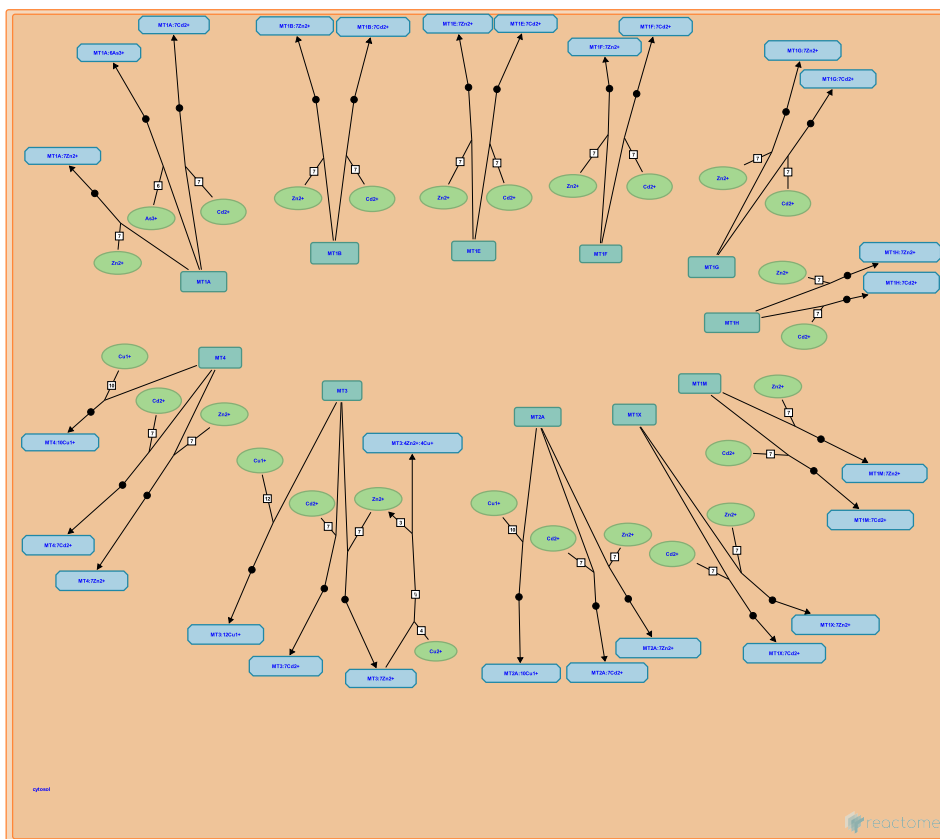


Metallothioneins bind metals



Atrian, S., May, B.

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Introduction

Reactome is open-source, open access, manually curated and peer-reviewed pathway database. Pathway annotations are authored by expert biologists, in collaboration with Reactome editorial staff and cross-referenced to many bioinformatics databases. A system of evidence tracking ensures that all assertions are backed up by the primary literature. Reactome is used by clinicians, geneticists, genomics researchers, and molecular biologists to interpret the results of high-throughput experimental studies, by bioinformaticians seeking to develop novel algorithms for mining knowledge from genomic studies, and by systems biologists building predictive models of normal and disease variant pathways.

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Literature references

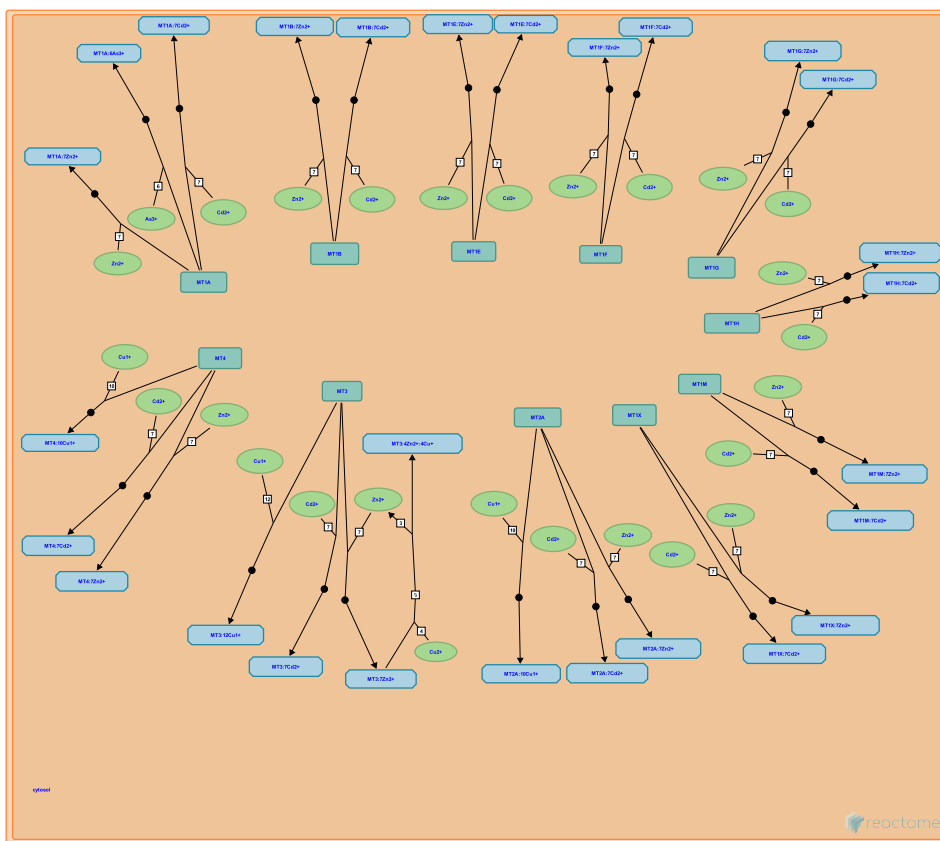
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Reactome database release: 70

This document contains 1 pathway and 27 reactions ([see Table of Contents](#))

Metallothioneins bind metals ↗

Stable identifier: R-HSA-5661231



Metallothioneins are highly conserved, cysteine-rich proteins that bind metals via thiolate bonds (recent general reviews in Capdevila et al. 2012, Blindauer et al. 2014, reviews of mammalian metallothioneins in Miles et al. 2000, Maret 2011, Vasak and Meloni 2011, Thirumoorthy et al. 2001, Babula et al. 2012). Mammals contain 4 general metallothionein isoforms (MT1,2,3,4). The MT1 isoform has radiated in primates to 8 or 9 functional proteins (depending on classification of MT1L). Each mammalian metallothionein binds a total of 7 divalent metal ions in two clusters, the alpha and beta clusters. Though the functions of metallothioneins have not been fully elucidated, they appear to participate in detoxifying heavy metals (reviewed in Sharma et al. 2013), storing and transporting zinc, and redox biochemistry. Metallothioneins interact with many other cellular proteins, with most interactions involving proteins of the central nervous system (reviewed in Atrian and Capdevila 2013).

Literature references

- Sharma, S., Rais, A., Sandhu, R., Nel, W., Ebadi, M. (2013). Clinical significance of metallothioneins in cell therapy and nanomedicine. *Int J Nanomedicine*, 8, 1477-88. ↗
- Capdevila, M., Bofill, R., Palacios, Ò., Atrian, S. (2012). State-of-the-art of metallothioneins at the beginning of the 21st century. *Coord. Chem. Reviews*, 256, 46-62.
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- Miles, AT., Hawksworth, GM., Beattie, JH., Rodilla, V. (2000). Induction, regulation, degradation, and biological significance of mammalian metallothioneins. *Crit. Rev. Biochem. Mol. Biol.*, 35, 35-70. ↗
- Blindauer, CA. (2014). Metallothioneins, Binding, Transport and Storage of Metal Ions in Biological Cells. *Royal Society of Chemistry*, 594-653.

Editions

2015-01-07	Authored, Edited	May, B.
2015-09-19	Reviewed	Atrian, S.

