunic et al. \(2015\); Schultz et al. \(1998\)](#) (Fig. 24). Hover the mouse over these domains to see their names and exact start and end positions.

The screenshot shows the Eukaryotic Linear Motif (ELM) resource interface. At the top, there's a logo and navigation links for ELM Home, ELM Prediction, ELM DB, ELM Candidates, ELM Information, and ELM downloads. A user account labeled 'admin' is visible. A search bar at the top right contains the query 'p53'. Below the search bar, a message states: 'Your search for p53 resulted in 0 ELM classes, 31 ELM Instances, 5 ELM candidate classes, and 44 ELM Switches.'

ELM instances

Identifier	Sequence	Start	Stop	Logic	Taxon	Info
DEG_APCC_DBOX_1	P53350 PLK1 PLK1_HUMAN	336	344	TP	Homo sapiens (Human)	
DEG_APCC_TPR_1	P53197 CDH1 CDH1_YEAST	564	566	TP	Saccharomyces cer...	
DEG_MDM2_SWIB_1	P04637 TP53 P53_HUMAN	19	26	TP	Homo sapiens (Human)	1YCR
DOC_CYCLIN_1	P04637 TP53 P53_HUMAN	381	385	TP	Homo sapiens (Human)	1H26
DOC_MAPK_gen_1	P53355 DAPK1 DAPK1_HUMAN	1385	1393	FP	Homo sapiens (Human)	
DOC_PP2B_PxIxI_1	P53968 CRZ1 CRZ1_YEAST	330	336	TP	Saccharomyces cer... (Baker's yeast)	
DOC_USP7_MATH_1	P04637 TP53 P53_HUMAN	364	368	TP	Homo sapiens (Human)	2FOJ
DOC_USP7_MATH_1	P04637 TP53 P53_HUMAN	359	363	TP	Homo sapiens (Human)	2F1X 2FOO
DOC_WW_Pin1_4	P04637 TP53 P53_HUMAN	312	317	TP	Homo sapiens (Human)	1A
DOC_WW_Pin1_4	P04637 TP53 P53_HUMAN	30	35	TP	Homo sapiens (Human)	1A
DOC_WW_Pin1_4	P04637 TP53 P53_HUMAN	78	83	TP	Homo sapiens (Human)	1A
Fungi and Amoebozoa.">LIG_APCC_Cbox_2	P53197 CDH1 CDH1_YEAST	55	61	TP	Saccharomyces cer...	
LIG_CaM_IQ_9	P53141 MLC1 MLC1_YEAST	84	102	TP	Saccharomyces cer... (Baker's yeast)	
LIG_CID_NIM_1	P53632 PAP2 PAP2_YEAST	574	583	TP	Saccharomyces cer...	2MOW
	DE3200_XAP1400					

Figure 22: The results retrieved when performing a general search for P53_HUMAN using the query “p53”.

In order to be functional motifs to be accessible, and therefore they are usually not found within globular domains and structured regions (Davey et al. (2012)). Any motifs detected by the ELM prediction pipeline inside of a smart domain are less likely to be functional, and are shown as a gray box background (see also the “structural filter” described in step XXX).

6. The third row shows globular and disordered regions in the sequence as predicted by GlobPlot (Linding et al. (2003)). The fourth and fifth rows contain results from IUPred (Dosztányi et al. (2005)), another predictor of disordered protein regions. Protein segments with an IUPred score above 0.5 are considered to be disordered.

Motifs are typically only functional when found in intrinsically disordered regions. Any motif occurrence detected by the ELM prediction pipeline that falls within disordered regions are more likely to be functional.

7. The 5th row (Fig. 24) contains information on secondary structure. The secondary structure is

ELM

ELM Prediction

The **ELM prediction** tool scans user-submitted protein sequences for matches to the regular expressions defined in ELM. Distinction is made between matches that correspond to experimentally validated motif instances already curated in the ELM database and matches that correspond to putative motifs based on the sequence. Since SLiMs are short and degenerate, overprediction is likely and many putative SLiMs will be false positives. However, predictive power is improved by using additional filters based on contextual information, including taxonomy, cellular compartment, evolutionary conservation and structural features.

Protein sequence

Enter Uniprot identifier or accession number: (auto-completion)
e.g. [EPN1_HUMAN](#), [P04637](#), [TAU_HUMAN](#), [\[RANDOM\]](#)

Or paste the sequence (Single letter code sequence only or FASTA format):

```
>P53_HUMAN
MEEPQSDPSVEPPLSQETFSDLWKLPPENNVLSPLPSQAMDDILMSLPDDIEQWFTEDPGPDEAPRMPEAAPVAPAPAAPTFA
APAPAFPSWPLSSVPSQRTYGGYFRGLFLHSGTAKSVCCTYSPALNMCFQLAKTFCVQLWMDSTPPPGTRVAMAIYKQS
QHMTTEVVRRCFHERCSDSGLAPPQHLIRVEGNLRVEYLDRNTFRHSVVVPYEPPEPVGSDCTTHIYNMCMNSCMGGMNRR
PILTIITLEDSSGNLLGRNSFEVRCACPGDRRTEENLKKGEPHHELPGSTKRALPNNTSSPQKKPLDGEYFTLQI
RGREFRFEMFREIMALELKDAQAGKEPGGSRAHSSHLSKKGQSTSRRHKLMFKTEGPDS
```

Cell compartment (one or several):

- not specified
- extracellular
- nucleus
- cytosol**
- peroxisome
- glycosome
- glyoxosome
- Golgi apparatus
- endoplasmic reticulum
- lysosome
- endosome
- plasma membrane
- mitochondrion

Taxonomic Context

Type in species name (auto-completion):

Motif Probability Cutoff:

Submit **Reset Form**

ELM DB

The ELM relational database stores different types of data about experimentally validated SLiMs that are manually

ELM database update
We have added new instances for: [LIG_APCC_ABBA_1](#), [LIG_APCC_ABBAvCdc20_2](#) as well as [DOC_MAPK_HePTP_8](#), [DOC_MAPK_MEF2A_6](#) and [DOC_MAPK_DCC_7](#)

ELM Database Update
We have updated several MOD_CDk motifs and added new instances:
MOD_CDk_1 is now: [MOD_CDk_SPxK_1](#), and [MOD_CDk_SPK_2](#) [MOD_CDk_SPxxK_3](#) have been added.

ELM database update
Several new ELM classes and instances have been added:
[LIG_BH_BH3_1](#), [DEG_COP1_1](#)

ELM database update
The class [DOC_PP2A_KARD_1](#) has been replaced by [DOC_PP2A_B56_1](#), and new instances have been added.

ELM database update
Several new ELM classes and instances have been added:
[LIG_CSK_EPIYA_1](#), [LIG_Rb_LxCxE_1](#), [DOC_MAPK_JIP1_4](#), [DOC_MAPK_NFAT4_5](#)

ELM database update
Several new ELM classes and instances have been added:
[DOC_MAPK_RevD_3](#), [LIG_ANK_PxPxL_1](#), [LIG_CSL_BTD_1](#), [LIG_G3BP_FGDF_1](#), [LIG_KLC1_TPR_1](#), [LIG_PALB2_WD40_1](#), [LIG_UFM1_UFIM_1](#)

These ELM classes have been updated:

Figure 23: The ELM input page for predicting motifs in a protein.

predicted using a pipeline mapping motif occurrence onto high quality reference domain structures [Via et al. \(2009\)](#). Check the graphical representation, and if the output of the secondary structure filter and the disorder predictors agree with respect to which parts of the sequence are considered structured and which disordered.

8. The remainder of the figure (below “secondary structure” output) displays predicted and annotated motif instances, overlaid with the structural context from rows 2 and 3 (SMART domains and GlobPlot). A blue square indicates a single motif occurrence, and intensity of the color indicates the conservation of this sequence across a group of homologous proteins. Boxes in gray are motif occurrences which have been filtered out by the structure filter. Boxes that are blue & gray are neutral (residing in structural context, but the secondary structure detected a loop region). If the sequence is already present in the ELM database, any motif instances that have already been annotated are shown as ovals. Lastly, any motifs detected which are annotated to be functional in homologous sequences, are shown as red & blue rectangles.

In the case that not enough homologous sequences were detected to build an alignment, no