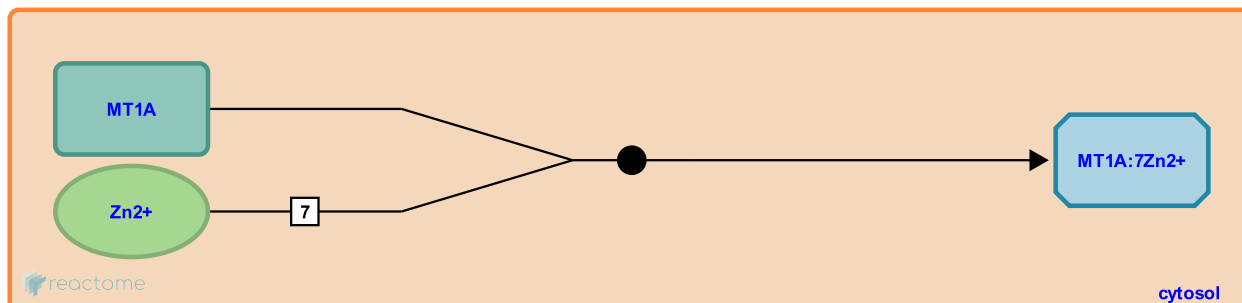
MT1A binds zinc ↗

Location: [Metallothioneins bind metals](#)

Stable identifier: R-HSA-5661217

Type: binding

Compartments: cytosol



The MT1A metallothionein binds 7 zinc(II) atoms, 3 at the N-terminal beta domain and 4 at the C-terminal alpha domain (Sunderland et al. 2012). Binding is non-cooperative (Sunderland et al. 2012) and occurs via thiolate bonds between zinc and cysteine residues of the protein. MT1A binds 5 atoms of zinc before clustering of the zinc occurs (Summers et al. 2013). The 2 remaining zinc atoms bind MT1A with significantly less affinity (Summers et al. 2013).

Literature references

- Summers, KL., Sutherland, DE., Stillman, MJ. (2013). Single-domain metallothioneins: evidence of the onset of clustered metal binding domains in Zn-rhMT 1a. *Biochemistry*, 52, 2461-71. ↗
- Sutherland, DE., Summers, KL., Stillman, MJ. (2012). Modeling the Zn(2+) and Cd(2+) metalation mechanism in mammalian metallothionein 1a. *Biochem. Biophys. Res. Commun.*, 426, 601-7. ↗
- Sutherland, DE., Summers, KL., Stillman, MJ. (2012). Noncooperative metalation of metallothionein 1a and its isolated domains with zinc. *Biochemistry*, 51, 6690-700. ↗

Editions

2015-01-07	Authored, Edited	May, B.
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MT1A binds cadmium ↗

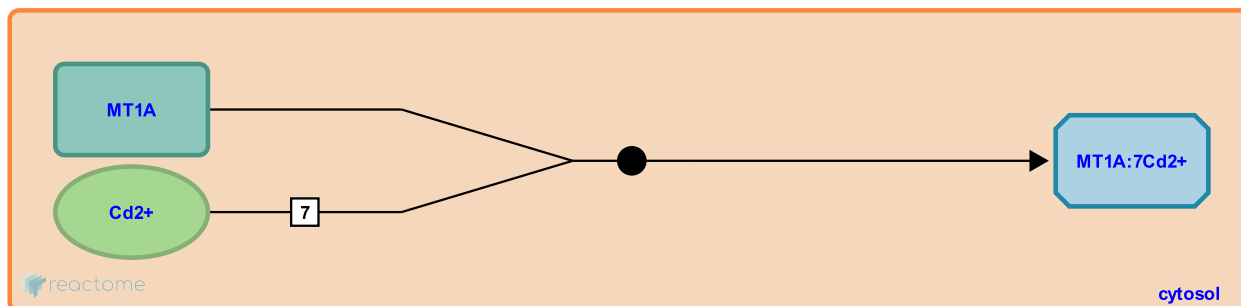
Location: [Metallothioneins bind metals](#)

Stable identifier: R-HSA-5661219

Type: binding

Compartments: cytosol

Inferred from: [Mt1 binds cadmium \(Mus musculus\)](#)



MT1A binds 7 atoms of cadmium(II), 3 atoms at the N-terminal beta domain and 4 atoms at the C-terminal alpha domain (Rigby Duncan et al. 2008, Sunderland and Stillman 2008, Sutherland et al. 2012). A fifth cadmium atom bound to the alpha domain may be an intermediate formed during metal exchange (Rigby Duncan et al. 2008). Binding of cadmium is non-cooperative (Rigby Duncan and Stillman 2007, Sunderland and Stillman 2008). As inferred from mouse Mt1, MT1A may show less preference for zinc compared with cadmium and may therefore serve more than other metallothionein isoforms to detoxify cadmium.

Literature references

- Sutherland, DE., Stillman, MJ. (2008). Noncooperative cadmium(II) binding to human metallothionein 1a. *Biochem. Biophys. Res. Commun.*, 372, 840-4. ↗
- Rigby Duncan, KE., Kirby, CW., Stillman, MJ. (2008). Metal exchange in metallothioneins: a novel structurally significant Cd(5) species in the alpha domain of human metallothionein 1a. *FEBS J.*, 275, 2227-39. ↗
- Rigby Duncan, KE., Stillman, MJ. (2007). Evidence for noncooperative metal binding to the alpha domain of human metallothionein. *FEBS J.*, 274, 2253-61. ↗
- Sutherland, DE., Summers, KL., Stillman, MJ. (2012). Modeling the Zn(2+) and Cd(2+) metalation mechanism in mammalian metallothionein 1a. *Biochem. Biophys. Res. Commun.*, 426, 601-7. ↗
- Sutherland, DE., Willans, MJ., Stillman, MJ. (2012). Single domain metallothioneins: supermetalation of human MT 1a. *J. Am. Chem. Soc.*, 134, 3290-9. ↗

Editions

2015-01-07	Authored, Edited	May, B.
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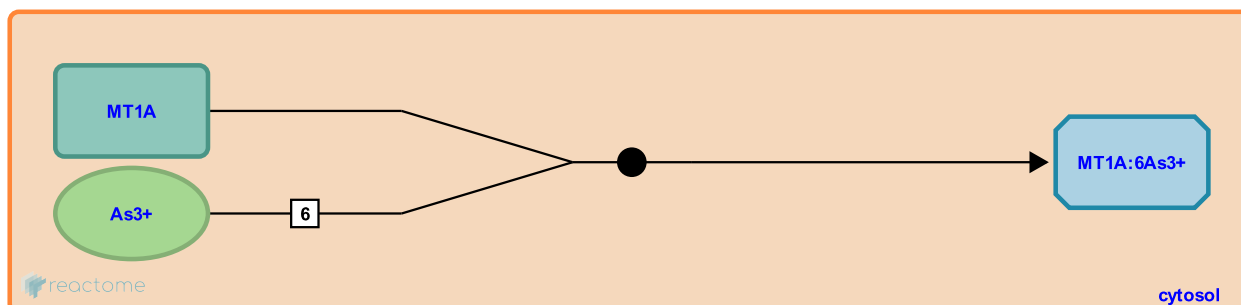
MT1A binds arsenic [↗](#)

Location: [Metallothioneins bind metals](#)

Stable identifier: R-HSA-5661230

Type: binding

Compartments: cytosol



Metallothionein MT1A binds 6 atoms of arsenic(III), 3 atoms at the N-terminal beta domain and 3 atoms at the C-terminal alpha domain (Ngu and Stillman 2006, Irvine et al. 2013). Each arsenic atom binds 3 cysteine thiols (Ngu and Stillman 2006, Irvine et al. 2013).

Literature references

Irvine, GW., Summers, KL., Stillman, MJ. (2013). Cysteine accessibility during As³⁺ metalation of the β- and α-domains of recombinant human MT1a. *Biochem. Biophys. Res. Commun.*, 433, 477-83. [↗](#)

Ngu, TT., Stillman, MJ. (2006). Arsenic binding to human metallothionein. *J. Am. Chem. Soc.*, 128, 12473-83. [↗](#)

Editions

2015-01-07	Authored, Edited	May, B.
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MT1B binds zinc ↗

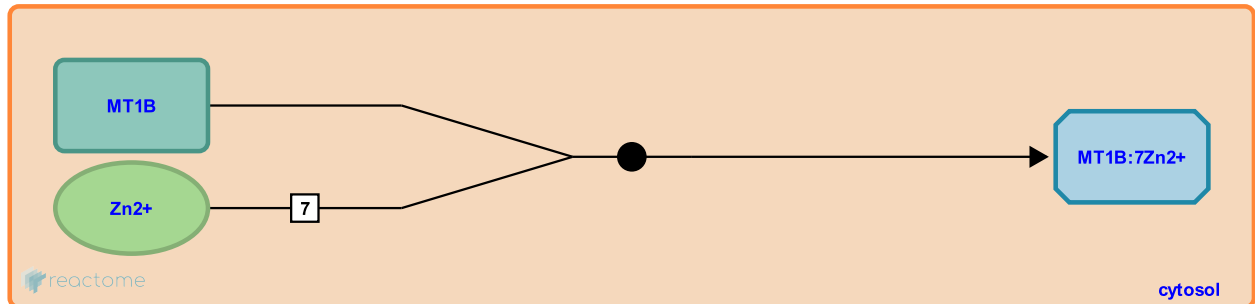
Location: [Metallothioneins bind metals](#)

Stable identifier: R-HSA-5662603

Type: binding

Compartments: cytosol

Inferred from: [MT1A binds zinc \(Homo sapiens\)](#)



As inferred from MT1A, the metallothionein MT1B binds 7 atoms of zinc(II) non-cooperatively.

Editions

2015-01-09	Authored, Edited	May, B.
2015-09-19	Reviewed	Atrian, S.

MT1B binds cadmium ↗

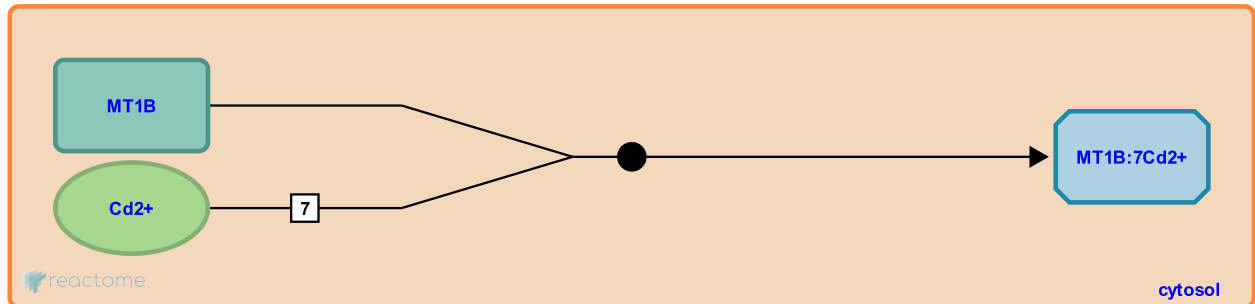
Location: [Metallothioneins bind metals](#)

Stable identifier: R-HSA-5662610

Type: binding

Compartments: cytosol

Inferred from: [MT1A binds cadmium \(Homo sapiens\)](#)



As inferred from MT1A, the metallothionein MT1B binds 7 atoms of cadmium(II) non-cooperatively.

Editions

2015-01-09	Authored, Edited	May, B.
2015-09-19	Reviewed	Atrian, S.

MT1E binds zinc ↗

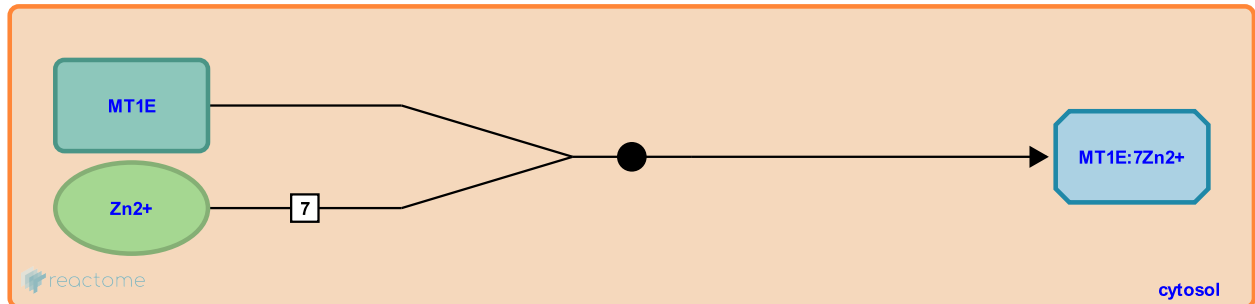
Location: [Metallothioneins bind metals](#)

Stable identifier: R-HSA-5662614

Type: binding

Compartments: cytosol

Inferred from: [MT1A binds zinc \(Homo sapiens\)](#)



As inferred from MT1A, the metallothionein MT1E binds 7 atoms of zinc(II) non-cooperatively.

Editions

2015-01-09	Authored, Edited	May, B.
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MT1E binds cadmium ↗

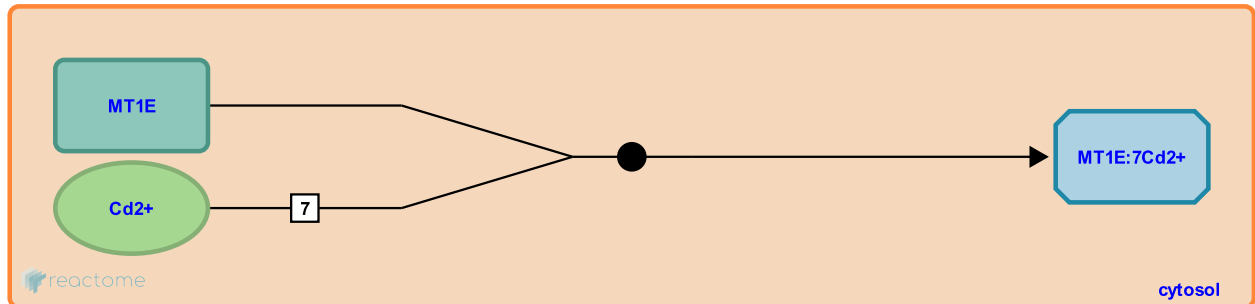
Location: [Metallothioneins bind metals](#)

Stable identifier: R-HSA-5662595

Type: binding

Compartments: cytosol

Inferred from: [MT1A binds cadmium \(Homo sapiens\)](#)



As inferred from MT1A, the metallothionein MT1E binds 7 atoms of cadmium(II) non-cooperatively.

Editions

2015-01-09	Authored, Edited	May, B.
2015-09-19	Reviewed	Atrian, S.