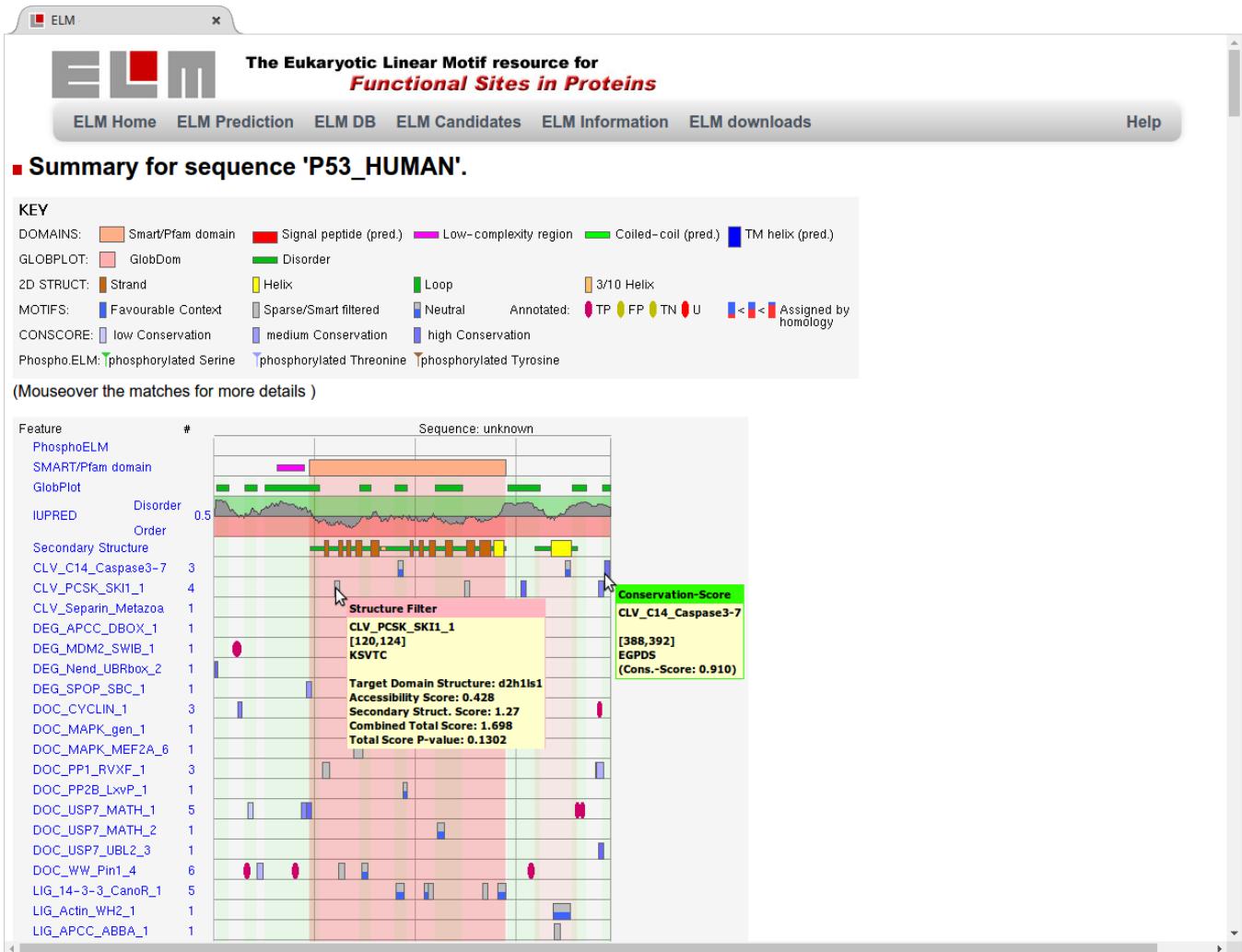


Figure 24: The graphical results summary of the ELM Prediction pipeline for P53_HUMAN . Note that not all motif detections are shown (the image is truncated at the bottom). The top five rows show a set of structural features. Annotated and predicted motifs are shown as differently colored ovals/boxes. The info screens for two motifs are shown: CLV_C14_CASPASE3-7 and CLV_PCSK_SKI1_1 .

conservation score can be calculated. Therefore all of the motif occurrences will be shown in a uniform shade of blue.

TODo: EXPLAIN / SHOW ANNOTATED INSTANCES Marc: Use mouse over in this figure.

9. Place the cursor over the blue box for motif occurrence CLV_C14_CASPASE3-7 at the end of the sequence (position 388-392). This will trigger the green and yellow information screen shown on the top right in Fig. 24. This motif is in a disordered region, and has not been filtered out by the structural filter. Also, its conservation score of 0.910 is very high, indicating that this motif is highly conserved.

The confidence score is based on how conserved the sequence is across a set of homologous proteins from other sequences. An full description of the method can be found in Chica et al.

(2008). The higher the conservation score (max. 1), the more conserved the motif's sequence is, and the more likely it is a functional motif for this prediction.

- Place the cursor over the blue & gray rectangle for motif CLV_PCSK_SKI1_1 at position 120-124, a motif which was flagged as “neutral” by the ELM prediction pipeline. This will trigger the information screen (with the pink header) shown in Fig. 24 to appear. This motif resides inside of the P53 Pfam domain, and thus has been subjected to “structural filtering”. However, the secondary structure prediction suggests this motif occurs within the looped region of this domain, so may be accessible.

The information screen pop-up shows scores for all of the individual criteria used by the secondary structure filter: The name of the domain, the accessibility score , secondary structure score, combined total score, and the associated total score P-value Via et al. (2009).

The screenshot shows the ELM software interface. At the top, there is a menu bar with 'File', 'Edit', 'View', 'Search', 'Help', and a 'Run' button. Below the menu is a toolbar with icons for 'New', 'Open', 'Save', 'Print', 'Copy', 'Paste', 'Find', 'Replace', 'Select All', 'Copy Structure', 'Copy Sequence', 'Copy Pattern', 'Copy Description', 'Copy Logic', 'Copy Position', 'Copy Species', 'Copy Location', 'Copy Score', 'Copy P-value', 'Copy Instances', 'Copy Elms', 'Copy Filtered By', 'Copy Retained By', 'Copy Total', 'Copy All', 'Copy Query', 'Copy Help', 'Copy About', and 'Copy License'. The main window title is 'ELM'.

Filtering summary

User supplied cellular location(s): nucleus, cytosol, endoplasmic reticulum, mitochondrion, Cytoplasm
User supplied taxon: Homo sapiens

(An ELM is listed as filtered when all its matching instances have been filtered out.)

		Elms	Instances
FILTERED BY:	Species	4	26
	Cellular location (counts only those ELMs not already excluded by species.)	5	11
	Structural score (below medium threshold score)	8	29
	Smart (in a domain and no structural filter info available)	0	0
TOTAL FILTERED:		17	66
RETAINED BY:	Smart (outside domain and no structural filter info available)	12	48
	Structural score (at or above medium threshold score)	32	58
TOTAL RETAINED:		44	106
TOTAL	all found (before filtering)	61	172

Query sequence:
>P53_HUMAN
MEEPQSDPSVEPPLSQETFSDLWKLPPENNVLSPLPSQAMDDMLSPDDIE0WFTEDPGP
DEAPRMPPEAAPPVAPAPAAAPTAAAPAPAPSWPLSSVPSPQTYGSGYGRFLGFLHSGTKAK
SVTCTYSFALNPKHFCQLAKTCPVQLWVDSTPPGTRVRAMAIIYKQSQHMTEVVRRCPHHE
RCSDSDGLAPPQHLIRVEGNLRVEYLDDRNTRHSVVVPYEPPEVGSDCTIHYNYMCNS
SCMGGMNRNPILTTILEDSSGNLGRNSFEVRVCACPGDRRTEEENLRKKGEPEHHELP
PGSKRALPNNTSSSOPKPKPLDGEYFTLQIQRGRERFEMFRRELNEALELKDAQAKKEPG
GSRAHSSHLSKKGQSTSRSRKKLMFKTEGPDSD

Globular domains/ TM domains and signal peptide detected by the SMART server

Domain	Start	End
Pfam:P53	95	289

The ELMs in the following table are known instances annotated from the literature.

Click on the link at positions to see experimental evidence.

Elm Name	Instances (Matched Sequence)	Positions	Logic	Elm Description	Cell Compartment	Pattern
MOD_PIKK_1	PPLSQET	12-18	true positive	(ST)Q motif which is phosphorylated by PIKK family members.	nucleus	...([ST])Q..
DOC_USP7_MATH_1	PGGSR AHSSH	359-363 364-368	true positive true positive	The USP7 MATH domain binding motif variant based on the MDM2 and p53 interactions.	nucleus	[PA][^P][^FYWL]S[^P]
DEG_MDM2_SWIB_1	FSDLWKLL	19-26	true positive	An amphipathic α -helix found in p53 family members that binds in the hydrophobic cleft of MDM2's SWIB domain.	nucleus, cytosol	F[^P](3)W(^P)(2,3)[VIL]

Figure 25: This section of the results contains additional details on the homologue alignments used to calculate the conservation score, filtering results and globular domains.

- Scroll down to below the results graphic to find additional information on the ELM prediction

pipeline's results (Fig. 25). The first section contains links to download or view the multiple sequence alignments of homologous proteins used to calculate the conservation score. Click on the link "Click here to enable the multiple sequence alignment viewer" to open the alignment in Jalview (note: this requires the Java browser plugin, which might not be available on some browsers). Alternatively you can also download the "alignment", "conservation features" and "phosphosite features" files separately to view on a desktop (non-browser) installation of Jalview (Waterhouse et al. (2009)).

The search for possible homologues is performed against the UniRef90 database, a dataset of protein sequences with less than 90 percent identity between any two of them Suzek et al. (2007). It may occur that the BLAST results are not finished when the results page is shown: We suggest to refresh the page if you see the message "Either not enough data available to calculate a sequence alignment or the calculations haven't finished yet". In some cases it is also possible that no homologues will be detected. If you have refreshed the page after waiting for more than 3 minutes, this is most likely the case.

12. Scroll down to the section titled "Filtering Summary" to view some statistics about how many motifs and instances were filtered out (Fig. 25). The first two lines contain information on whether and which filters were applied in step 1 of this protocol. In this case 4 motifs (elms) representing 26 instances were filtered out as they did not occur in *Homo sapiens*. An additional 5 motifs (representing 11 instances) were filtered out because they are not annotated to the cell compartments automatically filled in on the search page (Step 1). The next three lines ("SMART" & "Structural score") show how many motifs and instances were not removed by the SMART and Secondary structure filters. A total of 42 motifs (representing 106 instances) passed the structural filter.

Note that the graphical summary above does not contain sequences filtered out by the "cell compartment" and "taxonomic context" filters. However those filtered out by the SMART and Structural scores are shown in the graphic above (as gray rectangles).

13. Scroll down to the section with the header "Globular domains/ TM domains and signal peptide detected by the SMART server" (Fig. 25). This section contains information on which domains were detected by the SMART server, and their positions. Clicking on their names will bring you to the entry for that domain on the SMART or Pfam homepage. In this case the only domains detected is the "P53" Pfam domain.
14. On the results page, scroll down to the heading: "The ELMs in the following table are known instances annotated from the literature" (26). This table has details of the motifs and instances which have been manually annotated in the ELM database. The columns show each motif name, the sequence(s) that matched the motif as well as their starting and ending positions and the logic of the annotation followed by a short description of each motif, to which cell compartments its has been associated, and finally the regular expression of the motif.
15. Scroll further down to the section title "Results of ELM motif search after globular domain filtering, structural filtering and context filtering" to obtain an overview of all of the motifs and motif instances detected (27) Each of the rows is a "predicted" motif: A sequence matching a motif's regular expression has been detected that has also passed the "structural filter". Each row displays the motif identified, the matching peptide sequence and its position. Additional information is shown about the motif, its cell compartment and its regular expression. If the motif was detected in a homologue, the column "PHI-Blast Instance mapping" contains a link to the multiple sequence alignment of the

■ The ELMs in the following table are known **instances** annotated from the literature.