MT1F binds zinc ↗

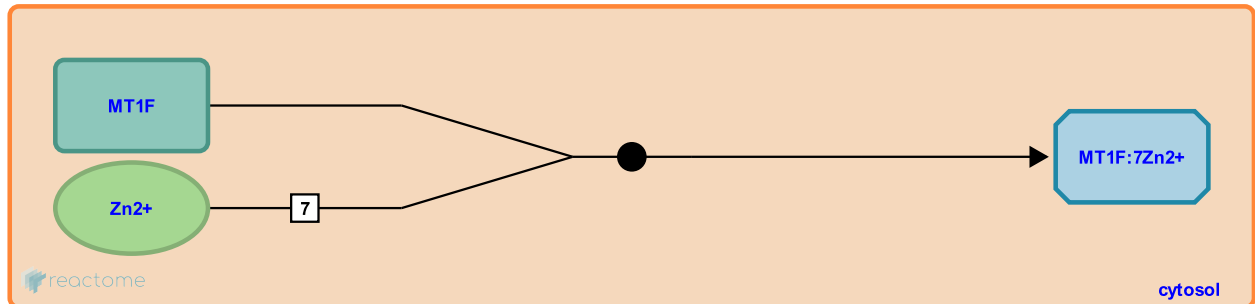
Location: [Metallothioneins bind metals](#)

Stable identifier: R-HSA-5662623

Type: binding

Compartments: cytosol

Inferred from: [MT1A binds zinc \(Homo sapiens\)](#)



As inferred from MT1A, the metallothionein MT1F binds 7 atoms of zinc(II) non-cooperatively.

Editions

2015-01-09	Authored, Edited	May, B.
2015-09-19	Reviewed	Atrian, S.

MT1F binds cadmium ↗

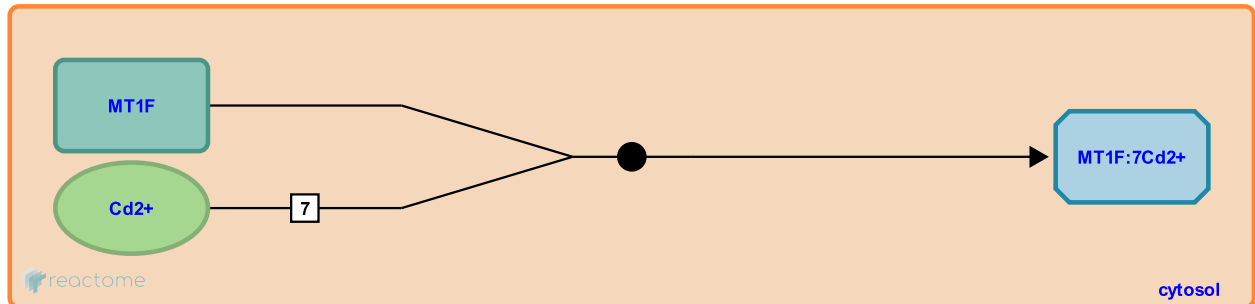
Location: [Metallothioneins bind metals](#)

Stable identifier: R-HSA-5662596

Type: binding

Compartments: cytosol

Inferred from: [MT1A binds cadmium \(Homo sapiens\)](#)



As inferred from MT1A, the metallothionein MT1F binds 7 atoms of cadmium(II) non-cooperatively.

Editions

2015-01-09	Authored, Edited	May, B.
2015-09-19	Reviewed	Atrian, S.

MT1G binds zinc ↗

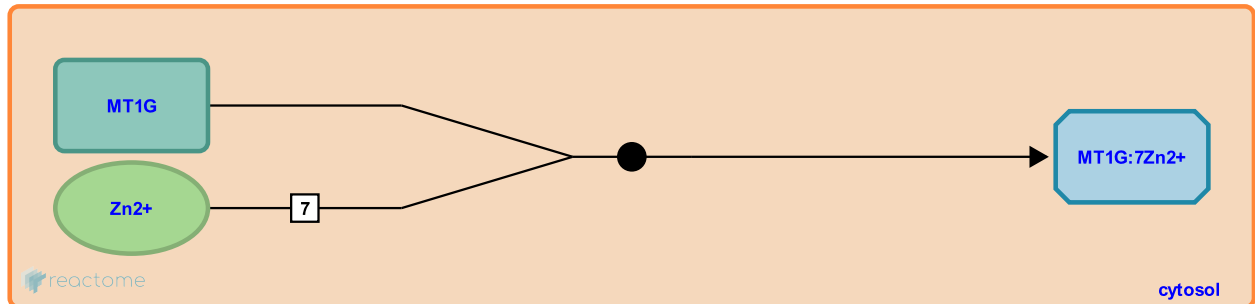
Location: [Metallothioneins bind metals](#)

Stable identifier: R-HSA-5662618

Type: binding

Compartments: cytosol

Inferred from: [MT1A binds zinc \(Homo sapiens\)](#)



As inferred from MT1A, the metallothionein MT1G binds 7 atoms of zinc(II) non-cooperatively.

Editions

2015-01-09	Authored, Edited	May, B.
2015-09-19	Reviewed	Atrian, S.

MT1G binds cadmium ↗

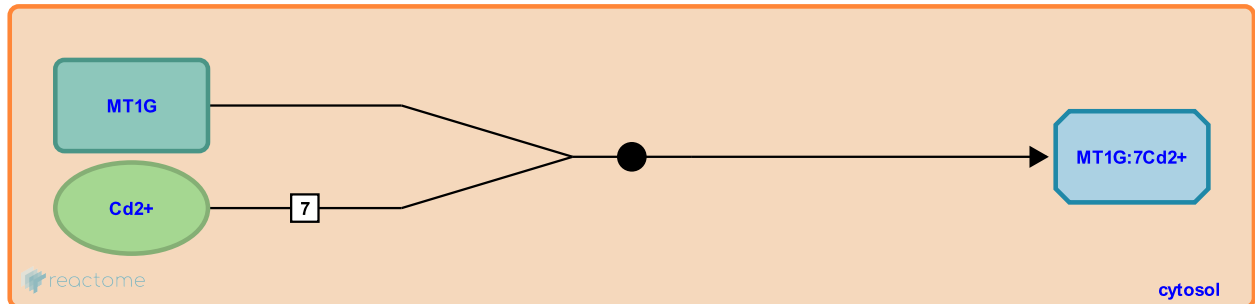
Location: [Metallothioneins bind metals](#)

Stable identifier: R-HSA-5662617

Type: binding

Compartments: cytosol

Inferred from: [MT1A binds cadmium \(Homo sapiens\)](#)



As inferred from MT1A, the metallothionein MT1G binds 7 atoms of cadmium(II) non-cooperatively.

Editions

2015-01-09	Authored, Edited	May, B.
2015-09-19	Reviewed	Atrian, S.

MT1H binds zinc ↗

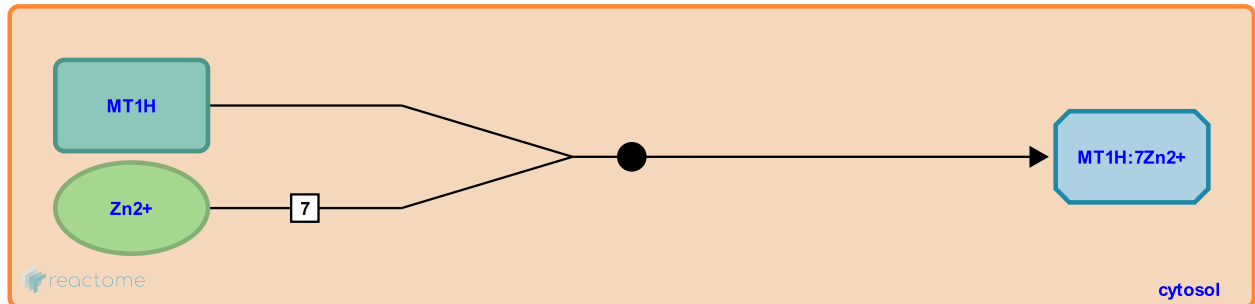
Location: [Metallothioneins bind metals](#)

Stable identifier: R-HSA-5662619

Type: binding

Compartments: cytosol

Inferred from: [MT1A binds zinc \(Homo sapiens\)](#)



As inferred from MT1A, the metallothionein MT1H binds 7 atoms of zinc(II) non-cooperatively.

Editions

2014-02-07	Edited	May, B.
2015-01-09	Authored	May, B.
2015-09-19	Reviewed	Atrian, S.