Click on the link at positions to see experimental evidence.

Elm Name	Instances (Matched Sequence)	Positions	Logic	Elm Description	Cell Compartment	Pattern
MOD_PIKK_1	PPLSQET	12-18	true positive	(ST)Q motif which is phosphorylated by PIKK family members.	nucleus	...((ST)Q..
DOC_USP7_MATH_1	PGGSR AHSSH	359-363 364-368	true positive true positive	The USP7 MATH domain binding motif variant based on the MDM2 and p53 interactions.	nucleus	[PA][^P][FYWIL]S[^P]
DEG_MDM2_SWIB_1	FSDLWKLL	19-26	true positive	An amphipatic α -helix found in p53 family members that binds in the hydrophobic cleft of MDM2's SWIB domain.	nucleus, cytosol	F[^P](3)W(^P)(2,3)[VIL]
DOC_CYCLIN_1	KKLMF	381-385	true positive	Substrate recognition site that interacts with cyclin and thereby increases phosphorylation by cyclin/cdk complexes. Predicted proteins should have a CDK phosphorylation site. Also used by cyclin/cdk inhibitors.	cytosol, nucleus	[RK].L.(0,1)[FYLIVMP]
MOD_SUMO_for_1	FKTE	385-388	true positive	Motif recognised for modification by SUMO-1	nucleus, PML body	[VILMAFP](K).E
MOD_GSK3_1	NVLSPPLS	30-37	true positive	GSK3 phosphorylation recognition site	cytosol, nucleus	...((ST))...[ST]
TRG_NLS_Bipartite_1	KRALPNNTSSSPQPKKKPL	305-323	true positive	Bipartite variant of the classical basically charged NLS.	nucleus, Nuclear pore, NLS-dependent protein nuclear import complex	[KR][KR].(7,15)[^DE] (((K[RK])(RK))(([^DE] [KR]))((K[RK][^DE])))[^DE]
MOD_CK1_1	SQETFSD	15-21	true positive	CK1 phosphorylation site	cytosol, nucleus	S..((ST))...
DOC_WW_Pin1_4	NVLSP AAPTPA TSSSPQ	30-35 78-83 312-317	true positive true positive true positive	The Class IV WW domain interaction motif is recognised primarily by the Pin1 phosphorylation-dependent prolyl isomerase.	cytosol, nucleus	...((ST))P.
TRG_NES_CRM1_1	EMFRELNEALELKD	339-352	true positive	Some proteins re-exported from the nucleus contain a Leucine-rich nuclear export signal (NES) binding to the CRM1 exportin protein.	nucleus, cytosol	((DEQ).(0,1)[LIM].(2,3) [LIVMF][^P](2,3)[LMVF]. [LMIV].{0,3}[DE]) ((DE), (0,1)[LIM].(2,3)[LVMF] [^P](2,3)[LMVF].[LMIV]. (0,3)[DEQ])

Figure 26: The ELM prediction pipeline section displaying the P53 motifs that are “known”, and have been annotated in the ELM database.

homologous proteins. If a motif instance has been filtered out by the “structural filter”, the “Structural filter info” column contains a link to a page with details on why. The last column contains information on the Probability filter: the probability reflects the chance to observe this motif in any random amino acid sequence (see section [Protocol 1](#))

16. Scroll further down to the heading “List of excluded ELMs falling inside SMART/Pfam domains and/or scoring poorly with the structural filter (if applicable).” (Fig. 28) This table is similar to the one described above, but shows motif matches which were rejected by the structural filter.

(Alternate) Predicting ELMs in novel sequences

TODO: DESCRIBE MOST PROBABLE MOTIF INSTANCES (COMPARED TO FILTERED)

■ Results of ELM motif search after globular domain filtering, structural filtering and context filtering.

Matches falling inside globular protein domains are excluded from this list unless having an acceptable structural score (if the structural filter (BETA version) is applicable). If the structural filter (BETA version) is applicable it is possible to view these structures with Jmol

Elm Name	Instances (Matched Sequence)	Positions	View in Jmol	Elm Description	Cell Compartment	Pattern	PHI-Blast Instance Mapping	Structural Filter Info	
CLV_C14_Caspase3-7	SDSDG ELKDA EGPDS	183-187 [A] 349-353 [A] 388-392 [A]	183-187 349-353 -	Caspase-3 and Caspase-7 cleavage site.	cytosol, nucleus	[DSTE][^P] [^DEWHFYC]D[GSAN]	-	Output	3.094e-03
CLV_Separase_Metazoa	EVVRR	171-175 [A]	171-175	Separase cleavage site, best known in sister chromatid separation.	centrosome, nucleus, cytosol	E[IMPVL][MLVP]R.	-	Output	3.410e-04
DEG_MDM2_SWIB_1	FSDLWKLL	19-26	-	An amphipatic α -helix found in p53 family members that binds in the hydrophobic cleft of MDM2's SWIB domain.	nucleus, cytosol	F[^P](3)W(^P)(2,3)VIL	Output Summary	-	2.125e-05
DEG_SPOP_SBC_1	PLSSS	92-96 [A]	92-96	The S/T rich motif known as the SPOP-binding consensus (SBC) of the MATH-BTB protein, SPOP, is present in substrates that undergo SPOP/Cul3-dependent ubiquitination.	nuclear speck, nucleus, Cul3-RING ubiquitin ligase complex	[AVP].[ST][ST][ST]	-	Output	9.380e-04
DOC_CYCLIN_1	KLLP RALP KKLMF	24-27 [A] 306-309 [A] 381-385	- - -	Substrate recognition site that interacts with cyclin and thereby increases phosphorylation by cyclin/cdk complexes. Predicted proteins should have a CDK phosphorylation site. Also used by cyclin/cdk inhibitors.	cytosol, nucleus	[RK].L.(0,1)[FYLIVMP]	Output Summary	-	5.324e-03
DOC_PP1_RVXF_1	RHKKLMFK HKKLMFK	379-386 [A] 380-386 [A]	- -	Protein phosphatase 1 catalytic subunit (PP1c) interacting motif binds targeting proteins that dock to the substrate for dephosphorylation. The motif defined is [RK](0,1)[VI] [^P][FW].	nucleus, protein phosphatase type 1 complex, cytosol	.[RK].(0,1)[VIL][^P][FW].	-	-	8.301e-04
DOC_PP2B_LxvP_1	LAPP	188-191 [A]	188-191	Docking motif in calcineurin substrates that binds at the interface of the catalytic CNA and regulatory CNB subunits.	cytosol, calcineurin complex, nucleus	L.[LIVAPM]P	-	Output	2.296e-03
DOC_USP7_MATH_1	PLPSQ PAPSW PLSSS	34-38 [A] 87-91 [A] 02-06 FA1	- - 02-06	The USP7 MATH domain binding motif variant based on the MDM2 and p53 interactions.	nucleus	[PA][^P][^FYWIL]S[^P]	Output Summary	Output	1.239e-02

Figure 27: This table contains the list of motifs detected in the sequence (only the top part of the table is shown). These are predictions in the sense that the sequence is present, however its is known whether they are *bona-fide* motifs which are biologically functional.

We will use protein CV_0974 (uniprot ID: Q7NZE8) as an example, a “probable tyrosine phosphatase” from *Chromobacterium violaceum*. This protein is predicted to be a tyrosine phosphatases because it has a “tyrosine phosphatase” (PTPc) domain.

Necessary Resources

Software & Hardware

A modern browser such as Firefox, Chrome, or Safari. ELM is best viewed on a laptop or desktop computer, although tablets and smartphones will also work.

Submitting a query to ELM

- Click on the “ELM Predictions” button in the menu to access the search query page (Fig. 29). Here you can provide either a protein accession (from uniprot) or an amino acid sequence (simply the sequence, or a FASTA formatted entry) in which you want to detect SLiMs. Retrieve the FASTA

■ List of excluded ELMs falling inside SMART/PFAM domains and/or scoring poorly with the structural filter (if applicable).

Matches in this list are only likely to be of interest if they are in accessible surface-exposed loops. Motif matches buried in stably folded cores of globular domains are not plausible candidates.

If the structural filter (BETA version) is applicable it is possible to view these structures with Jmol. For more info consult the PDB structure entry used for structure filtering or the SMART or PFAM entries for useful links to solved 3D structures.

Elm Name	Positions	View in Jmol	Elm Description	Cell Compartment	Pattern	PHI-Blast Instance Mapping	Structural Filter Info	Probability
DEG_APCC_DBOX_1	248-256 [A]	248-256	An RxL-based motif that binds to the Cdh1 and Cdc20 components of APC/C thereby targeting the protein for destruction in a cell cycle dependent manner	nucleus, cytosol	.R..L..[LIVM].	-	Output	
DOC_MAPK_gen_1	248-254 [A]	248-254	MAPK interacting molecules (e.g. MAPKKs, substrates, phosphatases) carry docking motif that help to regulate specific interaction in the MAPK cascade. The classic motif approximates (R/K)xxxx# where # is a hydrophobic residue.	nucleus, cytosol	[KR]{0,2}[KR], {0,2}[KR], {2,4} [ILVM].[ILVF]	-	Output	
DOC_MAPK_MEF2A_6	139-147 [A]	139-147	A kinase docking motif that mediates interaction towards the ERK1/2 and p38 subfamilies of MAP kinases.	cytosol, Transcription factor complex, nucleus	[RK]{2,4}[LIVMP].[LIV].[LIVMF]	-	Output	
DOC_PP1_RVXF_1	108-114 [A]	108-114	Protein phosphatase 1 catalytic subunit (PP1c) interacting motif binds targeting proteins that dock to the substrate for dephosphorylation. The motif defined is [RK]{0,1}[VI][^P][FW].	nucleus, protein phosphatase type 1 complex, cytosol	.[RK]{0,1}[VIL][^P][FW].	-	Output	
DOC_WW_Pin1_4	124-129 [A]	124-129	The Class IV WW domain interaction motif is recognised primarily by the Pin1 phosphorylation-dependent prolyl isomerase.	cytosol, nucleus	...([ST])P.	Output Summary	Output	
LIG_14-3-3_CanoR_1	213-217 [A] 267-271 [A]	213-217 267-271	Canonical Arg-containing phospho-motif mediating a strong interaction with 14-3-3 proteins.	cytosol, internal side of plasma membrane, nucleus	R[^DE]{0,2}[^DEPG][([ST])((FWYLMV).)[(^PRIKGN P)][(^PRIKGN){2,4}[VILMFWYP])]	-	Output	
LIG_APCC_ABBA_1	338-343 [A]	338-343	Amphipathic motif that is involved in APC/C inhibition by binding of CDH1/CDC20. In metazoan cyclin A, the motif also acts as a degron, enabling the cyclin's degradation in prometaphase.	spindle pole, nucleus, cytosol	[ILVMF].[ILMVVP][FHY].[DE]	-	Output	
LIG_FHA_1	128-144 [A]	128-	Phosphothreonine motif binding a subset of	nucleus	.(T).II.VI.	-	Output	

Figure 28: This table contains the list of motifs detected in the sequence (only the top part of the table is shown) which were excluded by the structural filter.

formatted sequence from Uniprot (<http://www.uniprot.org/uniprot/Q7NZE8.fasta>), and enter it into the “sequence input text box”.

TODO: MENTION NOT TO USE “CHROMOBACTERIUM VIOLACEUM” IN THE ORGANISM BOX AND WHY

2. The Results are summarized in the first figure on the results page (see Fig. 30) The Graphical summary shows all of the final and intermediate results generated by the ELM Prediction pipeline, and can be used infer whether or not a motif is present in a sequence, as well as how likely it is to be functional based on its structural context and evolutionary conservation.
3. Check the first row to see whether there are for phosphorylation sites acid is a serine, threonine or tyrosine. In this case, no phosphorylation data could be found in the Phospho.ELM database (Dinkel et al. (2011)).

ELM

ELM Prediction

The **ELM prediction** tool scans user-submitted protein sequences for matches to the regular expressions defined in ELM. Distinction is made between matches that correspond to experimentally validated motif instances already curated in the ELM database and matches that correspond to putative motifs based on the sequence. Since SLiMs are short and degenerate, overprediction is likely and many putative SLiMs will be false positives. However, predictive power is improved by using additional filters based on contextual information, including taxonomy, cellular compartment, evolutionary conservation and structural features.

Protein sequence

Enter Uniprot identifier or accession number: (auto-completion)
e.g. **EPN1_HUMAN, P04637, TAU_HUMAN, [RANDOM]**

Or paste the sequence (Single letter code sequence only or FASTA format):

```
>CV_0974
MSTIQTGIGQLGGRQLDLSRLDSLSGVNADKARIGIRKDGTLLVYTYGRSYLLHPDQTRRADQFLKHDLLIPGQKPREFRLAQI
FDPRMDALTQRNTQANETIARIPTQDVTTRGGKPKLWRADQAARPSGEPSRGERASLKQRNGAEHLKLQAPRAEAPRKH
DAIKTELASLGSSDQPSGLLQLKAQVGSSAEGARFLNDVGQARFRDITPAATQVRAPDGAPLPAKRVQVGGVNVIAISQY
PKAAQLESYFGMLAANRTPVLVVLASADAMAKQGRGKADLPDYFSQSGRYGRVEVESKSKGSTTLEGGLEVRAYHLNRGAD
HKSVSIPLVHPNWADFEAQGATALKALAQHVDAVADKTTAFYRDNNSSALNDPDKLLPVICRAGVGRGTGQIQAABELLKPG
ASSLESIVADMGRSRNHLMVQTSGQLSTLVLAQQQGRAILQPETAAEPIYANQAQAEPIYANDAPPPLRRPR
```

Cell compartment (one or several):

- not specified
- extracellular
- nucleus
- cytosol
- peroxisome
- glycosome
- glycosome
- Golgi apparatus
- endoplasmic reticulum
- lysosome
- endosome
- plasma membrane
- mitochondrion

Taxonomic Context

Type in species name (auto-completion):

Motif Probability Cutoff:

100

Submit **Reset Form**

ELM DB

The ELM relational database stores different types of data about experimentally validated SLiMs that are manually

peptide from ELM class LIG_PTB_Apo_2

- ELM database update
We have added new instances for: **LIG_APCC_ABBA_1**, **LIG_APCC_ABBAvCdc20_2** as well as **DOC_MAPK_HePTP_8**, **DOC_MAPK_MEF2A_6** and **DOC_MAPK_DCC_7**
- ELM Database Update
We have updated several MOD_CDk motifs and added new instances:
MOD_CDk_1 is now: **MOD_CDk_SPxK_1**, **MOD_CDk_SPK_2**, **MOD_CDk_SPxxK_3** have been added.
- ELM database update
Several new ELM classes and instances have been added:
LIG_BH_BH3_1, **DEG_COP1_1**
- ELM database update
The class **DOC_PP2A_KARD_1** has been replaced by **DOC_PP2A_B56_1**, and new instances have been added.
- ELM database update
Several new ELM classes and instances have been added:
LIG_CSK_EPIYA_1, **LIG_Rb_LxCxE_1**, **DOC_MAPK_JIP1_4**, **DOC_MAPK_NFAT4_5**
- ELM database update
Several new ELM classes and instances have been added:
DOC_MAPK_RevD_3, **LIG_ANK_PxPxL_1**, **LIG_CSL_BTD_1**, **LIG_G3BP_FGDF_1**, **LIG_KLC1_TPR_1**, **LIG_PALB2_WD40_1**, **LIG_UFM1_UFIM_1**

Figure 29: **Figure BACT-BP-1:** The input query page for finding motifs in ELM. The sequence for *C. vilaceum* protein CV_0974 was used as an example for this protocol.

4. Check the second row showing SMART and Pfam domains. Hover the mouse over these domains to see their names and exact start and end positions.
5. The third row shows globular and disordered regions in the sequence as predicted by GlobPlot ([Linding et al. \(2003\)](#)). The 4th & 5th rows contain results from IUPred ([Dosztányi et al. \(2005\)](#)), another unstructured region prediction tool. Protein segments with an IUpred score above 0.5 are 95% likely to be disordered (REF??).
6. Place the cursor over the blue box for motif occurrence “DOC_USP7_MATH_1” at position 129-133. This motif is in a disordered region, and has not been filtered out by the structural filter. However, its conservation score is extremely low: 0.000, indicating it is not conserved in homologous proteins. Place the cursor over motif “DOC_MAPK_DCC_7” at positions “334-343”. Despite the high conservation score (1.000), this motif is inside the PTpC domain (and a Globular regions), and therefore has been filtered out.

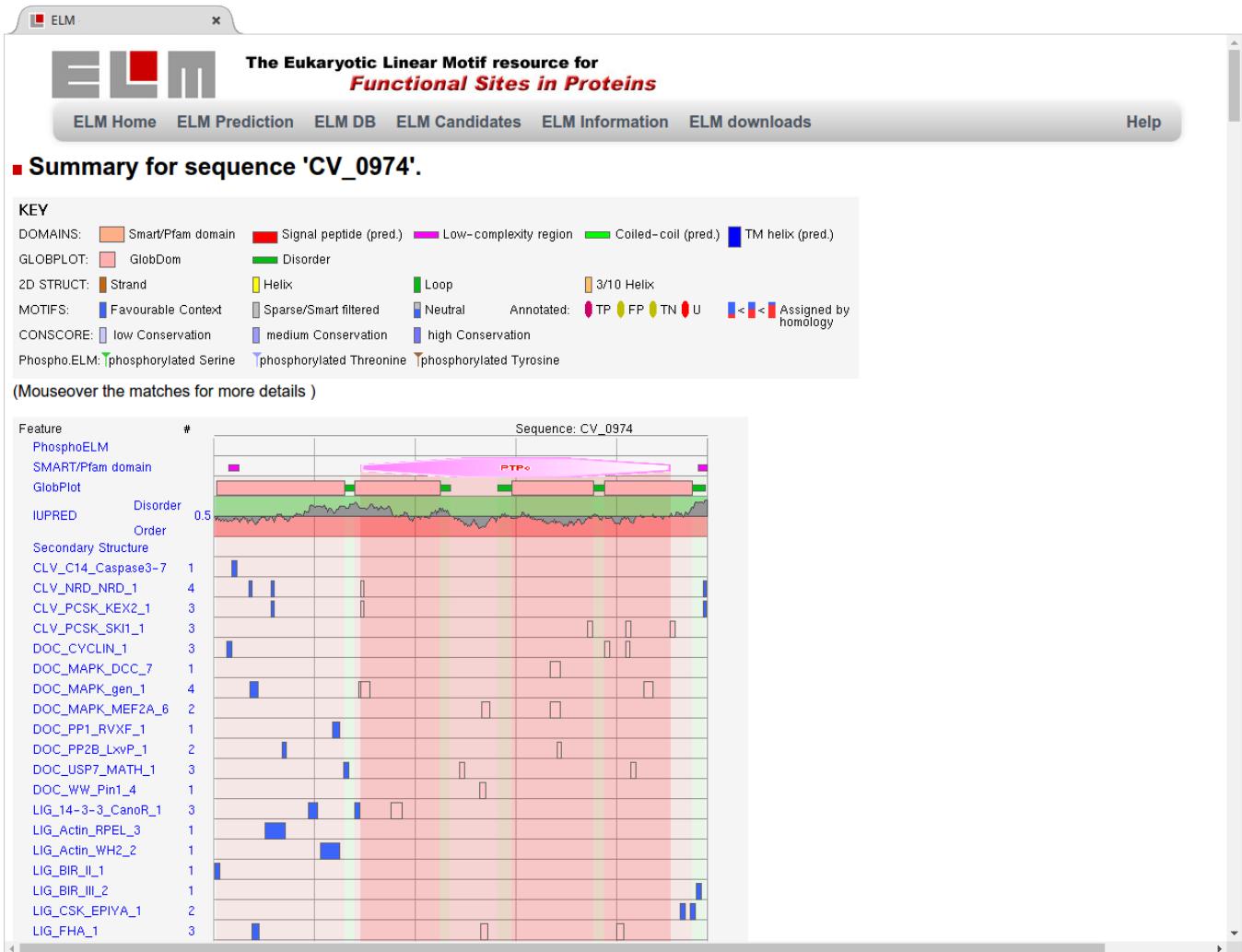


Figure 30: **Figure BACT-BP-2:** The graphical results summary of the ELM Prediction pipeline for Probable Tyrosine phosphate (CV_0974). Note that not all motif detections are shown (the image is truncated at the bottom). The top five rows show a handful of structural features. The motif occurrence are shown as blue boxes, the intensity of which indicates the conservation score. See steps XXX to YYY for more information.