MT1H binds cadmium ↗

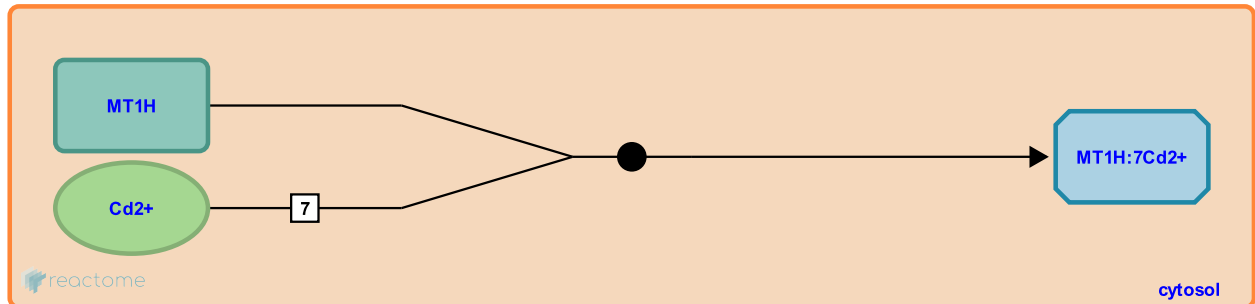
Location: [Metallothioneins bind metals](#)

Stable identifier: R-HSA-5662597

Type: binding

Compartments: cytosol

Inferred from: [MT1A binds cadmium \(Homo sapiens\)](#)



As inferred from MT1A, the metallothionein MT1H binds 7 atoms of cadmium(II) non-cooperatively.

Editions

2015-01-09	Authored, Edited	May, B.
2015-09-19	Reviewed	Atrian, S.

MT1M binds zinc ↗

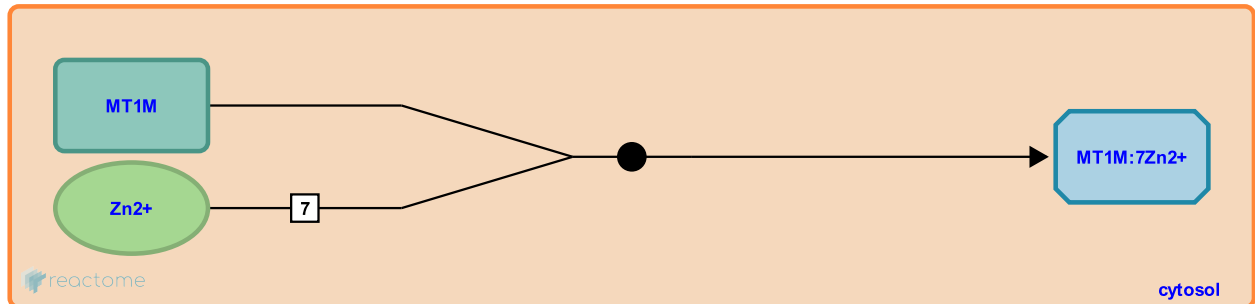
Location: [Metallothioneins bind metals](#)

Stable identifier: R-HSA-5662621

Type: binding

Compartments: cytosol

Inferred from: [MT1A binds zinc \(Homo sapiens\)](#)



As inferred from MT1A, the metallothionein MT1M binds 7 atoms of zinc(II) non-cooperatively.

Editions

2015-01-09	Authored, Edited	May, B.
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MT1M binds cadmium ↗

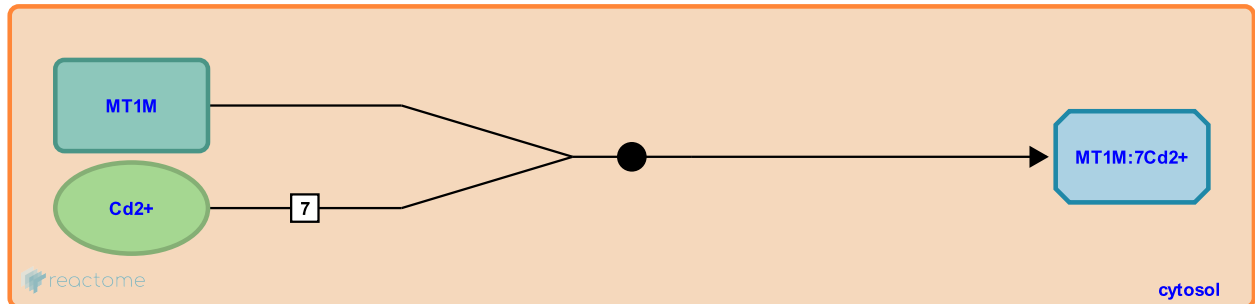
Location: [Metallothioneins bind metals](#)

Stable identifier: R-HSA-5662599

Type: binding

Compartments: cytosol

Inferred from: [MT1A binds cadmium \(Homo sapiens\)](#)



As inferred from MT1A, the metallothionein MT1M binds 7 atoms of cadmium(II) non-cooperatively.

Editions

2015-01-09	Authored, Edited	May, B.
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MT1X binds zinc ↗

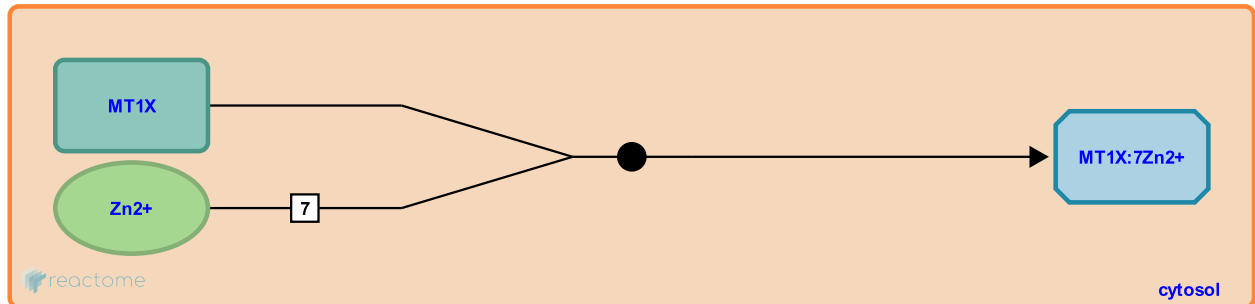
Location: [Metallothioneins bind metals](#)

Stable identifier: R-HSA-5662615

Type: binding

Compartments: cytosol

Inferred from: [MT1A binds zinc \(Homo sapiens\)](#)



As inferred from MT1A, the metallothionein MT1X binds 7 atoms of zinc(II) non-cooperatively.

Editions

2015-01-09	Authored, Edited	May, B.
2015-09-19	Reviewed	Atrian, S.

MT1X binds cadmium ↗

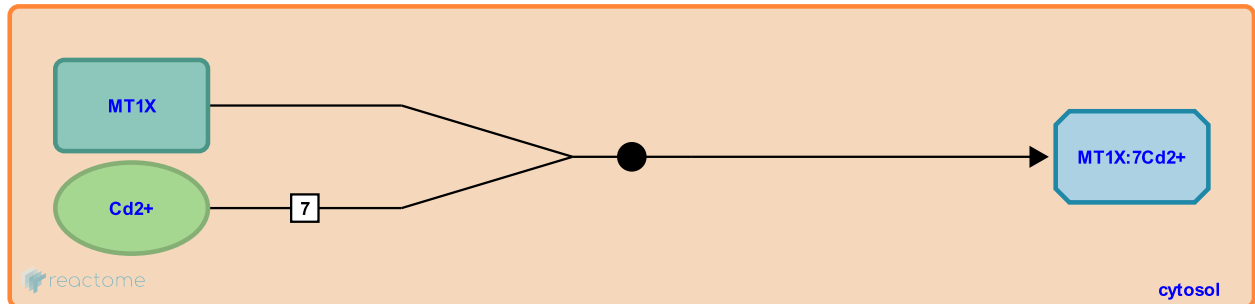
Location: [Metallothioneins bind metals](#)

Stable identifier: R-HSA-5662622

Type: binding

Compartments: cytosol

Inferred from: [MT1A binds cadmium \(Homo sapiens\)](#)



As inferred from MT1A, metallothionein MT1X binds 7 atoms of cadmium(II) non-cooperatively.