TODO: CHECK CONSERVATION FILTER

Interpreting the prediction results: Additional Information

TODO: DESCRIBE HOW TO INTERPRETE THE PREDICTIONS USING THIS BACTERIAL EXAMPLE (OF WHICH NOT MUCH IS KNOWN). FOCUS ON HOW ONE SHOULD INTERPRETE THESE PREDICTIONS (LOOK AT DISORDER/GLOBULARITY, CONSERVATION)

(Alternate) Predicting ELMS in sequences using the API

Querying ELM for motifs in a given sequence (as described in [Protocol 3](#) and [Protocol 4](#)), gives you a nice overview of putative and possibly annotated motifs in your query protein with a graphical representation using colors to highlight different regions of the protein sequence (eg. disordered vs. globular). It is however difficult to analyse a large set of protein sequences in this manner. Therefore, the ELM server provides an interface which you can use to submit your sequence in a programmatic way. Of course, this way, you won't receive the graphical output representation, but are limited to textual data representation.

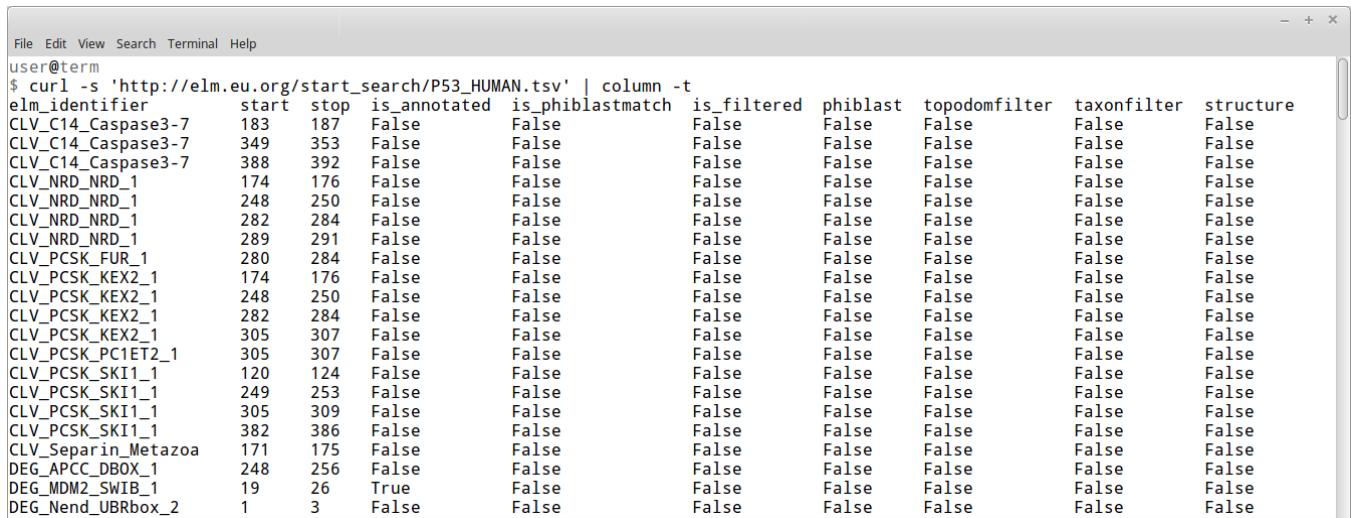
Currently, there exists a single URL (http://elm.eu.org/start_search/) to accept such queries. You can choose to either submit a uniprot name or accession (eg. http://elm.eu.org/start_search/P53_HUMAN.tsv) or submit your raw sequence (e.g.http://elm.eu.org/start_search/MAPRGFSCLLLTSEIDLKVRRRA). If the URL ends in ‘.tsv’ then the server assumes you are using a Uniprot id or accession; if it doesn’t, then it assumes you are using raw sequence. See below for details.

Necessary Resources

Software

Ideally use `curl` curl.haxx.se/ on the commandline. This program can be launched from the terminal in any of the major operating systems: OSX, Windows and Linux. Of course `curl` is only one of many different ways to access web content programmatically, and we suggest anyone to use which ever program they feel is better suited for their tasks.

Submitting a query to ELM via the REST API



The screenshot shows a terminal window with the following command and its output:

```
File Edit View Search Terminal Help
user@term $ curl -s 'http://elm.eu.org/start_search/P53_HUMAN.tsv' | column -t
elm_identifier start stop is_annotated is_phiblastmatch is_filtered phiblast topodomfilter taxonfilter structure
CLV_C14_Caspase3-7 183 187 False False False False False False False
CLV_C14_Caspase3-7 349 353 False False False False False False False
CLV_C14_Caspase3-7 388 392 False False False False False False False
CLV_NRD_NRD_1 174 176 False False False False False False False
CLV_NRD_NRD_1 248 250 False False False False False False False
CLV_NRD_NRD_1 282 284 False False False False False False False
CLV_NRD_NRD_1 289 291 False False False False False False False
CLV_PCSK_FUR_1 280 284 False False False False False False False
CLV_PCSK_KEX2_1 174 176 False False False False False False False
CLV_PCSK_KEX2_1 248 250 False False False False False False False
CLV_PCSK_KEX2_1 282 284 False False False False False False False
CLV_PCSK_KEX2_1 305 307 False False False False False False False
CLV_PCSK_PC1ET2_1 305 307 False False False False False False False
CLV_PCSK_SKI1_1 120 124 False False False False False False False
CLV_PCSK_SKI1_1 249 253 False False False False False False False
CLV_PCSK_SKI1_1 305 309 False False False False False False False
CLV_PCSK_SKI1_1 382 386 False False False False False False False
CLV_Separin_Metazoa 171 175 False False False False False False False
DEG_APCC_DBOX_1 248 256 False False False False False False False
DEG_MDM2_SWIB_1 19 26 True False False False False False False
DEG_Nend_UBRbox_2 1 3 False False False False False False False
```

Figure 31: The commandline output when `curl` is used to download all motifs predicted in Human P53. Note that we used a more advanced command that `curl` alone to make the columns align nicely (see text for an explanation).

1. Use curl to query ELM for all motifs predicted to occur in Human P53 by typing the following into a terminal: ‘curl ‘http://elm.eu.org/start_search/P53_HUMAN.tsv’. Each row represents a motif detection, and the first column “elm_identifier” indicates which class was identified. The columns “start” and “stop” show that first and last amino acid positions that matched form part of the motif. Column “is annotated” is True if this motif has been annotated in the database as an (experimentally validated) motif instance. The column “is phiblastmatch” is True if ?????. The column “is filtered” shows whether or not this motif was rejected by the ELM Prediction structure filter. Column “phibast” indicates whether ?????. The “topodomfilter” and “taxonfilter” shown whether ?????. The last column “structure” ?????

In figure 31 we use a slightly more advanced command to get the output to look nice in the terminal. We specified the -s option to silence all curl output other than the downloaded file, and piped the output directly to the column command (this command exists on most Linux and OSX machines).

TODO: Holger: what are the columns that are not described in the above section for?

```

File Edit View Search Terminal Help
user@term
$ curl -s -o query.tsv 'http://elm.eu.org/start_search/P53_HUMAN.tsv'
user@term
$ head query.tsv | column -t
elm_identifier      start    stop   is_annotated  is_phiblastmatch  is_filtered  phiblast  topodomfilter  taxonfilter  structure
CLV_C14_Caspase3-7  183     187   False        False          False        False    False        False        False
CLV_C14_Caspase3-7  349     353   False        False          False        False    False        False        False
CLV_C14_Caspase3-7  388     392   False        False          False        False    False        False        False
CLV_NRD_NRD_1       174     176   False        False          False        False    False        False        False
CLV_NRD_NRD_1       248     250   False        False          False        False    False        False        False
CLV_NRD_NRD_1       282     284   False        False          False        False    False        False        False
CLV_NRD_NRD_1       289     291   False        False          False        False    False        False        False
CLV_PCSK_FUR_1      280     284   False        False          False        False    False        False        False
CLV_PCSK_KEX2_1     174     176   False        False          False        False    False        False        False
user@term
$ █

```

Figure 32: It is possible to send amino acid sequences to the ELM Prediction pipeline. In this case we have used the curl option -o to download directly to the file query.tsv , and use a combination of the head and column commands to display the first 10 rows to the terminal.

2. Use curl to query ELM via protein sequence by using the URL http://elm.eu.org/start_search/MAPRGF (Fig. 32). In this case the query is an arbitrary short peptide sequence, but this can (of course) contain any sequence you are interested in analysing. The output format is exactly the same as in the previous step.

This way of querying ELM is unfortunately not stable for long protein sequences. Different browsers and computers have different maximum lengths for URLs, and the excess text is often simply ignored. We recommend not using this method for sequences longer than 2000 amino acids.

(Alternate) Searching the ELM database using the REST API

Many researchers are interested in large-scale analyses rather than information about individual protein sequences. To this end, individual queries to the ELM webserver with a single protein id at a time, are not practical.

For this reason, as much information as possible is made available via a REST interface [Fielding and Taylor \(2002\)](#). This allows the user to interact with the ELM database and ELM webserver via scriptable URL requests. Each request can easily be tested in the browser before it is being automated in a script.

In this section we will explore the various ways in which data can downloaded both in using the browser as well as via the commandline.

Necessary Resources

Software

Ideally use curl curl.haxx.se/ on the commandline. This program can be launched from the terminal in any of the major operating systems: OSX, Windows and Linux. Of course curl is only one of many different ways to access web content programmaticaly, and we suggest anyone to use which ever program they feel is better suited for their tasks.

Downloading all ELM classes

1. Direct your browser to the URL elm.eu.org/downloads or select ‘ELM Downloads’ from the main menu (Fig. 33). This page contains links and descriptions on how to download ELM data in text format. The datasets are split into several smaller collections (for example “Classes”, “Instances”, etc). Each table contains links (in orange) to download the data in various formats.

Each table also shows the ‘last modified date’ indicating when the data was last updated. This is useful if you want to know when to update your local data with the most up to date ELM data.

2. Click on the first orange ‘html’ link in the table “Classes” to navigate to the following URL: elm.eu.org/elms/elm_index.html. This page shows all of the annotated ELM classes in the database. This page is the same one as shown in figure 4.
3. Navidate to the folling URL: elm.eu.org/elms.html?q=CSK specifying q=CSK to limit the list of ELMs to those matching the search query “CSK”. This page is again similar to the one shown in figure 4, but with less classes.

This search result is identical to the result you would obtain by doing a “manual” search on the ELM Classes page described in step 3 of Protocol 1 (Fig. 4).

4. Open the following URL: elm.eu.org/elms.tsv?q=CSK to download a list of classes that match the search query “CSK” (as in the previous step) in the “tab separated values” format. By exchanging the .html part of the url with .tsv , we ask the webserver to give us the data in “tab-separated values” format.

The screenshot shows the ELM Downloads page. At the top, there's a navigation bar with links to ELM Home, ELM Prediction, ELM DB, ELM Candidates, ELM Information, ELM downloads, and Help. A search bar is also present. To the right, a sidebar lists categories: Classes, Instances, Interactions, Interaction Domains, Methods, PDBs, GOTerms, Renamed ELM classes, and Media / Files.

Classes

Last modified on: Dec. 7, 2016, 5:28 p.m.

Name	Example	URL
all	html	/elms/elm_index.html
all	tsv	/elms/elms_index.tsv
by query term	tsv	/elms/elms_index.tsv?q=PCSK
by ELM id	html	/ELME000012.html

Instances

Last modified on: Dec. 8, 2016, 2:56 p.m.

Annotated ELM instances can be queried in a variety of ways. You are encouraged to use the [search form](#) to get a feeling for the parameters. Common examples include limiting the query by either instance logic or taxon.

Name	Example	URL
all	html	/elms/instances.html?q=*
by Uniprot acc	fasta	instances.fasta?q=P12931
by Uniprot name	gff	instances.gff?q=SRC_HUMAN
by Uniprot acc	tsv	instances.tsv?q=P12931
by query term	pir	instances.pir?q=PCSK
by query term	tsv	instances.tsv?q=src
by query term	mitab	instances.mitab?q=src
by query term	xml	instances.psimi?q=src
by query term using additional parameter "instance logic"	tsv	instances.tsv?q=src&instance_logic=true+positive
by Instance id	html	/ELMI000123.html
All docking motifs annotated in taxon "mouse"	tsv	instances.tsv?q=DOC_&taxon=mus+musculus

Figure 33: The ELM downloads page, which holds information about the different types of data (such as “Classes”, “Instances”, etc; see menu to the right) that can be obtained from the server. The orange boxes are clickable links, the URL following them are used to highlight the URL scheme used by the server (bold font denotes specifics used in the examples such as query terms, or formats).

Depending on which browser you are using, the file may open directly in your browser, or you may be prompted to download the file or save it to a separate location. In the latter two cases you can open the downloaded file using a (plain) text file viewer, or possibly a spreadsheet viewer (such as Microsoft Excel or LibreOffice Calc).

5. Type the following command into a command line terminal to download the same data from the previous step directly into the terminal: `curl 'http://elm.eu.org/elms/elms_index.tsv?q=CSK'`. The output should look similar to figure 34. The column names are the same ones as shown in the table in figure 4.

Use the curl option -o to save the results directly to a file. For example: `curl -o classes.tsv 'http://elm.eu.org/elms/elms_index.tsv?q=CSK'` will save the data to a file called classes.tsv.

```

File Edit View Search Terminal Help
user@term
$ curl 'http://elm.eu.org/elms.tsv?q=CSK'
#ELM_Classes_Download_Version: 1.4
#ELM_Classes_Download_Date: 2017-01-05 16:17:30.881105
#Origin: elm.eu.org
#Type: tsv
#Num_Classes: 7
"Accession" "ELMIdentifier" "FunctionalSiteName" "Description" "Regex" "Probability" "#Instances" "#Instances_in_PDB"
"ELME000101" "CLV_PCSK_FUR_1" "PCSK cleavage site" "Furin (PACE) cleavage site (R-X-[RK]-R|-X)." "R.[RK]R." "0."
"ELME000108" "CLV_PCSK_KEX2_1" "PCSK cleavage site" "Yeast kexin 2 cleavage site (K-R|-X or R-R|-X)." "[KR]R." ""
"ELME000100" "CLV_PCSK_PC1ET2_1" "PCSK cleavage site" "NEC1/NEC2 cleavage site (K-R|-X)." "KR." "0.00390276834" "6"
"ELME000103" "CLV_PCSK_PC7_1" "PCSK cleavage site" "Protein convertase 7 (PC7, PCSK7) cleavage site (R-X-X-[RK]-R)" "Subtilisin/kexin isozyme-1 (SKI1) cleavage site ([RK]-X-[hydrophobic amino acid])" "0.00390276834" "6"
"ELME000146" "CLV_PCSK_SKI1_1" "PCSK cleavage site" "Csk Src Homology 2 (SH2) domain binding EPIYA motif" "Members of the non-receptor tyrosine kinase Csk family phosphorylation sites" "0.00390276834" "6"
"ELME000424" "LIG_CSK_EPIYA_1" "EPIYA ligand motif for CSK-SH2" "Csk Src Homology 2 (SH2) domain binding EPIYA motif" "Members of the non-receptor tyrosine kinase Csk family phosphorylation sites" "0.00390276834" "6"
"ELME00013" "MOD_TYR_CSK" "TYR phosphorylation site" "Members of the non-receptor tyrosine kinase Csk family phosphorylation sites" "0.00390276834" "6"
user@term
$ 

```

Figure 34: A screenshot of a terminal window using curl to download all ELM classes matching the term ‘CSK’.

```

File Edit View Search Terminal Help
user@term
$ curl 'http://elm.eu.org/instances.gff?q=p53_human'
##gff-version 3
P04637 ELM sequence_feature 19 26 . . . ID=DEG_MDM2_SWIB_1
P04637 ELM sequence_feature 381 385 . . . ID=DOC_CYCLIN_1
P04637 ELM sequence_feature 359 363 . . . ID=DOC_USP7_MATH_1
P04637 ELM sequence_feature 364 368 . . . ID=DOC_USP7_MATH_1
P04637 ELM sequence_feature 30 35 . . . ID=DOC_WW_Pin1_4
P04637 ELM sequence_feature 78 83 . . . ID=DOC_WW_Pin1_4
P04637 ELM sequence_feature 312 317 . . . ID=DOC_WW_Pin1_4
P04637 ELM sequence_feature 315 319 . . . ID=MOD_CDK_SPxxK_3
P04637 ELM sequence_feature 15 21 . . . ID=MOD_CK1_1
P04637 ELM sequence_feature 30 37 . . . ID=MOD_GSK3_1
P04637 ELM sequence_feature 12 18 . . . ID=MOD_PIKK_1
P04637 ELM sequence_feature 385 388 . . . ID=MOD_SUMO_for_1
P04637 ELM sequence_feature 339 352 . . . ID=TRG_NES_CRM1_1
P04637 ELM sequence_feature 305 323 . . . ID=TRG_NLS_Bipartite_1
##FASTA
>P04637
MEEPQSDPSVEPPLSQETFSDLWKLLPENNVLSPPLSQAMDDMLLSPDDIEQWFTEDPGPDEAPRMPAAPPVAPAPAAPTAAAPAPAPSPLSSSVPSQKTYQGSYGRFLGLHSGTAKSVCYTSPALNK
MFCQLAKTCPVQLWVDSTPPGTRVRAMAIVKQSQHMTEVVRRCPHHERCSDSDGLAPPQHLIRVEGNLRVEYLDRNTFRHSVVVPYEPPEVGSDCTTIHYNYMCNSCMGGMNRRPILTIITLEDSSGNL
LGRNSFEVRVCACPGRDRRTEENLRKKGEPHELPPGSTKRALPNNTSSSPQPKKPLDGEYFTLQIRGRERFEMFRELNEALELKDAQAGKEPGGSRAHSSHLKSKGQSTSRRKKLMFKTEGPDSM
user@term
$ 

```

Figure 35: Screenshot of a terminal window using curl to download all ELM instances annotated for sequence p53_human.

- To download a list of all motif instances detected in Human P53, type the followin command into a terminal: curl ‘http://elm.eu.org/instances.gff?q=p53_human’ . The output should look similar to that shown in figure 31. The output is in the “General Feature Format” (see www.ensembl.org/info/website/upload/gff.html#moreinfo), with the FASTA formatted sequence appended to the end of the output.