Editions

2015-01-09	Authored, Edited	May, B.
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MT2A binds zinc ↗

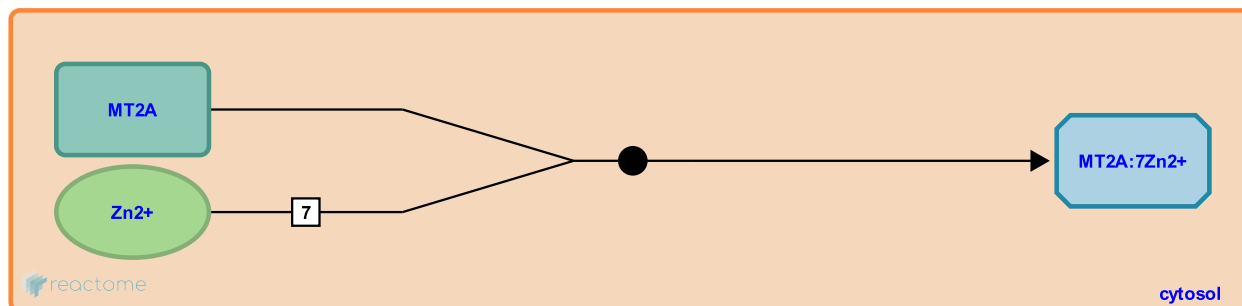
Location: [Metallothioneins bind metals](#)

Stable identifier: R-HSA-5662598

Type: binding

Compartments: cytosol

Inferred from: [Mt2 binds zinc \(Mus musculus\)](#)



The metallothionein MT2A binds 7 atoms of zinc(II) in two clusters, one at the N-terminal beta domain and one at the C-terminal alpha domain (Stillman et al. 2000, Yang et al. 2007). The cluster at the alpha domain is more stable than the cluster at the beta domain, making the beta domain a better zinc donor (Jiang et al. 2000). Each cluster assembles independently (Jiang et al. 2000).

Literature references

- Yang, F., Zhou, M., He, Z., Liu, X., Sun, L., Sun, Y. et al. (2007). High-yield expression in Escherichia coli of soluble human MT2A with native functions. *Protein Expr. Purif.*, 53, 186-94. ↗
- Stillman, MJ., Thomas, D., Trevithick, C., Guo, X., Siu, M. (2000). Circular dichroism, kinetic and mass spectrometric studies of copper(I) and mercury(II) binding to metallothionein. *J. Inorg. Biochem.*, 79, 11-9. ↗
- Jiang, LJ., Vasák, M., Vallee, BL., Maret, W. (2000). Zinc transfer potentials of the alpha - and beta-clusters of metallothionein are affected by domain interactions in the whole molecule. *Proc. Natl. Acad. Sci. U.S.A.*, 97, 2503-8. ↗

Editions

2015-01-09	Authored, Edited	May, B.
2015-09-19	Reviewed	Atrian, S.

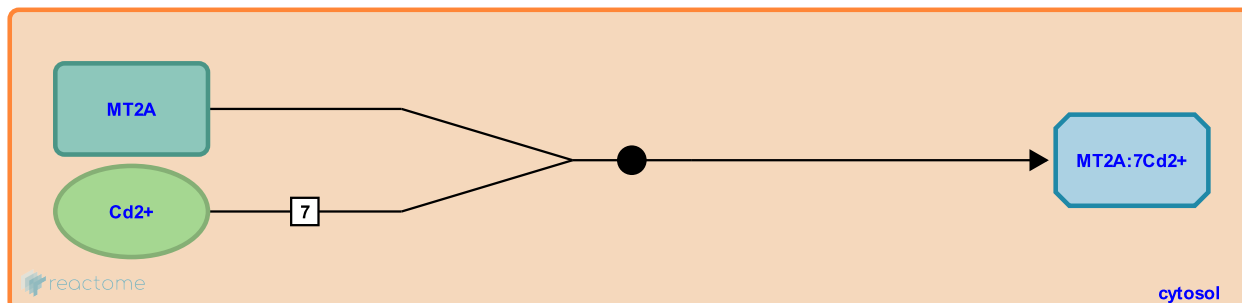
MT2A binds cadmium ↗

Location: [Metallothioneins bind metals](#)

Stable identifier: R-HSA-5662608

Type: binding

Compartments: cytosol



The metallothionein MT2A binds 7 atoms of cadmium(II), a cluster of 4 atoms at the alpha domain at the C-terminus and a cluster of 3 atoms at the beta domain at the N-terminus (Pan et al. 1999).

Literature references

Pan, PK., Zheng, ZF., Lyu, PC., Huang, PC. (1999). Why reversing the sequence of the alpha domain of human metallothionein-2 does not change its metal-binding and folding characteristics. *Eur. J. Biochem.*, 266, 33-9. ↗

Editions

2015-01-09	Authored, Edited	May, B.
2015-09-19	Reviewed	Atrian, S.

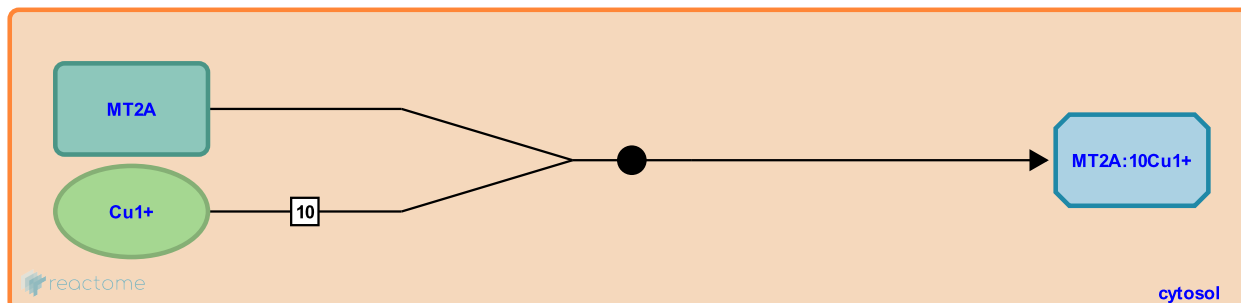
MT2A binds copper ↗

Location: [Metallothioneins bind metals](#)

Stable identifier: R-HSA-5662986

Type: binding

Compartments: cytosol



The metallothionein MT2A binds 10 atoms of copper(I). Complexes with up to 12 atoms of Cu⁺ are observed, however the predominant form appears to be MT2A:10Cu⁺ (Banci et al. 2010, Chung et al. 2010). Metallothioneins and CuZn-SOD have the highest affinities of cellular proteins for copper(I), but metallothioneins are incapable of removing copper from other cellular enzymes (Banci et al. 2010).

Literature references

Chung, RS., Howells, C., Eaton, ED., Shabala, L., Zovo, K., Palumaa, P. et al. (2010). The native copper- and zinc-binding protein metallothionein blocks copper-mediated Abeta aggregation and toxicity in rat cortical neurons. *PLoS ONE*, 5, e12030. ↗

Banci, L., Bertini, I., Ciofi-Baffoni, S., Kozyreva, T., Zovo, K., Palumaa, P. (2010). Affinity gradients drive copper to cellular destinations. *Nature*, 465, 645-8. ↗

Editions

2015-01-12	Authored, Edited	May, B.
2015-09-19	Reviewed	Atrian, S.