Many other file formats are available for downloading instances annotations, including the fasta , gff , pir , OR PSI-MI format (either xml or MiTab)

- To download a list of all instances matchin th search query “CLV” in the yellow fever mosquito (*Aedes agypti*), enter the following command into a terminal: curl ‘http://elm.eu.org/instances.tsv?q=CLV’ . In general any species name can be used, always replacing the “space” with a “+”. This should

- return a single instance, the only one matching CLV in *A. aegypti*.
8. More data (interactions, domains, methods, etc.) can be downloaded from ELM in analogous fashion as shown in the preceding steps. Take a look at the ELM Downloads page (<http://elm.eu.org/downloads>, figure 33) for an overview of which datasets can be downloaded, and what the different possible filters and formats are for each dataset.

Guidelines for Interpreting Results

instructions: A brief discussion of the theory and applications of your

notes: Maybe mention how findings are relevant to the lab? For example: Manually annotated content should be reliable, although one should look at the ‘confidence’ in the instance annotation. Predictions are probably trustworthy, but you need to take into account the ‘confidence score’, and other features like whether its in a domain, etc...

Commentary:

instructions: A brief discussion of the theory and applications of your

Background Information

In order to interpret the data contained in ELM and the results produced by the ELM prediction tool, it is important to have a basic understanding of SLiM’s and how they are affected by their structural and biological context. This background information summarises the different functionalities of SLiMs, describes the degenerate nature of motif sequences, and emphasises the need for contextual data for confident SLiM prediction.

ELM categorises SLiMs depending on their functionality

SLiMs mediate different types of interactions, and based on this functionality, the ELM classes annotated in the ELM database are grouped into six main ELM types (Figure 1) (Dinkel et al. (2014)). They can function as ligand binding sites or as sites for post-translational modification (PTM). Some ligand SLiMs are recognised by components of the cellular transport machinery and function as localisation signals that target proteins to specific sub-cellular compartments (TRG type). Other ligand SLiMs are abundantly present in interfaces that mediate the assembly of large macromolecular complexes and in highly modular scaffold proteins that act as multivalent platforms for protein complex assembly (LIG type). Docking motifs are ligand SLiMs that recruit modification enzymes to their substrates by binding to a site on the enzyme that is distinct from the active site (DOC type). A subset of these, known as degrons, recruit ubiquitin ligases, which subsequently polyubiquitylate their substrates and hence target them for proteasomal degradation (DEG type). SLiMs that act as sites for PTM can be targeted by specific enzymes for the addition or removal of a small chemical group (e.g. phosphorylation), a sugar molecule (e.g. glycosylation), a protein (e.g. ubiquitylation), or another moiety (e.g. lipidation) (MOD type). Other PTM SLiMs mediate

proteolytic cleavage by acting as target site for proteolytic enzymes (CLV type), or are recognised for structural modification by isomerases that catalyse cis-trans isomerisation of the peptide backbone (DOC type) [Van Roey et al. \(2014\)](#); [Lee et al. \(2015\)](#).

ELM regular expressions reflect the degenerate nature of SLiMs

As their name suggests, SLiMs are compact, being composed of a limited number of adjacent amino acids. Most of a motif's binding specificity however is conferred by only a subset of these amino acids. Those few residues that directly interact with the binding partner are evolutionary conserved, although in many cases a subset of amino acids that share certain properties (such as similar charge, size or hydrophobicity) are allowed in these hotspot positions. In the motif positions that contribute little to the interaction, there are even less constraints, i.e. a broader range of amino acids is allowed in these positions [Davey et al. \(2012\)](#). This sequence flexibility is captured in the regular expressions that are defined for each motif class. A first consequence of this degeneracy is that SLiMs co-operatively engage in interactions of relatively low affinity. Hence these binding events are transient and reversible, and can be readily modulated, for instance by PTM. These characteristics make SLiM-based interactions ideal mediators of the dynamic processes involved in cell signalling [Van Roey et al. \(2012\)](#). Another consequence is that it might take only a few or even a single point mutation to generate or disrupt a functional motif in a protein. The associated ability to evolve convergently might underlie the proliferation of SLiMs and the rewiring of interactomes [Davey et al. \(2015\)](#); [Kim et al. \(2012\)](#). Conversely, several SLiM-associated diseases have been characterised to date, for instance Liddle syndrome [Furuhashi et al. \(2005\)](#).

ELM integrates data to increase the confidence of SLiM prediction*

Due to their degenerate nature, motif sequences contain only very little information, and many short sequences in a proteome will match motif patterns. However, most of these matches will not represent functional motifs, and hence, when scanning a proteome for putative motifs using only the motif sequence patterns will yield a large number of false positive instances, far exceeding the number of true motifs. Therefore, reliable motif detection cannot go without experimental validation of candidate motifs, using different types of experiments and techniques [Gibson et al. \(2015\)](#). This however does not mean that bioinformatics analysis cannot guide researchers towards a subset of candidate motifs that have a higher probability to be functional and help rule out those candidate motifs that are likely to be false positives. Taking into account additional information, besides a match to a sequence pattern defining a SLiM, can greatly narrow the selection of putative motifs for experimental validation. Additional data for in silico analysis include conservation of the motif sequence, the location of the motif within the protein's structure and its accessibility for its binding partner, validated interaction with the binding partner, and in-cell co-localisation with the binding partner. The availability and usefulness of these additional data for SLiM discovery depends on their extensive and correct biocuration. A vast and increasing amount of biological data is available in a wide variety of sources, including the literature and large-scale datasets. In order to facilitate integration of data, they need to be collected, annotated and formatted in central data and knowledge repositories. The ELM database provides such a repository for experimentally validated linear motif classes and instances. The ELM prediction tool in turn relies on annotated data, both from the ELM database and other resources, to accurately analyse unknown sequences for candidate motifs and assist researchers in selecting the most plausible ones for experimental validation and discard likely false positive hits, saving them valuable time and assets [Dinkel et al. \(2012\)](#).

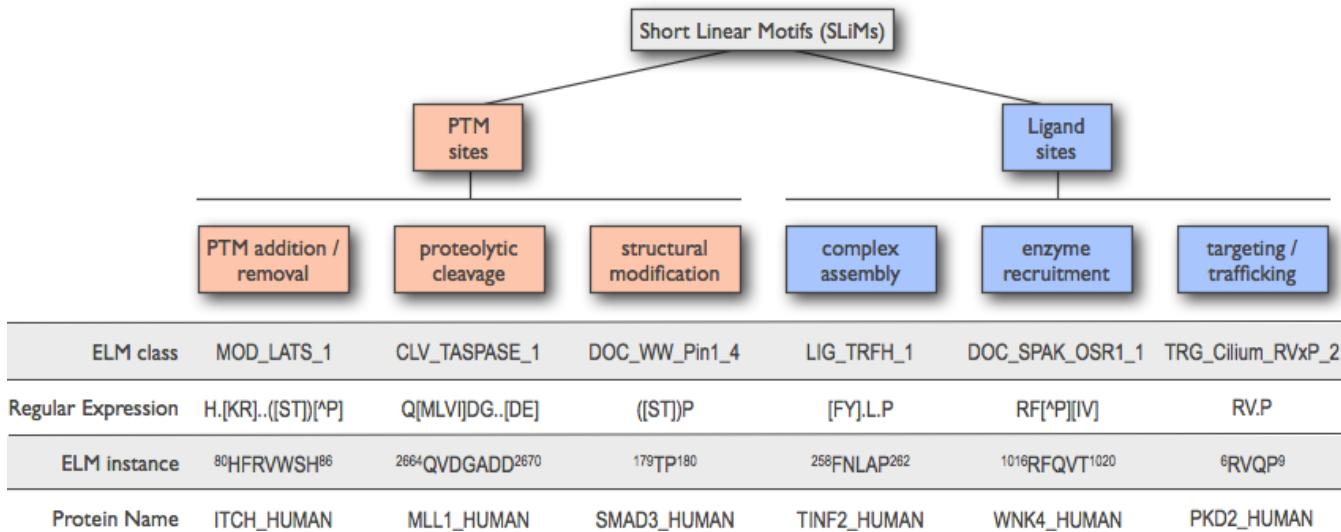


Figure 36: **Figure functional_classification_of_SLiMs** For each ELM class, the functional category to which it belongs is indicated by a three-letter prefix. Each ELM class is defined by a regular expression. Peptide sequences in proteins that match the regular expression of a specific ELM class and that were experimentally validated to be functional motifs are captured as ELM instances of that class. Degrons are a specific subtype of enzyme-recruiting docking motifs (see text for a detailed description).

Critical Parameters and Troubleshooting

instructions: optionally 2 separate sections.

Internet Resources with Annotations

<http://www.clustal.org/omega> Clustal Omega ([Sievers et al. \(2011\)](#)) is a tool for the alignment of multiple nucleic acid and protein sequences.

<http://www.jalview.org> Jalview ([Waterhouse et al. \(2009\)](#)) is a Java desktop application (and browser applet) that employs web services for sequence alignment and visualization.

<http://proviz.ucd.ie> ProViz ([Jehl et al. \(2016\)](#)) is an interactive protein exploration tool, which searches several databases for information about a given query protein. Data relevant to the protein like an alignment of homologues, linear motifs, post translational modifications, domains, secondary structure, sequence variations and others are graphically represented relative to their position in the protein.

References

Berman, H. M., T. Battistuz, T. N. Bhat, W. F. Bluhm, P. E. Bourne, K. Burkhardt, Z. Feng, G. L. Gilliland, L. Iype, S. Jain, P. Fagan, J. Marvin, D. Padilla, V. Ravichandran, B. Schneider, N. Thanki, H. Weissig, J. D. Westbrook, and C. Zardecki. 2002. The protein data bank. *Acta crystallographica. Section D, Biological crystallography* 58:899–907.