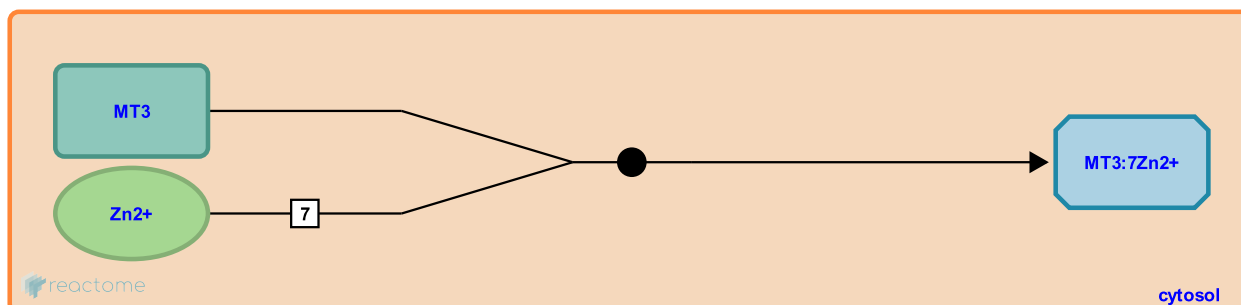
MT3 binds zinc ↗

Location: [Metallothioneins bind metals](#)

Stable identifier: R-HSA-5662606

Type: binding

Compartments: cytosol



The metallothionein MT3 binds 7 zinc(II) atoms in 2 clusters, one cluster of 4 atoms at the C-terminal alpha domain and one cluster of 3 atoms at the N-terminal beta domain (Eriste et al. 2003, Knipp et al. 2005, Meloni et al. 2007, Meloni et al. 2008, Meloni et al. 2009, Wu et al. 2014). Though MT3 has a lower overall affinity for zinc than MT2A does (Palumaa et al. 2005), MT3 is capable of binding an additional zinc atom with a binding constant of 100 micromolar (Eriste et al. 2003, Palumaa et al. 2005, Meloni et al. 2009). Stoichiometries up to MT3:11Zn²⁺ have been observed but the MT3:7Zn²⁺ form is more stable and predominates (Palumaa et al. 2002, Eriste et al. 2003, Palumaa et al.).

Followed by: [MT3 exchanges zinc for copper](#)

Literature references

- Meloni, G., Polanski, T., Braun, O., Vasák, M. (2009). Effects of Zn(2+), Ca(2+), and Mg(2+) on the structure of Zn(7)-metallothionein-3: evidence for an additional zinc binding site. *Biochemistry*, 48, 5700-7. ↗
- Meloni, G., Sonois, V., Delaine, T., Guilloreau, L., Gillet, A., Teissié, J. et al. (2008). Metal swap between Zn7-metallothionein-3 and amyloid-beta-Cu protects against amyloid-beta toxicity. *Nat. Chem. Biol.*, 4, 366-72. ↗
- Meloni, G., Faller, P., Vasák, M. (2007). Redox silencing of copper in metal-linked neurodegenerative disorders: reaction of Zn7metallothionein-3 with Cu²⁺ ions. *J. Biol. Chem.*, 282, 16068-78. ↗
- Knipp, M., Meloni, G., Roschitzki, B., Vasák, M. (2005). Zn7metallothionein-3 and the synaptic vesicle cycle: interaction of metallothionein-3 with the small GTPase Rab3A. *Biochemistry*, 44, 3159-65. ↗
- Palumaa, P., Tammiste, I., Kruusel, K., Kangur, L., Jörnvall, H., Sillard, R. (2005). Metal binding of metallothionein-3 versus metallothionein-2: lower affinity and higher plasticity. *Biochim. Biophys. Acta*, 1747, 205-11. ↗

Editions

2015-01-09	Authored, Edited	May, B.
2015-09-19	Reviewed	Atrian, S.

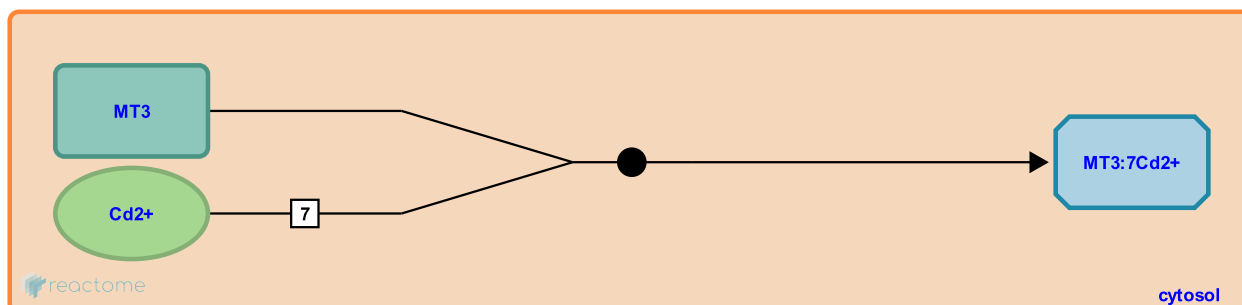
MT3 binds cadmium ↗

Location: [Metallothioneins bind metals](#)

Stable identifier: R-HSA-5662620

Type: binding

Compartments: cytosol



The metallothionein binds 7 atoms of cadmium(II) in 2 clusters, 4 atoms at the C-terminal alpha domain and 3 atoms at the N-terminal beta domain (Palumaa et al. 2002, Palumaa et al. 2005, Wu et al. 2014). MT3 binds cadmium with a lower affinity than MT2A does (Palumaa et al. 2005). MT3 can bind more than 7 cadmium atoms, however the MT3:7Cd²⁺ complex is most prevalent (Palumaa et al. 2002, Palumaa et al. 2005). Exposure of MT3:7Cd²⁺ to nitric oxide causes release of cadmium (Wang et al. 2008).

Literature references

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- Wu, Q., Li, B., Wu, F., Yang, L., Li, S., Li, H. et al. (2014). High level expression, efficient purification, and bioactivity of recombinant human metallothionein 3 (rhMT3) from methylotrophic yeast *Pichia pastoris*. *Protein Expr. Purif.*, 101, 121-6. ↗
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Editions

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MT3 binds copper ↗

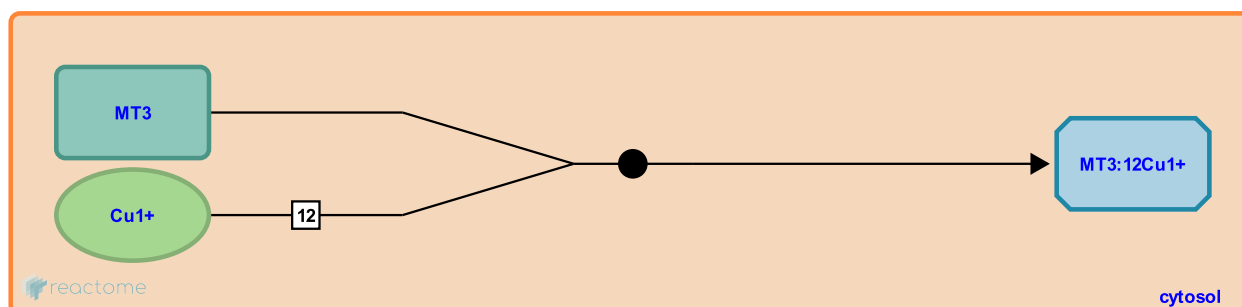
Location: [Metallothioneins bind metals](#)

Stable identifier: R-HSA-5663002

Type: binding

Compartments: cytosol

Inferred from: [Mt3 binds copper \(Mus musculus\)](#)



The metallothionein MT3 is able to bind 12 copper(I) atoms when fully saturated (Roschitzki et al. 2002). Initially, 4 copper(I) atoms bind to each of the alpha and beta domains followed by the binding of 4 more copper(I) atoms. As inferred from the mouse homolog, MT3 exhibits a Cu-thionein character stronger than that of the MT1 and MT2 isoforms and it displays a high capacity to bind Cu⁺ provided that this occurs in a non-oxidative milieu.