- Chica, C., A. Labarga, C. M. Gould, R. López, and T. J. Gibson. 2008. A tree-based conservation scoring method for short linear motifs in multiple alignments of protein sequences. *BMC bioinformatics* 9:229.
- Consortium, T. G. O. 2017. Expansion of the gene ontology knowledgebase and resources. *Nucleic acids research* 45:D331–D338.
- Consortium, U. 2015. Uniprot: a hub for protein information. *Nucleic acids research* 43:D204–12.
- Coordinators, N. R. 2017. Database resources of the national center for biotechnology information. *Nucleic acids research* 45:D12–D17.
- Davey, N. E., M. S. Cyert, and A. M. Moses. 2015. Short linear motifs à la ex nihilo evolution of protein regulation. *Cell Communication and Signaling* 13:43.
- Davey, N. E., K. Van Roey, R. J. Weatheritt, G. Toedt, B. Uyar, B. Altenberg, A. Budd, F. Diella, H. Dinkel, and T. J. Gibson. 2012. Attributes of short linear motifs. *Molecular bioSystems* 8:268–81.
- Diella, F. 2008. Understanding eukaryotic linear motifs and their role in cell signaling and regulation. *Frontiers in Bioscience Volume*:6580.
- Dinkel, H., C. Chica, A. Via, C. M. Gould, L. J. Jensen, T. J. Gibson, and F. Diella. 2011. Phospho.elm: a database of phosphorylation sites—update 2011. *Nucleic acids research* 39:D261–7.
- Dinkel, H., S. Michael, R. J. Weatheritt, N. E. Davey, K. Van Roey, B. Altenberg, G. Toedt, B. Uyar, M. Seiler, A. Budd, L. Jödicke, M. A. Dammert, C. Schroeter, M. Hammer, T. Schmidt, P. Jehl, C. McGuigan, M. Dymcka, C. Chica, K. Luck, A. Via, A. Chatr-Aryamontri, N. Haslam, G. Grebnev, R. J. Edwards, M. O. Steinmetz, H. Meiselbach, F. Diella, and T. J. Gibson. 2012. Elm—the database of eukaryotic linear motifs. *Nucleic acids research* 40:D242–51.
- Dinkel, H., K. Van Roey, S. Michael, N. E. Davey, R. J. Weatheritt, D. Born, T. Speck, D. Krüger, G. Grebnev, M. Kubán, M. Strumillo, B. Uyar, A. Budd, B. Altenberg, M. Seiler, L. B. Chemes, J. Glavina, I. E. Sánchez, F. Diella, and T. J. Gibson. 2014. The eukaryotic linear motif resource ELM: 10 years and counting. *Nucleic Acids Research* 42:D259–D266.
- Dosztányi, Z., V. Csizmok, P. Tompa, and I. Simon. 2005. Iupred: web server for the prediction of intrinsically unstructured regions of proteins based on estimated energy content. *Bioinformatics (Oxford, England)* 21:3433–4.
- Fielding, R. T. and R. N. Taylor. 2002. Principled design of the modern web architecture. *ACM Transactions on Internet Technology* 2:115–150.
- Finn, R. D., T. K. Attwood, P. C. Babbitt, A. Bateman, P. Bork, A. J. Bridge, H.-Y. Chang, Z. Dosztányi, S. El-Gebali, M. Fraser, J. Gough, D. Haft, G. L. Holliday, H. Huang, X. Huang, I. Letunic, R. Lopez, S. Lu, A. Marchler-Bauer, H. Mi, J. Mistry, D. A. Natale, M. Necci, G. Nuka, C. A. Orengo, Y. Park, S. Pesceat, D. Piovesan, S. C. Potter, N. D. Rawlings, N. Redaschi, L. Richardson, C. Rivoire, A. Sangrador-Vegas, C. Sigrist, I. Sillitoe, B. Smithers, S. Squizzato, G. Sutton, N. Thanki, P. D. Thomas, S. C. E. Tosatto, C. H. Wu, I. Xenarios, L.-S. Yeh, S.-Y. Young, and A. L. Mitchell. 2017. Interpro in 2017—beyond protein family and domain annotations. *Nucleic acids research* 45:D190–D199.

- Finn, R. D., P. Coggill, R. Y. Eberhardt, S. R. Eddy, J. Mistry, A. L. Mitchell, S. C. Potter, M. Punta, M. Qureshi, A. Sangrador-Vegas, G. A. Salazar, J. Tate, and A. Bateman. 2016. The pfam protein families database: towards a more sustainable future. *Nucleic acids research* 44:D279–85.
- Furuhashi, M., K. Kitamura, M. Adachi, T. Miyoshi, N. Wakida, N. Ura, Y. Shikano, Y. Shinshi, K.-i. Sakamoto, M. Hayashi, N. Satoh, T. Nishitani, K. Tomita, and K. Shimamoto. 2005. Liddle's Syndrome Caused by a Novel Mutation in the Proline-Rich PY Motif of the Epithelial Sodium Channel β -Subunit. *The Journal of Clinical Endocrinology & Metabolism* 90:340–344.
- Gibson, T. J., H. Dinkel, K. Van Roey, and F. Diella. 2015. Experimental detection of short regulatory motifs in eukaryotic proteins: tips for good practice as well as for bad. *Cell Communication and Signaling* 13:42.
- Jehl, P., J. Manguy, D. C. Shields, D. G. Higgins, and N. E. Davey. 2016. Proviz-a web-based visualization tool to investigate the functional and evolutionary features of protein sequences. *Nucleic acids research* 44:W11–5.
- Kanehisa, M., Y. Sato, M. Kawashima, M. Furumichi, and M. Tanabe. 2016. Kegg as a reference resource for gene and protein annotation. *Nucleic acids research* 44:D457–62.
- Kerrien, S., S. Orchard, L. Montecchi-Palazzi, B. Aranda, A. F. Quinn, N. Vinod, G. D. Bader, I. Xenarios, J. Wojcik, D. Sherman, M. Tyers, J. J. Salama, S. Moore, A. Ceol, A. Chatr-Aryamontri, M. Oesterheld, V. Stümpflen, L. Salwinski, J. Nerothin, E. Cerami, M. E. Cusick, M. Vidal, M. Gilson, J. Armstrong, P. Woppard, C. Hogue, D. Eisenberg, G. Cesareni, R. Apweiler, and H. Hermjakob. 2007. Broadening the horizon-level 2.5 of the hupo-psi format for molecular interactions. *BMC biology* 5:44.
- Kim, J., I. Kim, J.-S. Yang, Y.-E. Shin, J. Hwang, S. Park, Y. S. Choi, and S. Kim. 2012. Rewiring of PDZ Domain-Ligand Interaction Network Contributed to Eukaryotic Evolution. *PLoS Genetics* 8:e1002510.
- Lee, R. V. D., M. Buljan, B. Lang, R. J. Weatheritt, G. W. Daughdrill, A. K. Dunker, M. Fuxreiter, J. Gough, J. Gsponer, D. T. Jones, P. M. Kim, R. W. Kriwacki, C. J. Old, R. V. Pappu, P. Tompa, V. N. Uversky, P. E. Wright, and M. M. Babu. 2015. Classification of Intrinsically Disordered Regions and Proteins. *Prog Biophys Mol Biol* .
- Letunic, I., T. Doerks, and P. Bork. 2015. Smart: recent updates, new developments and status in 2015. *Nucleic acids research* 43:D257–60.
- Linding, R., R. B. Russell, V. Neduvia, and T. J. Gibson. 2003. Globplot: Exploring protein sequences for globularity and disorder. *Nucleic acids research* 31:3701–8.
- McKusick, V. A. 2007. Mendelian inheritance in man and its online version, omim. *American journal of human genetics* 80:588–604.
- Schultz, J., F. Milpetz, P. Bork, and C. P. Ponting. 1998. Smart, a simple modular architecture research tool: identification of signaling domains. *Proceedings of the National Academy of Sciences of the United States of America* 95:5857–64.
- Sievers, F., A. Wilm, D. Dineen, T. J. Gibson, K. Karplus, W. Li, R. Lopez, H. McWilliam, M. Remmert, J. Söding, J. D. Thompson, and D. G. Higgins. 2011. Fast, scalable generation of high-quality protein multiple sequence alignments using clustal omega. *Molecular systems biology* 7:539.

- Suzek, B. E., H. Huang, P. McGarvey, R. Mazumder, and C. H. Wu. 2007. Uniref: comprehensive and non-redundant uniprot reference clusters. Bioinformatics (Oxford, England) 23:1282–8.
- Tompa, P., N. E. Davey, T. J. Gibson, and M. M. Babu. 2014. A million peptide motifs for the molecular biologist. Molecular cell 55:161–9.
- Van Roey, K., H. Dinkel, R. J. Weatheritt, T. J. Gibson, and N. E. Davey. 2013. The switches.elm resource: a compendium of conditional regulatory interaction interfaces. Science signaling 6:rs7.
- Van Roey, K., T. J. Gibson, and N. E. Davey. 2012. Motif switches: decision-making in cell regulation. Current opinion in structural biology 22:378–85.
- Van Roey, K., B. Uyar, R. J. Weatheritt, H. Dinkel, M. Seiler, A. Budd, T. J. Gibson, and N. E. Davey. 2014. Short linear motifs: ubiquitous and functionally diverse protein interaction modules directing cell regulation. Chemical reviews 114:6733–78.
- Via, A., C. M. Gould, C. Gemünd, T. J. Gibson, and M. Helmer-Citterich. 2009. A structure filter for the eukaryotic linear motif resource. BMC bioinformatics 10:351.
- Waterhouse, A. M., J. B. Procter, D. M. A. Martin, M. Clamp, and G. J. Barton. 2009. Jalview version 2—a multiple sequence alignment editor and analysis workbench. Bioinformatics (Oxford, England) 25:1189–91.
- Wright, P. E. and H. J. Dyson. 1999. Intrinsically unstructured proteins: re-assessing the protein structure-function paradigm. Journal of molecular biology 293:321–31.