Literature references

Roschitzki, B., Vasák, M. (2002). A distinct Cu(4)-thiolate cluster of human metallothionein-3 is located in the N-terminal domain. *J. Biol. Inorg. Chem.*, 7, 611-6. ↗

Editions

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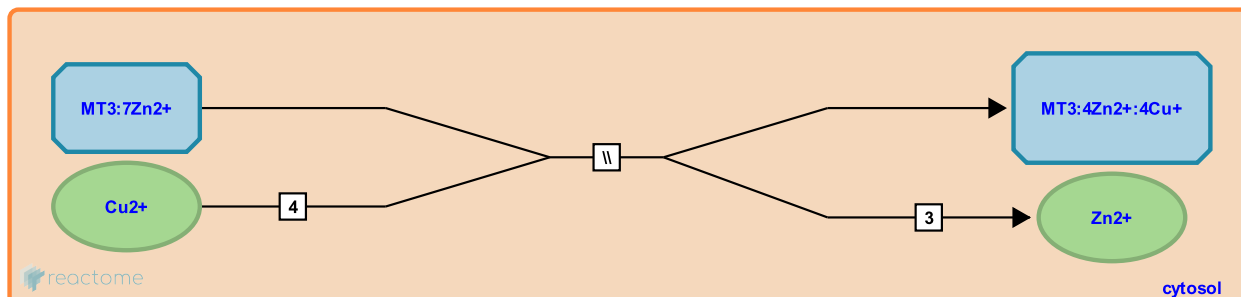
MT3 exchanges zinc for copper ↗

Location: [Metallothioneins bind metals](#)

Stable identifier: R-HSA-5662613

Type: omitted

Compartments: cytosol



MT3:7Zn²⁺ releases 3 zinc ions and binds 4 copper ions at the N-terminal beta domain (Roschitszi et al. 2003, Meloni et al. 2007, Meloni et al. 2008). By this mechanism MT3 is able to scavenge free copper ions and swap metal with an aggregated amyloid beta:copper(II) complex and a alpha-synuclein:copper(II) complex and thereby abolish production of reactive oxygen species (Meloni et al. 2008, Meloni and Vasak 2011, Pedersen et al. 2012, Luo et al. 2013). The copper ions are divalent (copper(II), Cu²⁺) before binding but univalent (copper(I), Cu¹⁺) after binding (Meloni et al. 2008).

Preceded by: [MT3 binds zinc](#)

Literature references

- Meloni, G., Sonois, V., Delaine, T., Guilloreau, L., Gillet, A., Teissié, J. et al. (2008). Metal swap between Zn₇-metallothionein-3 and amyloid-beta-Cu protects against amyloid-beta toxicity. *Nat. Chem. Biol.*, 4, 366-72. ↗
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Editions

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MT4 binds zinc ↗

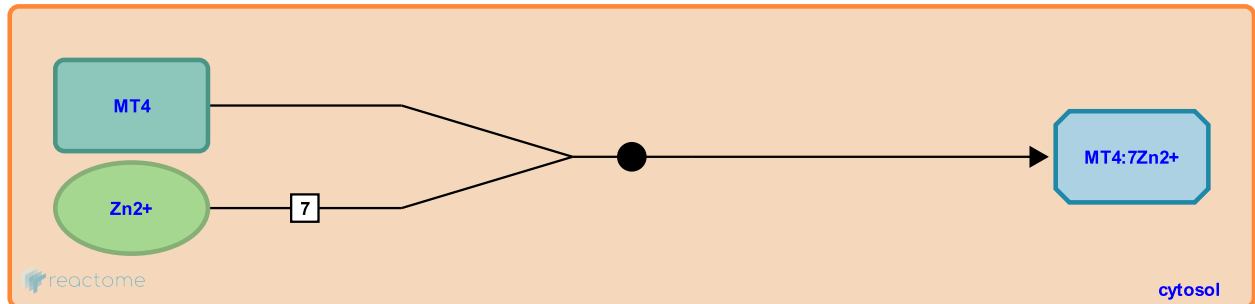
Location: [Metallothioneins bind metals](#)

Stable identifier: R-HSA-5662653

Type: binding

Compartments: cytosol

Inferred from: [Mt4 binds zinc \(Mus musculus\)](#)



As inferred from the mouse homolog, MT4 binds 7 atoms of zinc(II).

Editions

2015-01-12	Authored, Edited	May, B.
2015-09-19	Reviewed	Atrian, S.

MT4 binds cadmium [↗](#)

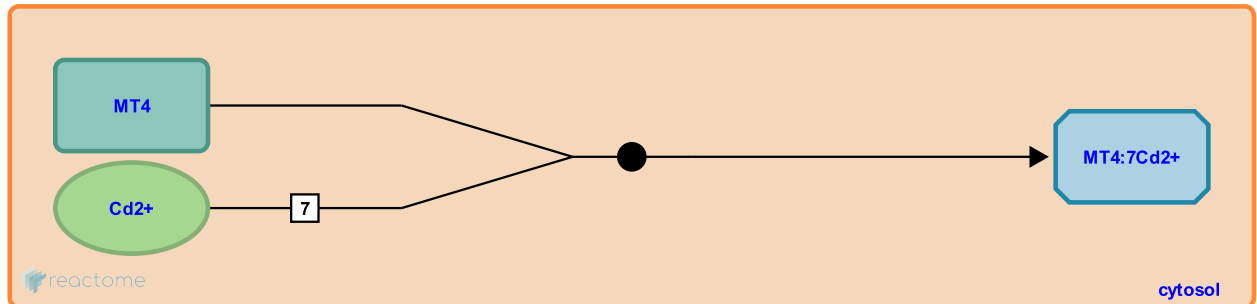
Location: [Metallothioneins bind metals](#)

Stable identifier: R-HSA-5662649

Type: binding

Compartments: cytosol

Inferred from: [Mt4 binds cadmium \(Mus musculus\)](#)



As inferred from the mouse homolog, MT4 binds 7 atoms of cadmium(II).

Editions

2015-01-12	Authored, Edited	May, B.
2015-09-19	Reviewed	Atrian, S.

MT4 binds copper ↗

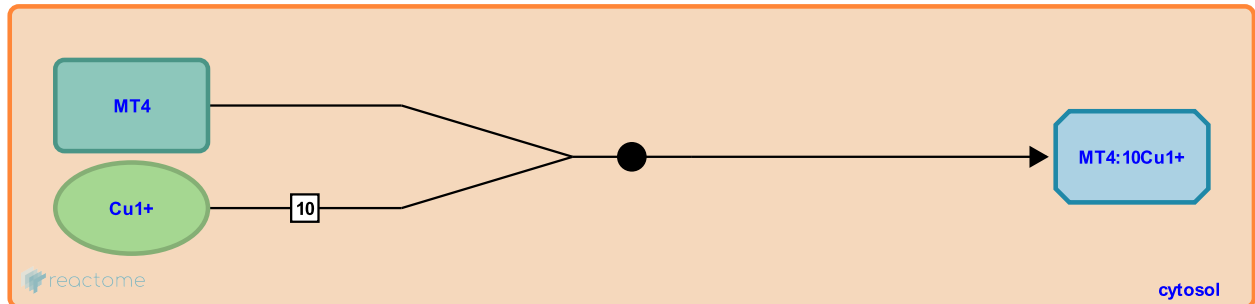
Location: [Metallothioneins bind metals](#)

Stable identifier: R-HSA-5662647

Type: binding

Compartments: cytosol

Inferred from: [Mt4 binds copper \(Mus musculus\)](#)



As inferred from the mouse homolog, MT4 binds 10 atoms of copper(I).

Literature references

Tío, L., Villarreal, L., Atrian, S., Capdevila, M. (2004). Functional differentiation in the mammalian metallothionein gene family: metal binding features of mouse MT4 and comparison with its paralog MT1. *J. Biol. Chem.*, 279, 24403-13. ↗

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